Integrated Community Energy Systems

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DOI
10.4233/uuid:10d555dd-8f03-4986-b5bf-ef09a63c92e1

Publication date
2017

Document Version
Final published version

Citation (APA)
Koirala, B. (2017). *Integrated Community Energy Systems*. [Dissertation (TU Delft), Delft University of Technology, Universidad Pontificia Comillas, KTH Royal Institute of Technology]. https://doi.org/10.4233/uuid:10d555dd-8f03-4986-b5bf-ef09a63c92e1

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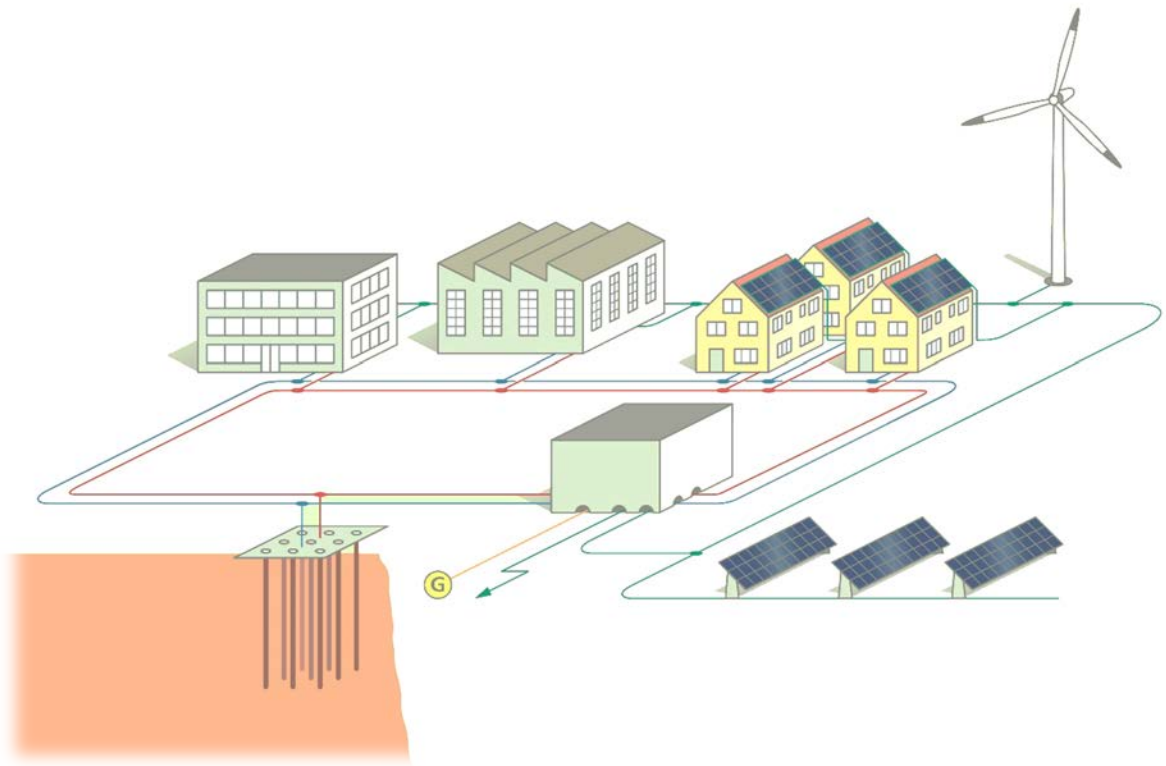
Binod Prasad Koirala



Doctoral Thesis

Delft, The Netherlands 2017

INTEGRATED COMMUNITY ENERGY SYSTEMS

Binod Prasad Koirala

Layout and printing: Gildeprint, Enschede, The Netherlands

INTEGRATED COMMUNITY ENERGY SYSTEMS

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op vrijdag 27 oktober 2017 om 10:00 uur

door

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TRITA-EE 2017- 061
ISSN 1653-5146
ISBN 978-94-6186-827-5

This research was funded by the European Commission through the Erasmus Mundus Joint Doctorate Program on Sustainable Energy Technologies and Strategies and Delft University of Technology.

Keywords: Energy communities, energy system integration, distributed energy resources, local energy exchange, smart grids, institutional design, willingness to participate, grid defection

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Printed in the Netherlands

Dit proefschrift is goedgekeurd door de

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Samenstelling promotiecommissie:

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TRITA-EE 2017- 061
ISSN 1653-5146
ISBN 978-94-6186-827-5

The doctoral research has been carried out in the context of an agreement on joint doctoral supervision between Comillas Pontifical University, Spain, KTH Royal Institute of Technology, Stockholm , Sweden and Delft University of Technology, the Netherlands.

Keywords: Energy communities, energy system integration, distributed energy resources, local energy exchange, smart grids, institutional design

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Printed in the Netherlands

SETS Joint Doctorate

The Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies, SETS joint doctorate, is an international programme run by six institutions in cooperation:

- Comillas Pontifical University, Madrid, Spain
- Delft University of Technology, Delft, the Netherlands
- Florence School of Regulation, Florence, Italy
- Johns Hopkins University, Baltimore, USA
- KTH Royal Institute of Technology, Stockholm, Sweden
- University Paris-Sud 11, Paris, France

The doctoral degrees issued upon completion of the programme are issued by Comillas Pontifical University, Delft University of Technology and KTH Royal Institute of Technology.

The degree certificates are giving reference to the joint programme. The doctoral candidates are jointly supervise, and must pass a joint examination procedure set up by the three institutions issuing the degrees.

This thesis is a part of the examination for the doctoral degree. The invested degrees are official in Spain, the Netherlands and Sweden, respectively.

SETS Joint Doctorate was awarded the Erasmus Mundus **excellence label** by the European commission in year 2010, and the European Commission's Education, Audio-visual and Culture Executive Agency, EACEA, has supported the funding of this programme.

The EACEA is not to be held responsible for the content of the Thesis.

This book is dedicated to my family.

ACKNOWLEDGEMENTS

I started my PhD journey four years ago at Energy and Industry section of Engineering Systems and Services department of Faculty of Technology, Policy and Management at the Delft University of Technology. I was part of Erasmus Mundus Joint doctorate in Sustainable Energy Technologies and Strategies (SETS). These four years my PhD journey has been both adventurous and rewarding. I have definitely grown up both physically and intellectually into a better person and researcher. I would like to take this opportunity to express my gratitude to every individual who supported me in this journey.

Dr. Rudi Hakvoort provided me the opportunity and funding to do this PhD research under his supervision. Your guidance and career support helped me to evolve into an independent researcher. I am indebted to you for your valuable advices, for your time and commitment to my work. I will always miss your Dutch sense of humor that lightened my mood and helped me to stay positive. Your philanthropist activities are an inspiration to me. My sincere gratitude to Prof. Dr. Paulien Herder for advising me through this PhD research. Your network, guidance and support definitely helped me to gain confidence from the very beginning of the long way to this PhD and to finish my research on time. My sincere thanks to Dr. Tienke Ruigh van der Ploeg for mentoring me throughout this research. I am thankful to you for motivating me to improve my skills, for encouraging me to overcome all the obstacles and our hearty conversations. I am also thankful to all my committee members. Your feedback helped to further improve this thesis.

This research would not have been as successful without collaboration with other researchers. Thanks to Elta, Cherelle, Daniel, Marteen, Amineh, Yashar, Jose, Tomas, Jonas, Rudi and Paulien for co-authoring research papers with me. My sincere thanks to Mary and Erik for writing their master thesis with me. It was my pleasure to advise Cristina, Till, Marina, Jessie and Freek in the interdisciplinary project group. My sincere thanks to Eric Woittiez for providing the access to the data of the Heerhugowaard project.

Thanks to my colleagues in TPM for inspiring me and making my stay in Delft so much fun. I thoroughly enjoyed our section outings, section dinners, lunches and drinks. I would especially like to thank Laurens for helping me to shape my research at the beginning. I will miss regular dinner and discussion at your place. My sincere thanks to Reinier for helping me with Dutch translations and also for opposing my thesis. Jorge, my friend, you were very helpful throughout my stay in Delft and beyond, and I will always cherish our friendship and days we spent together. Yesh, you helped me through a difficult moment and I am indebted to you. The research stay in Delft would not have been so fun without my officemates - thanks to Jose, Kaveri, Joao, Salman, Ibtihal and Martin. It was also a lot of fun to work with Jorge, Jan, Lotte and Samaneh in the PhD council. The presentation and discussion at the power rangers peer group meeting were very useful to shape my research. I will miss the lunch discussion with Jose, Juliana, Jorge, Kaveri, Yesh, Elta, Ben, Esther, Tristan, Ozge, Frank, Shantanu and Graciela. My sincere thanks also to Zofia, Andrew, Cherelle, Emile, Sriram, Amineh, Yashar, Remco, Petra, Lidia, Helle, Andrea, Diedre, Frank, Thorben, Kasper, Ivo, Rob, Jaco, Riccardo, Prad, Gijsbert, Chris, Igor, Gerard, Margot, Amit, and Arthur for their support and inspiration.

My sincere thanks to Energy and Industry secretariat. Thank you, Eveline and Prisca for your support during early years as well as Laura and Diones for your support during latter years of my PhD research. I am also thankful to Connie for her support. I am also thankful to Martijn, Leslie and Janine from TPM graduate school. I am also grateful to Sara for supporting through the SETS related issues.

My one year stay in Institute for Research in Technology (IIT) at Comillas Pontifical University in Madrid would not have been successful without the support of Prof. Dr. Tomas Gomez and Dr. José Pablo Chaves Avila. I had to struggle a lot with Spanish bureaucracy but it did not feel much due to your great support. Tomas and my friend, José, I will miss cycling with you around Madrid. Jose, you and Adrian, did everything to feel us home in Madrid. The stay in IIT was very pleasant thanks to also the support of my other colleagues on the fourth floor Pablo, Rafael, Carlos, Ibtihal, Andrea, Mercedes, Andres, Bettina, Mahdi, Luis and Pedro. The presence of SETS colleagues in Madrid was very helpful, my sincere gratitude to José, Zarrar, Cristian, Nenad, Omar, Marina, William, Desta and Mahdi for helping to make the stay in IIT a memorable one.

My sincere thanks to my wonderful parents and siblings for providing support and love from Nepal. Although both of my parents never went to school, they wanted to give me what their parents could not give them – the gift of education. This PhD research is as much honor to them as much as a success to me.

I would also like to take this opportunity to thank my wife, Meline and my daughter, Elise. Meline, I met you at the very beginning of this PhD research. I would not have come this far without your sacrifice, encouragement, support and unconditional love. I am very much indebted to you. Elise, you were born half way through my PhD research. You both are my inspiration and the most beautiful thing that happened to my life.

Binod Koirala

Delft, 30 August 2017

Abstract in English Language

Author: Binod Prasad Koirala
Thesis Title: Integrated Community Energy Systems
Affiliation: Faculty of Technology, Policy and Management, TU Delft
Language: Written in English
Keywords: Energy Communities, Energy System Integration, Distributed Energy Resources, Local Energy Exchange, Smart Grids, Institutional Design

Energy systems across the globe are going through a radical transformation as a result of technological and institutional changes, depletion of fossil fuel resources, and climate change. Accordingly, local energy initiatives are emerging and increasing number of the business models are focusing on the end-users. This requires the present centralized energy systems to be re-organized. In this context, Integrated community energy systems (ICESs) are emerging as a modern development to re-organize local energy systems allowing simultaneous integration of distributed energy resources (DERs) and engagement of local communities. With the emergence of ICESs new roles and responsibilities as well as interactions and dynamics are expected in the energy system. Although local energy initiatives such as ICESs are rapidly emerging due to community objectives, such as cost and emission reductions as well as resiliency, assessment and evaluation of the value that these systems can provide to both local communities and the whole energy system are still lacking. The value of ICESs is also impacted by the institutional settings internal and external to the system. With this background, this thesis aims to understand the ways in which ICESs can contribute to enhancing the energy transition.

This thesis utilizes a conceptual framework consisting of institutional and societal levels in order to understand the interaction and dynamics of ICESs implementation. Current energy trends and the associated technological, socio-economic, environmental and institutional issues are reviewed. The developed ICES model performs optimal planning and operation of ICESs and assesses their performance based on economic and environmental metrics. For the considered community size and local conditions, grid-connected ICESs are already beneficial to the alternative of solely being supplied from the grid, both in terms of total energy costs and CO_2 emissions, whereas grid-defected systems, although performing very well in terms of CO_2 emissions reduction, are still rather expensive. ICESs ensure self-provision of energy and can provide essential system services to the larger energy system. This thesis has demonstrated the added value of ICESs to the individual households, local communities and the society. A comprehensive institutional design considering techno-economic and institutional perspectives is necessary to ensure effective contribution of ICESs in the energy transition.

Samenvatting in het Nederlands

Auteur: Binod Prasad Koirala
Titel Proefschrift: Integrated Community Energy Systems (ICESs)
Instituut: Faculteit Techniek, Bestuur en Management, TU Delft
Taal: Geschreven in het Engels
Trefwoorden: Energiegemeenschappen, Energiesysteemintegratie, Lokale Energiebronnen, Lokale Energie-uitwisseling, Slimme Netten, Institutioneel Ontwerpen

Energiesystemen over de hele wereld gaan door een radicale transformatie als gevolg van technologische en institutionele veranderingen, uitputting van fossiele brandstoffen en klimaatverandering. Bijgevolg komen lokale energie-initiatieven op en richten steeds meer verdienmodellen zich op de eindgebruikers. Dit vereist dat de huidige gecentraliseerde energiesystemen opnieuw worden georganiseerd. In deze context komen geïntegreerde energiegemeenschapssystemen (ICESs) op als een moderne ontwikkeling om lokale energiesystemen te reorganiseren, welke gelijktijdige integratie van lokale energiebronnen en betrokkenheid van lokale gemeenschappen mogelijk maakt. Het wordt verwacht dat de opkomst van ICESs zowel nieuwe rollen en verantwoordelijkheden met zich meebrengt. Hoewel lokale energie-initiatieven zoals ICESs snel opkomen door de doelstellingen van de gemeenschap, zoals kosten- en emissiereducties en veerkracht, schort het nog steeds aan beoordeling en evaluatie van de waarde die deze systemen kunnen hebben voor zowel de lokale gemeenschappen als het hele energiesysteem. De waarde van ICESs wordt ook beïnvloed door de institutionele kenmerken binnen en buiten het systeem. Met deze achtergrond beoogt dit proefschrift te begrijpen op welke manieren de ICESs kunnen bijdragen aan de verbetering van de energietransitie.

Dit proefschrift maakt gebruik van een conceptueel raamwerk bestaande uit institutionele en maatschappelijke niveaus om de interactie en dynamiek van de implementatie van de ICES te begrijpen. De huidige energietrends en de bijbehorende technologische, sociaal-economische, milieu- en institutionele problemen worden beoordeeld. Het ontwikkelde ICES-model voert optimale planning en gebruik van ICESs uit en beoordeelt hun prestaties op basis van economische en milieu-indicatoren. Voor de beschouwde gemeenschapsgrootte en lokale omstandigheden zijn op het net aangesloten ICESs al voordelig ten opzichte van het alternatief waarbij uitsluitend vanuit het net wordt geleverd, zowel wat betreft de totale energiekosten als de CO_2-uitstoot, terwijl de grid-defected systemen, hoewel heel goed presterend in termen van CO_2-emissiereductie, nog steeds vrij duur zijn. ICESs zorgen voor zelfvoorziening van energie en kunnen essentiële systeemdiensten leveren aan het grotere energiesysteem. Dit proefschrift heeft de toegevoegde waarde van ICESs voor de individuele huishoudens, lokale gemeenschappen en de samenleving aangetoond. Een uitgebreid institutioneel ontwerp met inachtneming van techno-economische en institutionele perspectieven is nodig om de effectieve bijdrage van de ICESs in de energietransitie te waarborgen.

Resumen en español

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Título de tesis: Sistemas integrados de energía comunitaria (ICESs)
Afiliación: Facultad de Tecnología, Política y Gestión, TU Delft
Idioma: Escrito en Inglés
Palabras clave: Comunidades energéticas, Integración de sistemas energéticos, Recursos energéticos distribuidos, Intercambio energético local, Redes inteligentes, Diseño institucional

Los sistemas energéticos en todo el mundo atraviesan una transformación radical como resultado de cambios tecnológicos e institucionales, el agotamiento de combustibles fósiles y el cambio climático. Por consiguiente, las iniciativas locales de energía están surgiendo y los modelos de negocio se centran cada vez más en los usuarios finales. Esto requiere la reorganización de los actuales sistemas energéticos centralizados. En este contexto, los sistemas integrados de energía comunitaria (ICES, por sus siglas en inglés) están emergiendo como un desarrollo moderno para reorganizar los sistemas energéticos locales, permitiendo la integración simultánea de los recursos energéticos distribuidos y la participación de las comunidades locales. Con la aparición de ICESs se esperan nuevos roles y responsabilidades, así como interacciones y dinámicas, en el sistema energético. Aunque las iniciativas locales en materia de energía, como las ICESs, están surgiendo rápidamente debido a los objetivos de la comunidad, tales como la reducción de costos y emisiones, así como la resiliencia, y la evaluación, siguen careciendo del valor que estos sistemas pueden brindar tanto a las comunidades locales como a todo el sistema energético. El valor de los ICESs también se ve afectado por los entornos institucionales tanto internos como externos al sistema. Con este trasfondo, esta tesis pretende comprender las formas en que los ICESs pueden contribuir a mejorar la transición energética.

Esta tesis utiliza un marco conceptual que consiste en niveles institucionales y sociales para comprender la interacción y dinámica de la implementación de los ICESs. Además, esta tesis revisa las tendencias actuales de energía y los problemas tecnológicos, socioeconómicos, ambientales e institucionales asociados. La tesis desarrolla un modelo que optimiza la planificación y el funcionamiento óptimos de ICESs y evalúa su funcionamiento basado en métricas económicas y ambientales. Para el tamaño de la comunidad y las condiciones locales consideradas, los ICESs conectados a la red ya son beneficiosos tanto en términos de costos totales de energía como de emisiones de CO_2 comparado con la alternativa de ser suministrados únicamente desde la red, mientras que los sistemas aislados y desconectados de la red, aunque desempeñándose muy bien en términos de reducción emisiones de CO_2, siguen siendo bastante más costosos. Los ICESs garantizan el autoabastecimiento de energía y pueden proporcionar servicios esenciales al resto del sistema energético. Esta tesis demuestra el valor añadido de los ICESs a los hogares individuales, las comunidades locales y la sociedad. Un diseño integral que considere las perspectivas tecno-económicas e institucionales es necesario para asegurar la contribución efectiva de los ICESs en la transición energética.

Sammanfattning på svenska

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Avhandlingstitel: Integrerade gemenskapens energisystem (ICES)
Anknytning: Tekniska fakulteten, politik och ledning, TU Delft
Språk: Skriven på engelska
Nyckelord: Energifællesskab, Energisystemintegration, Distribuerade energiresurser, Lokal energibyte, Smart Grids, Institutionell design

Energisystem över hela världen går igenom en radikal omvandling till följd av tekniska och institutionella förändringar, utarmning av fossila bränsleresurser och klimatförändringar. Följaktligen växer lokala energiinitiativ fram och ett ökande antal affärsmodeller fokuserar på slutanvändarna. Detta förutsätter att de nuvarande centraliserade energisystemen omorganiseras. I det här sammanhanget utvecklas integrerade samhällsenergisystem (ICES) som en modern utveckling för att omorganisera lokala energisystem som möjliggör samtidig integration av distribuerade energiresurser och engagemang från lokala samhällen. Med framväxten av ICES nya roller och ansvarsområden samt interaktioner och dynamik förväntas i energisystemet. Även om lokala energiinitiativ som ICES snabbt framträder på grund av samhällsmål, såsom kostnad och utsläppsminskningar samt resiliens, bedömning och utvärdering av det värde som dessa system kan ge till både lokala samhällen och hela energisystemet saknas fortfarande. Värdet av ICES-värden påverkas också av de institutionella inställningarna internt och externt för systemet. Med denna bakgrund syftar denna avhandling till att förstå hur ICES kan bidra till att förbättra energiövergången.

Denna avhandling använder en konceptuell ram som består av institutionella och samhälleliga nivåer för att förstå samspelet och dynamiken i ICES-genomförandet. Nuvarande energitrender och de därtill hörande tekniska, socioekonomiska, miljömässiga och institutionella frågorna ses över. Den utvecklade ICES-modellen utför optimal planering och drift av ICES och bedömer deras prestanda baserat på ekonomiska och miljömässiga mätvärden. För den ansedda samhällsstorleken och lokala förhållandena är nätanslutna ICES redan fördelaktiga jämfört med alternativet att endast försörjas från nätet, både när det gäller totala energikostnader och koldioxidutsläpp, medan nät-defekterade system, även om de fungerar väldigt bra i termer av minskningen av koldioxidutsläppen fortfarande är ganska dyra. ICES garanterar självförsörjning av energi och kan tillhandahålla viktiga systemtjänster till det större energisystemet. Denna avhandling har visat mervärdet av ICES till de enskilda hushållen, lokalsamhällena och samhället. En omfattande institutionell utformning med hänsyn till de tekno-ekonomiska och institutionella perspektiven är nödvändigt för att säkerställa ett effektivt bidrag från ICES i energiövergången.

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Chapter 1
Introduction

"Any intelligent fool can make things bigger and more complex. It takes a touch of genius – and a lot of courage to move in the opposite direction."

-Albert Einstein

This chapter provides a general background of this thesis. First, the changes in the energy landscape due to ongoing energy transition are highlighted and integrated community energy system (ICES) is conceptualized. Then the conceptual framework of the research is introduced followed by the research objective, scope and the research questions. Finally, the research approach, relevance as well as the thesis structure is outlined.

1.1 Background: Energy transition and changing energy landscape

Traditionally, the energy system was developed by the enterprises to meet the energy needs of the local communities [1,2]. Due to economies of scale, increasing demand, resource complementarities as well as technological and political developments, the energy systems evolved into the present complex, centralized and networked form. In the centralized energy systems, the electricity produced in the large power plants is transferred unidirectional to the households, industry and the commercial buildings through transmission and distribution networks [3]. The centralized energy supply systems based on fossil fuels are, however, losing some of their appeals, mainly due to vulnerabilities and insecurities associated with the energy infrastructures related to geo-politics, depletion of fossil fuels and their climate change impacts [3,4]. The present energy system has to decarbonise while maintaining energy security and affordability. Accordingly, the present energy system is going through a rapid technological and institutional changes [5].

The energy system is at the crossroad, providing a tremendous opportunity for the re-organization and transformation towards a more sustainable system. Thanks to the restructuring of the energy sector and increasing penetration of distributed energy resources (DERs) in both developed and developing countries worldwide, the energy landscape is changing from dominant vertical integration of centralized generation, transmission and distribution systems towards a combination of top-down and bottom-up systems. Accordingly, parts of the present centralized energy system is transitioning towards a more diverse, low-carbon, co-operative and decentralized system. This requires new organization and business models as well as coordination and interaction among different actors across the whole energy system and beyond.

These energy system transformations are resulting techno-economic changes in the power system as summarized in Table 1.1. These imply not only political, economic and social issues in the energy system transformation but also fundamental shifts in the way energy system is organized [5]. The energy system has to cope with rising demand due to increasing electrification in the developed countries as well as increasing energy access in the developing countries. With increasing intermittent generation, the mismatch will increase between supply and demand. The current market design pushes conventional but reliable power plants into reserve and results into low capacity factor for them. New forms of market and institutional design, as well as technical and social innovation, are necessary for the future energy system.

Table 1.1. Overview of techno-economic changes in the energy landscape [6].

	Traditional Power system	**Future Power System**
Technical	Centralized	Centralized and distributed
	Schedule supply to meet demand: base load, off-peak and peak power plants meet the demand	Match supply and demand with flexibility, grid expansion, demand side management, storage and flexible back-up
	Passive network management	Active network management
	Flexibility from ramping-up and down, peak-power plants, interruptible loads, interconnection	Flexibility market, demand response, storage, interconnection, curtailment
Economic	Centralized day-ahead, intraday and balancing markets	Centralized and decentralized markets for energy and other services including flexibility
	CO_2 emissions are external	CO_2 emissions are internalized through carbon tax, carbon pricing
	Retail prices are in proportion to the wholesale prices	Mismatch between wholesale and retail prices due to increasing fixed costs
	Volumetric network tariffs	Advanced network tariffs
	Price inelastic consumers	Price elastic consumers

In this thesis, the focus is on the energy system transformation in the built environment, mainly involving residential consumers. At present, the built environment accounts for two-third of the worldwide primary energy demand and 70% of the global CO_2 emissions [1]. Moreover, the urban population is projected to reach two-third of the world population by 2030 [7]. In this context, cities and communities around the globe are expected to have an increasingly important role in the future energy system. European directives on the energy performance of the buildings require all the new buildings to be nearly zero-energy buildings by the end of 2020 [8]. Hence, integration of local generation, energy efficiency and demand side management are becoming increasingly important in the local energy landscape.

Increasing numbers of residential consumers are becoming co-providers by engaging themselves in generating, storing, conserving, sharing, consuming and exporting energy locally thanks to the recent developments such as the implementation of suitable policies, cost reduction of renewables, the emergence of information and communication technologies (ICTs) and internet of things (IoT) as well as environmental awareness [9]. This implies the important role of cities and communities around the globe in driving the transformation of the future energy system [7]. Sustainable energy communities may be part of the solution to confront with economic, environmental and social challenges of the present energy system [10]. In the remaining part of this sub-section, the major trends in the local energy landscape are highlighted.

1.1.1 Distributed energy resources and energy system integration

In the local energy landscape, DERs such as solar photovoltaics, solar thermal, micro-wind, fuel cells, energy storage, heat pumps, micro-combined heat and power, electric vehicles as well as demand side management are increasingly becoming common, as presented in Figure 1.1 [11]. Currently, one-quarter of the electricity generation worldwide is attributed to distributed generation [12]. The increasing intermittent renewables in European energy systems and elsewhere is leading to an increase in the reliability and stability problems as well as energy, capacity and ancillary-service related costs [13,14]. Therefore, the key challenge of the future energy system is the integration of these increasing amount and types of DERs.

According to O'Malley et al (2016), "Energy system integration is the process of coordinating the operation and planning of energy system across multiple pathways and/or geographical scales to deliver reliable, cost-effective services with minimal impact on the environment"[15]. This process combines energy carriers such as electricity, heat and fuels with infrastructures such as communications, water and transportation [16]. There are already opportunities for energy systems integration at a building and a community level, Figure 1.2 [17]. Several technical options for energy system integration are available such as virtual power plants, energy hubs, community micro-grids, prosumers community groups, community energy systems and integrated community energy systems (ICESs) [11-21]. For the detailed explanations on each of these option, refer to Koirala et al (2016) [29].

Figure 1.1 Distributed energy resources and system integration at buildings [10]

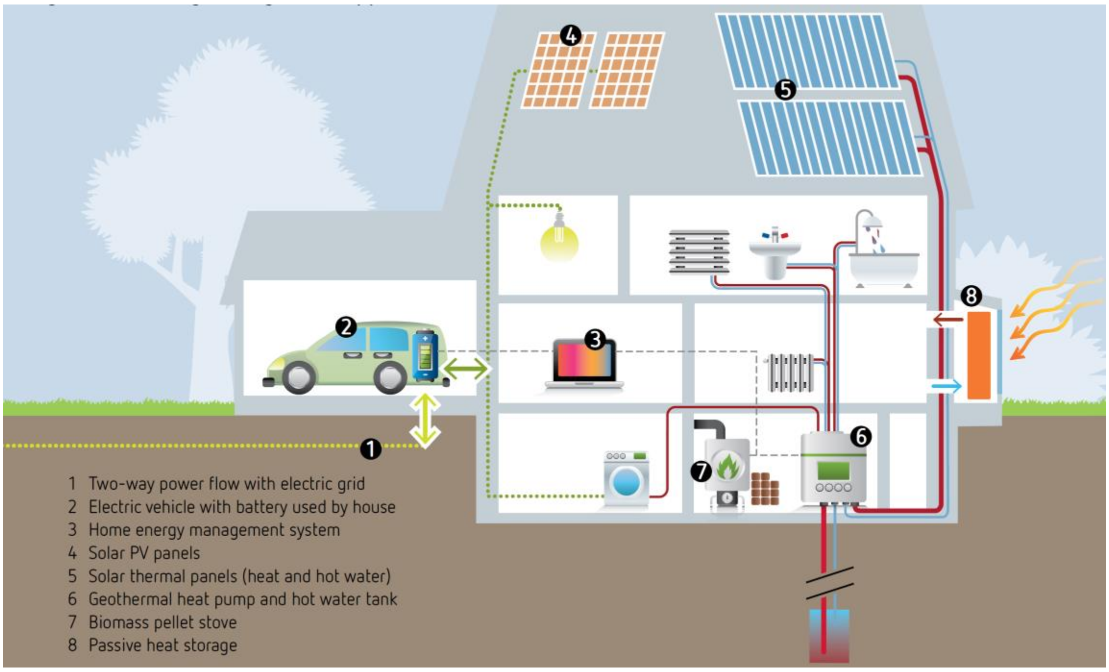
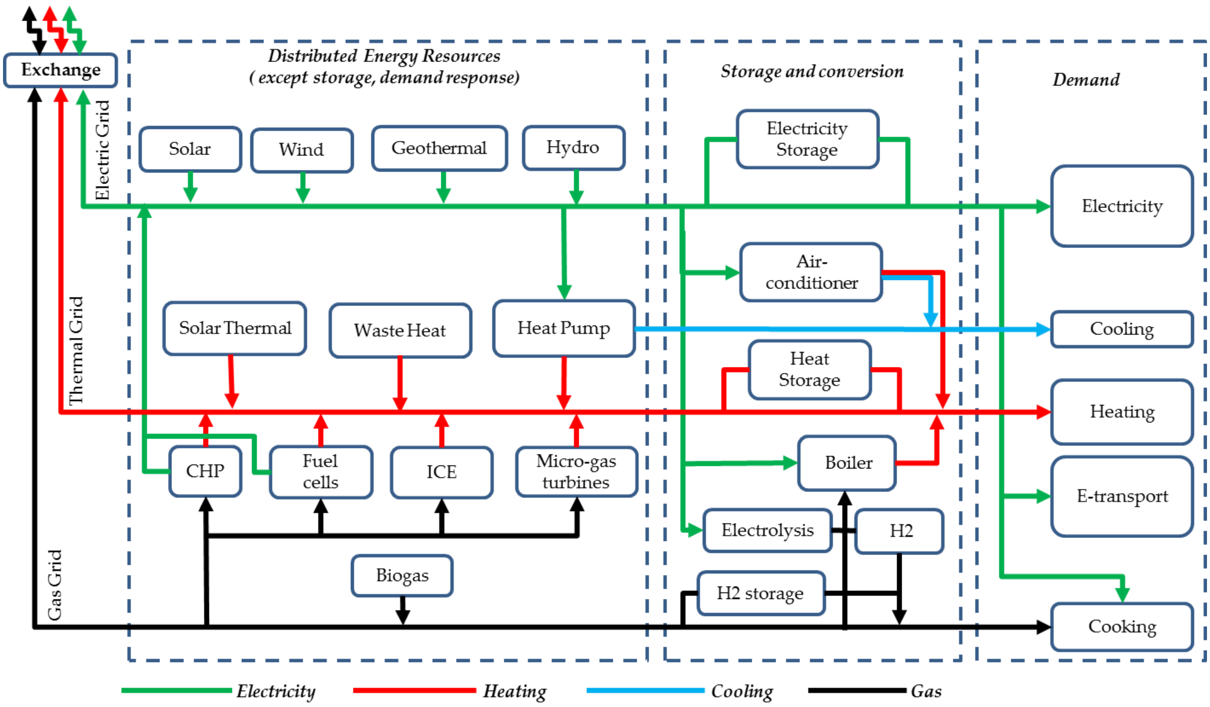


Figure 1.2. Integrated operation opportunities at the local level



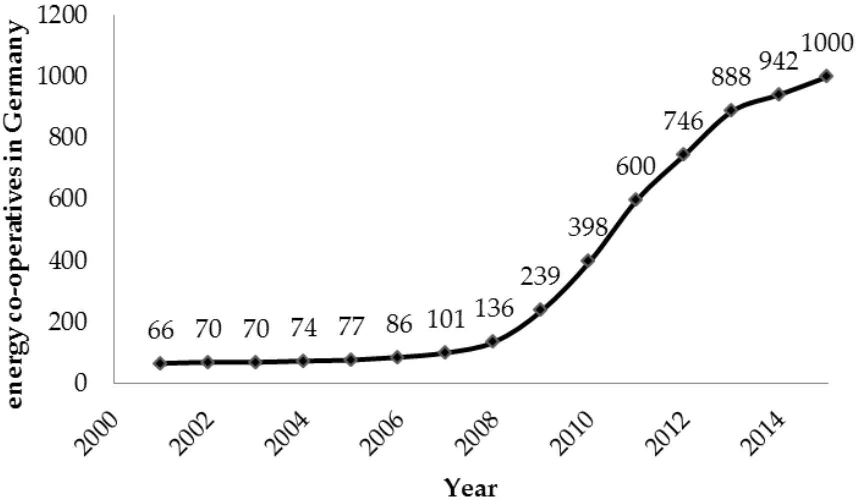
1.1.2 Emergence of local energy initiatives

Local communities vary widely by size, population, development level and climate conditions. A community is the sense of place, identity, localism and shared values and its notions vary from one literature to another [10,20,30–32]. Walker (2008) made a distinction between communities of locality and communities of interest [20]. In this thesis, the focus is on the former, as it offers economic and environmental benefits as well as the range of technical and institutional advantages to the local communities. Local communities might be well-placed to identify local energy needs, take proper initiatives and bring people together to achieve common goals such as self-sufficiency, resiliency, and autonomy.

Schweizer-Ries (2008) has introduced the concept of sustainable energy communities which use renewable energy and energy efficiency technologies and act in an energy efficient way [10]. Local communities have started to respond to the challenges posed by unsustainable production and consumption practices in the energy sector. In some cases, the need to adjust local energy system seems to be more urgent than the regional and national level. Some prominent examples in this regard are the recent growth of local energy co-operatives in Germany and 'van gas los' discussions in the Netherlands[33,34]. In the recent years, more and more distributed energy resources (DERs) have been installed at the household and the community level [35,36]. When consumers have more control, they tend to self-organize and co-operate to form a community energy system [24,25,31,32,37]. In Europe, there are more than 2800 such initiatives in the form of energy co-operatives of which around 1000 are in Germany and around 350 are in the Netherlands [36,38,39]. Organizing local energy collectively often makes sense for economic and logistic reasons as well as for effective resource mobilization [32]. With further facilitation from the smart grid development, more local communities are expected to engage themselves to match their supply and demand.

The local energy initiatives are emerging with varying numbers, success rate and strategies in Europe [40]. The diversity in the success of these community initiatives could be partially attributed to prevailing structural, strategic and biophysical conditions. For example, in Germany, the motivation so far has mainly been the mixture of environmental awareness and economic incentives. The lucrative feed-in tariffs in Germany attracted local investment in DERs through energy cooperatives [36]. However, the market conditions and support incentives in terms of feed-in tariffs have changed resulting in stagnation of the growth of energy co-operatives in Germany, see Figure 1.3 [41]. These co-operatives now have to compete with the centralized generation with economies of scale, highlighting the obsolescence of current business models.

Figure 1.3. The growth of energy co-operatives in Germany



1.1.3 Load and grid defection

The grid so far has always been an enabler for the system integration of DERs [42]. This has positively impacted the penetration of DERs all around the world. For example, the excess energy from DERs can be sold through the electricity grid and the local bio-gas can be mixed to the natural gas grid. Energy networks at their current state will have to overcome several problems in the future. Namely, a higher share of intermittent renewables demands higher investment in power lines and storage facilities. Moreover, the majority of grids today are reaching the end of their lifetime and need replacing in the coming years, consequently demanding investment for network expansion, replacement or reinforcement. In Europe alone there is a need for €600 billion in grid investments by 2020, of which more than two third are in the distribution grids [43].

Investment costs in the energy systems are ultimately passed on to the customers. Furthermore, policy cost of renewable energy support schemes and a nuclear phase out are also part of the cost socialized to the customers [44]. This means the fixed part of the electricity tariffs will rise in spite of a decrease in the wholesale electricity prices from increasing penetration of renewables. Soon, it might be profitable to generate energy locally, all while using local resources. Current high retail prices and charges for energy as well as improving economics of the DERs, are encouraging alternative organization of energy system at the local level. These local system should not be designed to take advantage of a wrong tariff scheme in the short-run but to be profitable in the medium and long-run. These local energy initiatives can either be integrated into the grid or defected from the grid [45,46]. If this happens on a larger scale, it might lead to load and grid defection, which means on-site generation may become cheaper due to the increase in grid tariffs resulting from investments needed for staying interconnected with the larger system [47–51].

With the technology learning, the cost of storage systems is also expected to decrease. Photovoltaic storage systems are expected to reach grid parity in the near future making the case of load and grid defection even stronger. Recently, the Rocky Mountain Institute in the U.S. published a detailed analysis of potential defection from the large electricity grid using storage together with solar photovoltaics [45]. This study suggests that solar photovoltaics together with storage can make the electric grid optional without compromising reliability and at the lower prices. Similarly, in Australia, rich solar resources and rising electricity prices will make grid defection economically viable in 2030–40 which will give a way for a third of consumers to go off-grid by 2050 [52]. The future distribution systems are expected to become more customer-centric where customers consume, trade, generate and store electricity.

1.1.4 Changing ownership and utility business models

Changing ownership structures and increasing local generation are affecting the traditional utility business models [53,54]. For example, more than half of the renewables installation in Germany is owned by citizens and cooperatives, whereas the share of the big four incumbents, namely E.ON, RWE, Vattenfall and EnBW, is only 6.5% [36]. The increasing share of renewables is affecting the capacity factor and economics of the large power plants. This is distorting their business case and incumbents are reporting significant revenue losses.

These developments have forced several energy utilities to develop new customer-centred business models for managing energy [53–56]. Accordingly, the incumbents are also starting to change their roles and strategies in the energy system. For example, the largest power producer in Germany, RWE, decided to depart from its traditional business model based on large-scale thermal power production to become an energy service company [54]. Similarly, E.ON has separated the conventional power plants business to focus on renewables, energy distribution and customer solutions [53]. RWE and E.ON are representative examples of the ongoing massive transformation in the present energy system.

1.1.5 Customer engagement and decentralized coordination

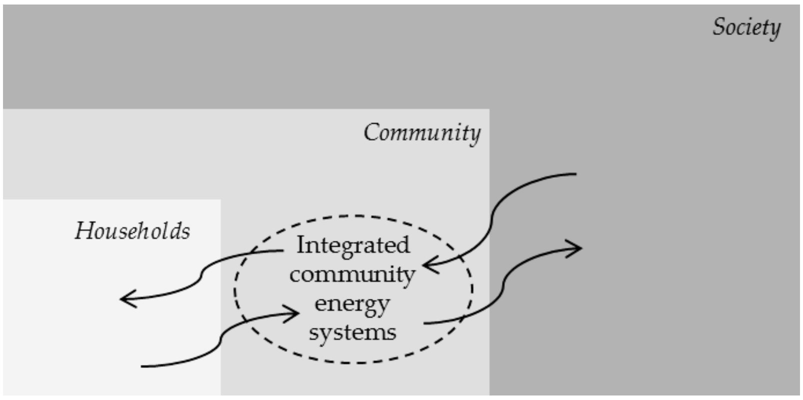
Recently, there has been widespread consensus on more active and central role of consumers in the energy system [57,58]. The passive role of individuals and communities as consumers is changing towards more engaged and active role, that empowers and mobilises citizens' participation in the energy system. Individual and collective action are needed for a more sustainable energy production and consumption. One of the prominent solution lies in increasing self-consumption by matching supply and demand at the local level.

Decentralized coordination is an emerging phenomenon in the local energy landscape [35,59,60]. It facilitates the collective action to self-supply the local energy demand. There are several local energy initiatives to realize such decentral co-ordination such as peer to peer exchange, prosumer community groups, energy co-operatives and integrated community energy systems (ICESs) [23,27,61]. Such local co-ordination might help to utilize the maximum potential of decentralized energy systems through the use of local resources and wider engagement of local communities. The important role of citizens and communities, as well as the local energy exchange, has also been highlighted in the recent clean energy for all proposals from the European union [57,62].

1.2 Integrated community energy systems (ICESs): concepts and definitions

Local energy initiatives are becoming a societal movement indicating the growing societal demand for sustainable and 'self-owned' energy with potentially significant impact on the energy system [60]. There is a widespread consensus that if energy systems are to provide more value to the society, different energy sectors and activities at the local level have to be integrated with the engagement of local communities. Such integrated approach impacts different levels of society such as individual households, local communities as well as the society at large, as presented in Figure 1.4.

Figure 1.4. ICESs impact on all three levels of the society and vice versa



According to Harcourt et al (2012), " Integrated community energy systems (ICESs) take advantage of cross-sectoral opportunities in the areas of land use, infrastructure, building, water and sanitation, transportation and waste to curb energy demand and reduce greenhouse gas emissions at the local level, while increasing energy security, enhancing the quality of life and realizing financial benefits for residents"[63]. Mendes et al (2011) define ICES as "a multi-faceted approach for supplying a local community with its energy requirement from high-efficiency co-generation or tri-generation, as well as from renewable energy technologies coupled with innovative energy storage solutions including electric vehicles and energy efficient demand-side measures". It also means looking at the existing energy infrastructures and available resources in the community and finding the tailored and innovative solutions such as local generation, local exchange, load shifting and energy conservations to meet the local energy demand. Therefore, ICESs include planning, design, implementation, and governance of energy systems at the community level to maximize energy performance while cutting costs and reducing environmental impacts [63].

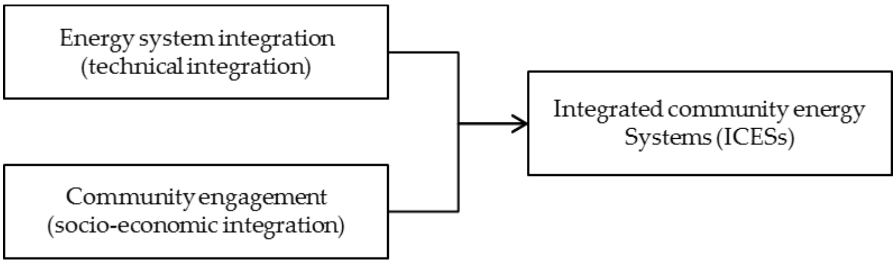
ICESs stand out in terms of self-provision and system support services over existing energy system integration options. In this way, system operation can be co-operatively optimized while keeping overall costs low, security of supply high and ultimately reaching climate policy objectives. Accordingly, ICESs are expected to improve the performance of local energy systems while contributing to renewable energy penetration and energy efficiency targets as well as climate policy goals for the next decades. Local energy projects such as ICESs are expected to be inclusive, democratic and sustainable and might lead to job creation and economic growth [64]. These initiatives might further the transition to a low-carbon energy system, help build consumer engagement and trust as well as provide valuable flexibility to the market. With the engagement of communities, the clean energy transition is expected to be achieved more quickly, fairly and with the added benefits [65].

The architecture of ICESs depends on available technologies and the corresponding political, market and regulatory frameworks as well as technical standards adopted [66]. The technologies invested and topologies chosen by local communities are expected to determine the architecture of the local energy system. The availability of numerous distributed technologies, different social preferences, different energy consumption patterns, policies, as well as the existing institutions, make the implementation of ICESs very complicated. In the remaining parts of this subsection, the added value of technical and socio-economic integration is presented.

1.2.1 Technical and socio-economic integration

In the context of this thesis, ICESs is considered as a comprehensive and integrated approach for local energy systems where communities can take complete control of their energy system and capture all the benefits of different energy system integration options, as presented in Figure 1.5.

Figure 1.5. Technical and socio-economic integration in ICESs



Chicco & Mancarella(2009) argue that adoption of composite multi-generation systems through coupling of combined heat and power units with absorptions/electric chillers, heat pumps and fuel cells leads to significant benefits in terms of higher energy efficiency, reduced CO_2 emissions and enhanced economy [67]. Moreover, electricity and heat generated through combined heat and power technologies, waste heat from nearby industry, as well as the flexibility of electric vehicles and storage systems, can all be utilized locally. The integration of combined heat and power technologies with intermittent solar and wind energy from the community may lead to a flexible and robust local energy system [68]. The advancement in information and communication technologies (ICTs), as well as smart grid technologies, will further facilitate such integrated operation [26,68,69].

An ICES stands out from other energy system integration options due to engagement of the local communities. The community could also decide to purchase or switch its energy and energy-related products collectively, hence with increased bargaining power. In a liberalized market, it is possible to establish local prosumer–consumer energy exchange platform enabling them to create a community-based energy system [2]. The engagement of citizens and communities is expected to increase the acceptance of the new energy systems. ICESs also help to keep the local money for the local economy and help fight energy poverty. It not only creates more jobs at the local level but also increases values such as trust, identity, and sense of community, helping to build stronger communities.

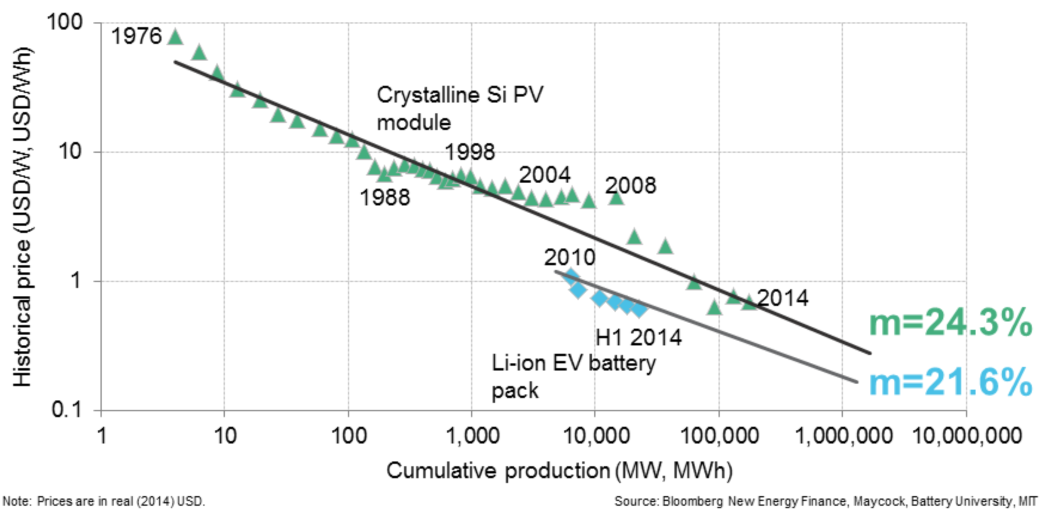
1.2.2 ICESs as complex socio-technical system

ICESs are complex socio-technical systems consisting of different decision-making entities and technological artefacts governed by energy policy in a multi-level institutional space [70,71]. The physical system consists of generation, distribution, storage and energy management technologies to manage the commodities flow. The social system with different actors such as consumers, prosumers, aggregators, energy suppliers and system operators ensures efficient economic operation at minimum environmental effects at the same time providing consumers with different services. The institutions and technologies surrounding ICESs need to adapt to changing energy landscape and should be aligned to each other for optimal performance.

Technologies

Recently, more decentralized technologies such as solar photovoltaics and energy storage have become affordable, further driving household and community investment in DERs, Figure 1.6 [13]. The major technical components of ICESs are households and community level DERs. Energy management systems such as home energy management systems, building energy management systems, battery management systems and community energy management systems together with DERs ensure effective control and operation of the energy communities. For example, combined heat and power, heat pumps, community energy storage and electric vehicles can already provide a basis for the energy system integration at a community level. The technologies will continuously be used in the future to develop energy independence through energy system integration such as the installation of heat pumps for district heating systems in combination with the renewables.

Figure 1.6. Learning curves for solar PV and energy storage technologies



The technologies to operate decentralized energy networks and markets have improved tremendously as a result of the advancements in information and communication technologies [3]. New services can be driven by ICTs through advancement in the smart grids, for example, to align local demand and supply in time and location, to facilitate local peer to peer exchange, and to provide flexibility [72] [73]. ICESs can be characterized by active management of both information and energy flows within the context of distributed generation, storage, consumption and flexible demand [58]. Advancement in smart-grid technologies and demand-side management technologies facilitates an increase in reliability and efficiency of such local energy systems.

Actors

Delivering energy to end users requires multiple actors both competitive and regulated for the procurement, production, conversion, and transformation of the energy [74]. The energy system is comprised of a great variety of public and private actors with different interest and functionalities within a specific institutional environment as presented in Table 1.2. The roles and responsibilities of these actors change in the context of ICESs.

Table 1.2. Various actors in the energy system and their interest in ICESs

	Actors	**Private interests**	**System interests**
Competitive parties	*Households*	Use of local, affordable and clean energy at a low cost	Sale surplus and purchase deficit energy
	Communities	Reduction in energy related costs, provision of local energy	Emission reductions, energy independence, energy supply security, resiliency
	Energy producers	Investment in local energy system (profit maximization)	Sale local generation
	Energy suppliers	Profit from deficit energy supply, portfolio optimization	Increase renewables in their portfolios, new roles and business models
	Energy service companies (ESCOs)	Profit from energy efficiency, operation and management of local generation	Role in energy efficiency improvement activities as well as operation and management of local generation
	Technology providers	Sell technologies to transform the existing energy landscape both production and consumption (e.g. circular economy)	Promotion of local generation as well as demand side management technologies
	Aggregators	Business model for generating profit, Maximize the value of flexibility in the markets (both with capacity and energy)	Role in making system more efficient

Regulated parties	*Balance responsible parties*	Portfolio optimization, balance energy procurement at lowest cost,	Provision of accurate scheduling to the system operator
	Transmission system operators (TSOs)	Maintain larger system balance of supply and demand at lowest cost to the consumers	Maintain larger system balance of supply and demand
	Distribution systems operators (DSOs)	Distribute energy to the neighborhood with safe, reliable and affordable grid,	Avoid grid congestion, defer network investments, self-balancing energy islands in smart grids
	Government, policy makers and regulators	ensure competition for affordable energy for end-users	Sustainable energy supply, transition to low-carbon energy system, energy security

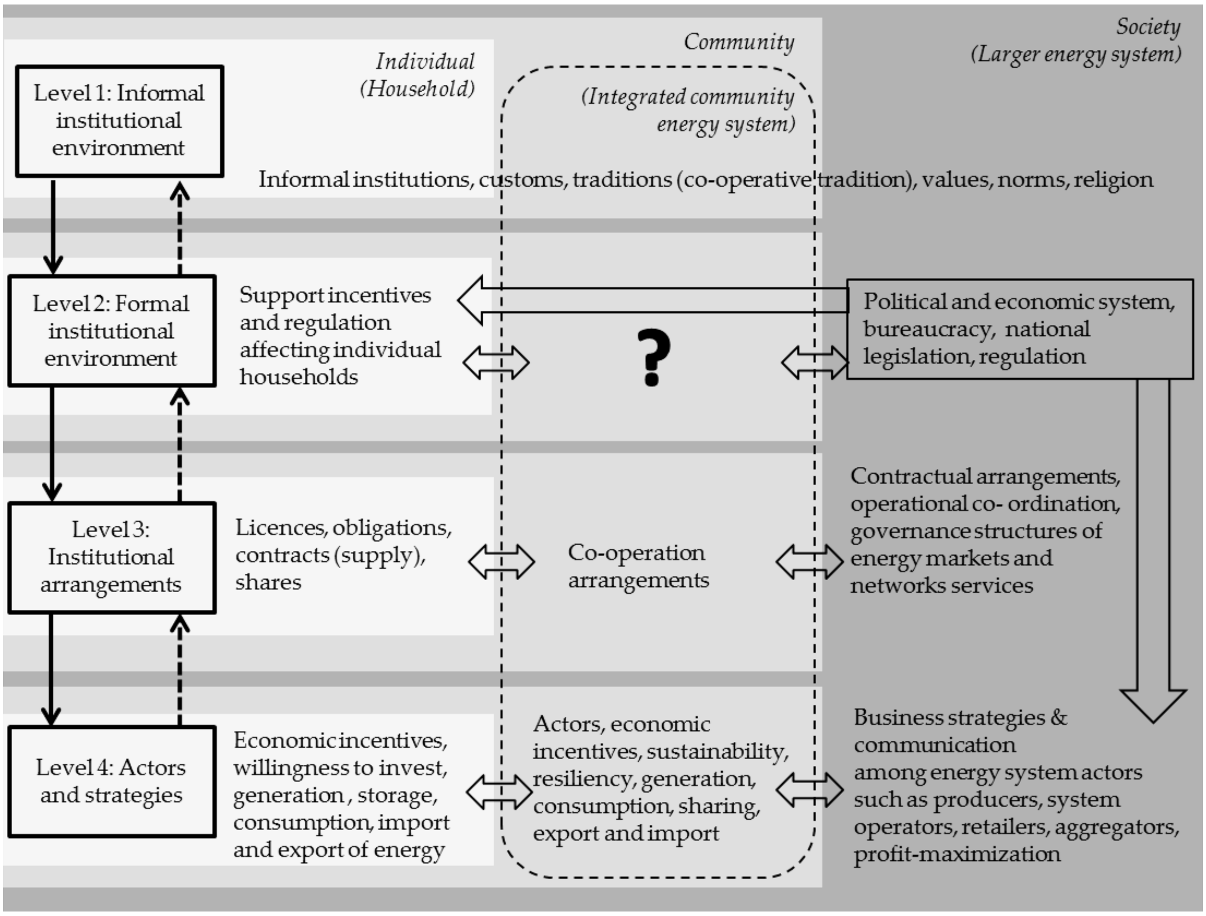
ICESs are community-based, providing more roles to them in investing, using, producing, selling and purchasing energy. The complex technical operation in ICESs often needs the engagement of third-party actors such as system operator or service provider. Actors in ICESs are inter-dependent in the realization of their goals and different actors have different expectations from ICESs. For instance, households want low-cost hassle free energy at their disposal while aggregators seek to maximize the value of flexibility in the various markets and policymakers want to ensure sustainable energy supply in the transition to low-carbon energy systems.

1.3 Conceptual framework

The various influences ICESs might be subjected to under changing energy landscape are complex and manifold. Complex socio-technical systems such as ICESs have the multiplicity of technical, socio-economic, environmental and institutional interactions with the larger energy system [58]. They emerge in a changing energy landscape with rapid technological and institutional developments. Therefore, to understand the systemic effects of ICESs, it should be analysed not only through a technical lens but also through socio-economic, environmental and institutional lenses. The analytical framework used in this thesis is the combination of Williamson's four levels of institutional analysis and the multi-level societal system consisting of individuals, community and the society, Figure 1.7. The functioning of an energy system at individual households level and societal level is relatively well understood. With the increasing penetration of DERs, new form of interactions and dynamics are unfolding at the community level. This framework is used to explore the interaction and dynamics of new organizational arrangements such as ICESs at the community level to the individual households and the larger energy system.

The Williamson's (2000) four-levels of institutional analysis is being widely used in energy research and subsequently modified by Koppenjan & Groenewegen (2005), Ghorbani (2012), Ottens et al (2005) and Moncada et al [75–80]. These layers are interconnected and the higher level imposes constraints on the lower level as indicated by the solid downward arrows and the dashed upward arrows signifies feedback from the lower layer to the upper layer [80].

Figure 1.7. Conceptual framework to analyse ICESs



The first level, informal institutional environment, deals with social embeddedness of human behaviour such as norms, values, customs, traditions, and religion. Since these informal institutions are socially and culturally inherited, they are rooted deeply in the society and influence the behaviour of individuals and local communities and on the way society conducts itself. Given the slow frequency of changes in these institutions, they are considered to be important as cooperative tradition, community trust and values play significant roles in ICESs.

The second level, formal institutional environment, deals with the formal legal arrangement. It sets the rules of the game and is composed of the policy makers and government agents who steer the macro behaviour of the energy system to the desired system objective. These rules can come from the local government, national government as well as the regional co-operation such as the European Union. The rules of the game are determined by the political, judicial and bureaucratic systems in place. Although this level deals with getting the institutional environment right, cumulative change of progressive kind is very difficult to orchestrate [80]. Often there are limited windows of opportunity to change these formal institutions which take between ten and hundred years.

The third level, institutional arrangements, deals with the different mechanisms of interaction between the actors to coordinate specific transactions based on the governance structure mandated by the formal institutional environment in the second layer. A contractual and organizational arrangement, as well as conflict resolution mechanism, are made to serve the objectives of different actors. This layers also deals with operational coordination between actors, governance structures of the energy markets and network services. The frequency of change in this layer ranges from a year to a decade.

The fourth level, actors and games, represents the rules, norms and shared strategies that influence the behaviour of individual actors and shape the interaction between the actors. This layer satisfies the marginal conditions for resource allocation to accomplish defined objectives. The problems in this layer are short-term and need to be resolved continuously. Therefore, the frequency of the change is continuous.

With respect to the multi-level societal framework, the individual households are the basic units. These households are can be economically rational profit maximizers or comfort maximizers. These households can invest in the local generation technologies to ensure effective energy balance and operation at the household level based on onsite conditions, energy prices, and available DER technologies. These individual households in the local communities can co-operate and collectively optimize their energy systems based on different economic and environmental objectives. The society level includes actors, strategies, institutions as well as infrastructures of the larger energy system.

This theoretical framework consisting of the four institutional levels and the three societal levels is considered as the starting point to research interaction and dynamics of transformation to ICESs and its potential contribution to the ongoing energy transition. This research assumes that the individual level and societal level of the energy system is relatively well understood and the focus is on understanding the impact of the local energy initiatives such as ICESs at the community level. ICESs actors perform activities such as generation, consumption, sharing, export and import with the collective objectives of economic incentives, sustainability and resiliency. The operation of ICESs is guided by the co-operation arrangements through (self-) governance practices such as collective action agreements, procedures for collective decision making, governance structures as well as local energy markets and exchange platforms. The strategies of relevant actors in the energy system will shape the respective activities in ICESs and strategic exchanges are expected both with individual households and larger energy system. In this way, the interactions and dynamics of ICESs emergence are expected to impact the larger energy system. These synergies and frictions will shape both ICESs and the future energy system.

1.4 Research objectives and questions

The energy sector transformation is being driven by technological and social innovation and disruptions taking place at the intersection of the distribution system and customer premises [81]. With the increasing consideration on smart grids by the policy makers and system operators as well as energy independence and environmental concerns by the local communities, local energy initiatives such as ICESs are emerging in Europe and elsewhere, with a potential for the energy system transformation. Bottom-up initiatives such as ICESs emerge in an environment with a century-long tradition of centralized power plants [82]. The interactions and dynamics caused by the local energy transformation through ICESs and their contribution to the energy transition is the main research agenda of this thesis.

Up till now in literature, the implementation of ICESs is often treated as a technical task and driven by the economic incentives. In this process, the important societal, institutional and system aspects are largely being neglected [10,58]. The stagnation in the growth of energy co-operatives in Germany, as presented in Figure 1.2, confirms the need for the alternative business models and service provisions for these local energy initiatives [41]. Given the multitudes of local initiatives and increasing governmental support for the community energy, it is important to understand the frictions and synergies of these initiatives to the whole energy systems. Particularly, this research focuses on the value of aggregating group of households in the form of ICESs to address the challenges of the present energy system such as decarbonisation, energy security and cost-effectiveness.

ICESs are governed by public policy in a multi-layer institutional context which ranges from norms and values to technical standards. Current institutional arrangements in the energy sector does not provide equal level playing field for ICESs as the latter were not foreseen during the development of these institutions. Therefore, the new institutions need to be established or (re-) designed or adapted to the existing ones to enforce the necessary roles, responsibilities, control and intervention [83]. New models of partnerships between the energy distribution networks, utility groups, private developers and communities need to be examined. Although technological advancement is a key to ensuring the sustainable energy future, institutional changes considering technological complexity and interdependencies are necessary to support these local energy initiatives to develop and diffuse. New patterns of collaboration and business models are expected to emerge with ICESs. In addition, performance expectations such as sustainability, flexibility and cost minimization also play an important role in shaping technology and institutions in ICESs.

The main research question for this research is:

How can integrated community energy systems contribute to enhance the energy transition?

The related sub-questions are:

1. *What are the technical, socio-economical, environmental and institutional dynamics and interactions of transformation towards ICESs?*
2. *How can we assess the added value of ICESs to the individuals, local communities as well as to the larger energy system?*
3. *What requirements exist from the techno-economic and institutional design perspective for the integration of ICESs in the energy system?*

This research assesses the techno-economic, social and environmental value of ICESs. The focus is not on the detailed technical design but on the understanding of the systemic effects of ICESs. The first research sub-question identifies the drivers, barriers and contributions of ICESs as well as the key technical, socio-economic, environmental and institutional issues related to the implementation and adaptation. Quantitative modelling and assessment through the ICES model in second research sub-question are expected to give further insight into the optimal planning and operation of ICESs as well as added techno-economic and environmental values of ICESs to the individual households, local communities as well to the larger energy system. The third research sub-question highlights the institutional precursors and techno-economic requirements for integrating ICESs in the energy system.

1.5 Research approach

This research uses mixed-method, both qualitative and quantitative, to address the main and sub-questions presented in Section 1.4. These methods are used to determine the added value of these local energy initiatives. Table 1.3 presents, the research methods used to answer each sub-questions.

Table 1.3. Research approach

	Research questions	Research approach
1	*What are the technical, socio-economical, environmental and institutional dynamics and interactions of transformation towards ICESs?*	Exploratory literature review, bibliometric analysis, survey
2	*How can we assess the added value of ICESs to the individuals, local communities as well as to the larger energy system?*	Optimization model, case studies
3	*What requirements exist from the techno-economic and institutional design perspective for the integration of ICESs in the energy system?*	Desk research, institutional analysis, case studies, modelling and simulation

This research develops a systematic and integrated quantitative model for the sizing and operation of the ICESs, considering energy efficiency, economic and environmental impact, simultaneously. The outcomes of the model, modelling process, analytical framework as well as institutional analysis are used to provide institutional design recommendations for embedding of ICESs in the energy system within the smart grid paradigm.

1.6 Scientific relevance

This thesis is a timely contribution to the topic of energy communities and energy system integration which is increasingly coming to the forefront at academia. From the academic perspectives, this research uses multiple methods such as exploratory research and techno-economic assessment to contribute to a deeper understanding of the complex socio-technical energy system such as ICESs with a multiplicity of techno-economic, social and environmental interactions and dynamics. It is essential to understand the impact of the emergence of local energy initiatives such as ICESs to the households, local community and the larger energy systems.

This research conceptualizes ICESs as modern development in the energy system in which energy system integration and customer engagement are effectively combined. This research identifies the techno-economic, social and institutional elements and linkages of ICESs. It also outlines the drivers and barriers in the implementation of ICESs as well as the contributions of ICESs to the ongoing energy transition.

One of the most important contributions of this research is the quantitative assessment of added techno-economic, social and environmental values of ICESs. With the aid of an ICES model for optimal operation and planning, this research provides a comparative assessment of the grid-integrated and grid-defected system based on economic and environmental performance indicators. With decreasing costs of DERs and increasing willingness of the consumers to self-organize their energy system, such assessments can prove helpful in the future energy system. In addition, this research also quantifies the added-value of ICESs to the individual households, to the local communities as well as to the larger energy system.

Citizens' willingness to participate and steer are necessary preconditions for the local energy initiatives such as ICESs. This research identifies the important demographic, socio-economic, socio-institutional and environmental factors in determining the citizens' willingness to participate and steer ICESs. The interactions and dynamics among different institutional and actor level help to better understand the impact of the local energy initiatives such as ICESs to the larger energy system. It also provides policy recommendation for increasing citizens' participation in ICESs as well as in the energy system.

In order to embed ICESs efficiently and effectively in deregulated and competitive energy system under the smart-grid paradigm, certain institutional preconditions are necessary. This research identifies the institutional precursors for the implementation of ICESs and provides institutional design recommendations from techno-economic and institutional perspectives.

1.7 Societal relevance

This thesis also has practical relevance for different actors of the energy systems. Different actors in the energy systems will not only be able to understand their changing roles and responsibilities but also be able to look through different value streams that these local initiatives might potentially offer. This research will help in understanding the role of the ICESs in the future energy systems which can be useful in decision support as it can help to ensure necessary precautions as well as arranging suitable institutions for the low-carbon transformation of the energy systems.

ICESs can transform local energy systems, becoming an inspiring example for sustainable development worldwide. ICESs might help to meet the international development targets. For example, ICESs can contribute towards United Nation's sustainable development goal 11 which aims to make cities and human settlements, safe, resilient and sustainable by 2030 [84]. ICESs can play an important role to achieve 2020 and 2030 climate and energy goals of European Union as well as the COP 21 commitments in Paris [85,86].

The European Commission has recognized the benefits of community-owned renewables and co-operatives in its recent proposals for consumer-centred clean energy transition after 2020 [85]. Consumers will be active and central players of the future energy markets and will have the possibility to generate and sell their own energy individually or collectively. DERs integration and consumer empowerment may make ICESs an effective and cost-efficient approach to meet citizens' need and expectation regarding energy resources, services and local engagement. This indicates the important role of ICESs in the future energy system and thus the higher relevance of this research.

1.8 List of Publications

The papers listed below and included in Appendix II – VI are the integrated part of this thesis:

Papers in Science Citation Index (JCR) journals:

Koirala, B. P.; Koliou, E.; Friege, J.; Hakvoort, R. A.; Herder, P. M. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renew. Sustain. Energy Rev.* 2016, *56*, 722–744

Koirala B, Chaves Ávila J P, Gómez T, Hakvoort R, Herder P. Local Alternative for Energy Supply: Performance Assessment of Integrated Community Energy Systems. Energies 2016;9:981

Koirala, B. P.; Araghi, Y.; Kroesen, M.; Ghorbani, A.; Hakvoort, R. A.; Herder P. Willingness to participate in integrated community energy systems, Energy Research and Social science, 2017 (under review)

Eid C, Bollinger LA, **Koirala B**, Scholten D, Facchinetti E, Lilliestam J. Market integration of local energy systems: Is local energy management compatible with European regulation for retail competition? Energy 2016;114:913–22.

Book Chapter:

Koirala, B. P.; Hakvoort, R. A. Integrated community-based energy systems: Aligning technology, incentives and regulations, *Innovation & disruption at the Grid's Edge*, edited by Fereidoon Sioshansi, Academic Press, 2017

Conference Papers:

Koirala, B. P.; Chaves-Ávila, J. P.; Hakvoort, R. A.; Gomez, T. Assessment of integrated community energy systems. *International Conference on European Energy Markets.* 2016, Porto, Portugal.

Binod Prasad Koirala, Dipti Vaghela, Mitavachan Hiremath, Raveen Kulenthran: Opportunities and Challenges of Community Energy Systems: Analysis of Community Micro-Hydro Systems in South and South-East Asia (SSEA). MES - BREG 2014: Innovating Energy Access for Remote Areas: Discovering Untapped Resources, University of California, Berkeley; 04/2014

Jiminez A., van Somoren, C.; **Koirala B.P.**; Ballarin A.; Shrestha, B. Empowering sustainable communities through energy co-operatives, *5th International De-growth Conference*, 2016, Budapest, Hungary

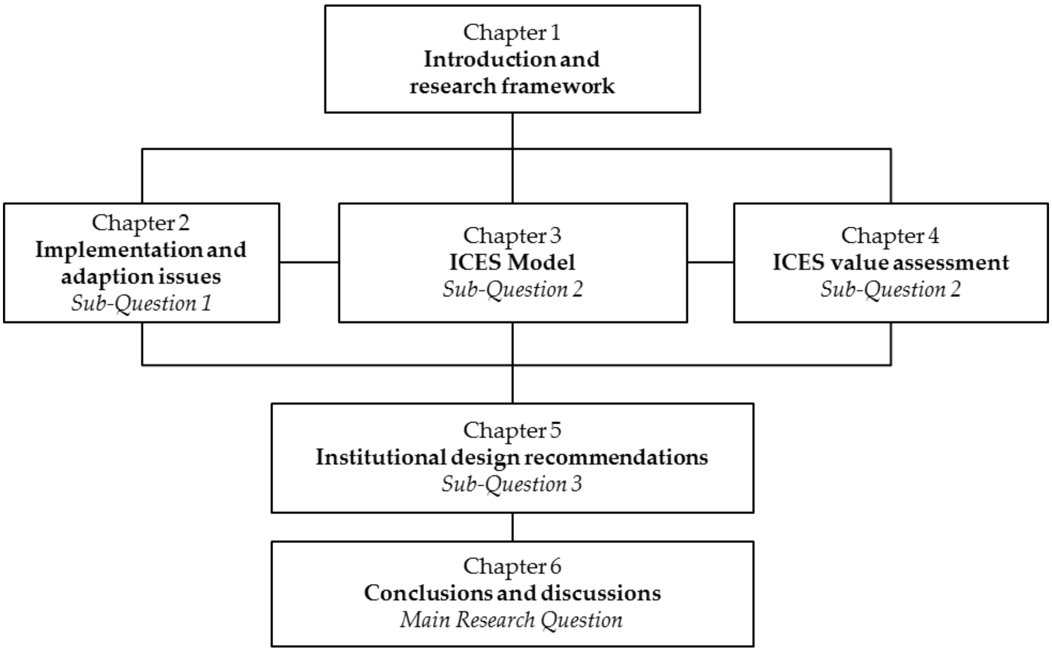
Mavrokapnidou M.; **Koirala B.P.**; Hakvoort R.A.; Herder P. Interplay between storage and flexibility in the power system, International energy storage conference, 2015, Dusseldorf, Germany

1.9 Thesis outline

This thesis consists of 6 chapters including the introduction chapter, as outlined in Figure 1.8. The key reasoning is presented in the chapters and the papers included in Appendix II - VI are integrated part of the thesis. The content of each chapter is outlined below.

With the aid of literature review, the drivers, barriers and key issues in the implementation of ICESs are outlined in **Chapter 2**. This chapter also covers the key technical issues, socio-economic conditions, environmental concerns and institutional settings in implementation and adaptation of ICESs. This chapter answers the first sub-question on interaction and dynamics of the transformation to ICESs.

Figure 1.8. Thesis outline



In **Chapter 3**, review on the state of the art energy system integration options. Then, the modelling approach as well as an ICES optimization model for optimal planning and operation and value assessment of ICESs are presented.

With the aid of this quantitative model, **Chapter 4** assesses the added techno-economic and environmental value of grid-integrated and grid-defected ICESs to the local communities. Through two case studies, this chapter also assesses the added value of ICESs to the individual households and to the society.

With the background research in Chapters 2-4, **Chapter 5** presents the necessary institutional precursors for ICESs as well as institutional design recommendations from techno-economic and institutional perspectives.

Chapter 6 concludes with the conclusions, policy recommendations and critical reflection including direction for future research and lessons learned for the developing countries.

Chapter 2
Key issues in implementation and adaptation

"Everything should be made as simple as possible, but not simpler."

- Albert Einstein

This chapter presents the work described in Koirala et al (2016a)[1] and Koirala & Hakvoort (2017)[2]. First, in continuation to the ICESs concept introduced in Chapter 1, characterization and categorization of ICESs is presented. Then, key drivers and barriers for ICESs as well contribution of ICESs to the energy system are discussed. Finally, the key technical, socio-economic, environmental and institutional issues related to the implementation of ICESs are outlined.

2.1 Background

Currently, households in the local communities are supplied individually by the centralized energy system. Thanks to technological advancement and socio-political acknowledgment, the potential of energy communities are now at the forefront of exploration with a key role in transitioning the energy systems [82]. Local communities are well placed to identify the local energy needs, and bring people together to achieve common goals such as self-sufficiency, resiliency and autonomy. Initiatives on ICESs are becoming a societal movement what indicates rapidly growing societal demand for sustainable and 'self-owned' energy with potentially significant impact on the whole energy system [60].

Transformative energy systems such as ICESs are also influenced by technological, socio-economic, environmental and institutional issues and interactions in the energy landscape [59]. In ICESs, a strong degree of complementarity is enabled via the physical and social network relationship. ICESs encompass a combination of technical elements, characteristics and active links. Although ICESs are often portrayed as neutral and inherently positive solutions, there are different barriers in the process of the transition. The drivers and barriers of ICESs will however continuously change on account of technological and institutional changes, fuel costs, economics of technologies, and incentives. For example, current energy systems are highly

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[1] Koirala, B. P.; Koliou, E.; Friege, J.; Hakvoort, R. A.; Herder, P. M. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renew. Sustain. Energy Rev.* 2016, *56*, 722–744

[2] Koirala, B. P.; Hakvoort, R. A. Integrated community-based energy systems: Aligning technology, incentives and regulations, *Innovation & disruption at the Grid's Edge*, edited by Fereidoon Sioshansi, Academic Press, 2017, 363 - 387

institutionalized, and these institutions did not develop with the focus on ICESs. ICESs as well as other forms of local energy systems are continuously shaped by the new trends in the energy landscape. As a result, these trends and issues influence the emergence of ICESs. These issues, interaction and trends should be adequately considered for a comprehensive assessment of ICESs.

2.2 Characterization and categorization of ICESs

For the implementation of ICESs, it is important to keep in mind that the energy system integration needs an existing system in place. Rarely, unless in rural areas of developing countries, ICESs will be working with a 'green field' where an ideal system is designed bottom up. More often it is the evolution of existing energy systems that creates a path dependence which inhibits innovation. ICESs can be identified based on the following characteristics: locality, modularity, flexibility, intelligence, synergy, customer engagement and efficiency.

Locality: The system should have a larger proportion of local investment and ownership. It should operate locally and the local generation should be used for self-provision through the local energy exchange.

Modularity: The system should be able to cope with the entry and exit of its members. Household and community level technologies could be added later so that it can adapt to the rising demand.

Flexibility: One of the important criteria for ICES is flexibility, which can be achieved through local demand response, local balancing, flexible load and supply. This flexibility can be utilized to provide energy and system services.

Intelligence: The system should co-ordinate the energy and information flow to match supply and demand locally.

Synergy: The system should allow synergies between different sectors such as electricity, heat and transport as well as between different technologies.

Customer engagement: The system should engage customers through different means such as investment, ownership, local energy exchange and economic incentives.

Efficiency: The system should be efficient both technically and economically.

According to the above characteristics, the categorization of ICESs becomes a focal point which is discussed below. ICESs can be categorized into different groups based on their activities, scale, grid connectivity, initiatives, location and topologies as summarized in Table 2.1. ICES activities can be categorized into local generation, storage and demand response, collective purchasing as well as energy exchange and trading. An ideal ICES consists of all these activities, although the communities also can voluntarily choose a single activity. A further distinction can be made between supply side activities such as collective purchasing of solar panels or collective ownership of windfarms and demand side activities such as energy conservation, retrofitting of dwellings or energy awareness raising initiatives [65]. In terms of scale, macro, meso and micro ICESs exist, applicable for city, neighbourhood and buildings level respectively. A further distinction can be made based on grid connectivity [7]. ICESs can be initiated either by a leadership of citizens or by the government and private enterprises [65]. ICESs also differ based on locations such as developed and developing countries or urban and rural areas. Various topologies of ICESs are possible such as state of the art integration of DERs, integration through a common point of coupling and autonomous systems. It is emphasized that such systems have to be categorized and analysed from different lenses and perspectives in order to derive their added value.

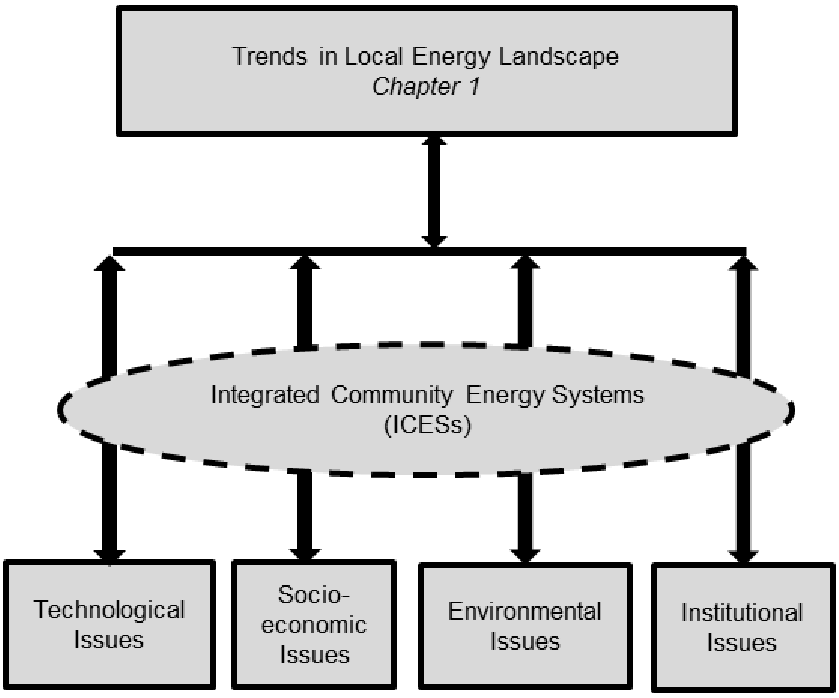
Table 2.1. Categorization of ICESs

Perspective	Categorization	Reference
Activities	Electricity generation including storage Heating/Cooling including storage Collective purchasing Energy management and demand response Energy exchange and trading	[60,82]
Scale	Large/macro: city, region Medium/meso: neighborhood Small/micro : household / buildings	[63] [87] [88]
Grid connection	Grid connected Off-grid	[89]
Initiatives	Led by citizens (energy cooperatives or businesses and collective procurement Led by government with citizens (participative area development and government initiatives)	[60]
Location	Developed countries-urban Developed countries-rural Developing countries-urban Developing countries-rural	Own assessment
Topologies	State of the art integration of DERs Integration through common point of coupling Autonomous ICESs	Own assessment

2.3 Research approach

This research assumes that ICESs are shaped by current trends and issues in the energy system. Different drivers, barriers and contribution of ICESs are reviewed. Technological, socio-economic, environmental and institutional issues related to the implementation of ICESs are highlighted. Figure 2.1 presents analytical framework considering issues and trends in the changing local energy landscape.

Figure 2.1. Analytical framework considering issues and trends in ICESs



2.4 Drivers of ICESs

ICESs are implemented with the aim of reducing energy cost, CO_2 emissions and dependency on the national grid. Other drivers of ICESs are to improve comfort and resistance to the utility. In the developed world, ICESs are being driven by increased climate awareness and willingness to become autonomous among pro-active communities. In developing countries, energy access is the main driving force. Different socio-cultural, political and socio-technological drivers cause transformation towards ICESs [59]. Community spirit, co-operative traditions and the norms of locality and responsibility are the central drivers behind the emergence and constitution of ICESs [32]. The potential to reduce the energy costs and CO_2 emissions as well as resiliency and autonomy drive the local communities to implement ICESs.

In recent years, the energy system is shifting towards more distributed generation driven mainly by techno-economic improvements and ambitious carbon and energy policy targets [31]. Implementation of ICESs is going to be benefited from the self-imposed and targeted local energy strategies. In addition, the involvement of the local government entities as well as the local business and residents will have a larger impact and a greater probability of success [88].

2.5 Barriers and challenges of ICESs

ICESs could often be inhibited by technical barriers such as lack of equipment, technical knowledge and expertise [20]. Although the technologies for ICESs are ubiquitous, there are major challenges in its institutional organization which must be satisfactorily resolved before they can be successfully deployed and integrated. Furthermore, the main factors affecting the deployment of DERs such as site conditions, grid connection issues, capital costs, as well as the allocation of the costs and benefits, as presented by Swider et al (2008), also affects the implementation of ICESs [90]. The allocation of the costs to individual households is complex in the case of community investment. Furthermore, scarcity of public and/or private space needed to install the generation units as well as the temporal availability of the resources present challenges for ICESs [91].

The main barriers for implementation of bottom-up energy initiatives such as ICESs come from the centralized design and regulation of present energy systems which do not always provide level playing field for ICESs. Actors and institutions such as government agencies, private companies and utilities favouring the centralized energy systems often inhibit implementation of ICESs [3]. In a centralized system, the energy and information flow are unidirectional. However, successful implementation of ICESs needs interaction among several actors of the energy system. For example, selling electricity to neighbours is complicated and affordable grid access for community generation can be long, complex and costly.

ICESs costs involve utility bills, capital costs for DERs and energy management system, fuel cost, operation and maintenance costs as well as network costs to interconnect the households and contribution to the larger energy network. Moreover, transaction costs associated with making contracts and billings should also be accounted. Within an ICES, the existing networks might also have to be adapted. There can be resistance from the incumbent grid-operator to transfer the ownership or lease the network to the community. In such case, local communities might have to develop their own local grid after an evaluation on the value of such network from national and community perspective. Moreover, the community can be connected to the national grid through a point of common coupling. If this is the case, the necessary network infrastructure should be installed. Sometimes, depending on the size, ICES can be connected directly to the Medium Voltage (MV) network.

As highlighted in Table 2.2, the challenges include financing, operation, revenue adequacy, community participation as well as the fair allocation of costs and benefits. Despite being local initiatives, ICESs might still face resistance from the local communities if they do not align with the local interests. For example, the issues of coordination and split-incentives can arise when costs and benefit of ICESs do not boil down to the same actor. Coordination requires transparency in the interactions between market parties in order to ensure mitigation of unfair cost-benefit allocation [92]. On the other hand, the local communities should also be very pro-active to take control of their energy system. The initiatives that will succeed should be able to get results without spending time consciously and the members of such communities should collaborate very well with each other.

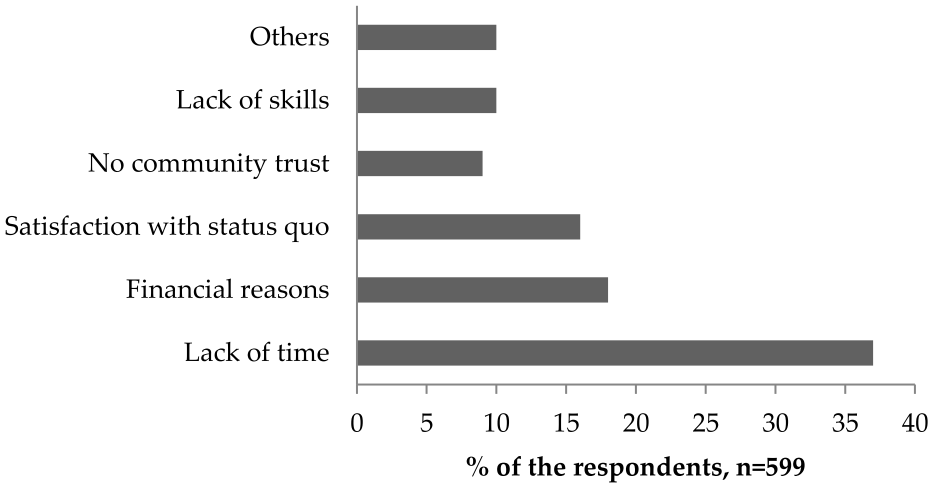
Table 2.2. Challenges of ICESs

Challenges	Description
Operation	Need a service provider or expert companies for complex technical operation beyond its technical capabilities
Financing	Access to private finance, micro-finance, and loans
Cost-benefit sharing	Fair allocation of costs incurred and revenue generated among actors
Business case	New business model for flexibility and ancillary services
Monetization of services	Monetization of essential community as well as other ICESs services
Managing utility relations or grid issues	Network access and cost recovery of network investment especially when energy networks are a natural monopoly.

Perceived barriers

Based on the survey results presented in the Appendix, the perceived barriers to participate in the ICESs as presented in Figure 2.2 are, lack of time (37%), financial reasons (18%), satisfaction with the current energy systems(16%), no trust in neighbourhood to develop ICESs (9%), not enough skills to support ICESs (10%) and other reasons (10%). The other reasons reported are, too much focus on the environment, trust in the government, limited thinking space, too big risk, already ownership of solar panels and heat-pumps, expectation of government initiative, financial sustainability, inclusive rent, old age, moving in near future, renting, no interest in initiative and leadership, lack of experience and already participating in a local energy system. The perceived barriers are in line with what has been reported in the literatures which are lack of financing and technical expertise as well as the lack of technical support [93–95].

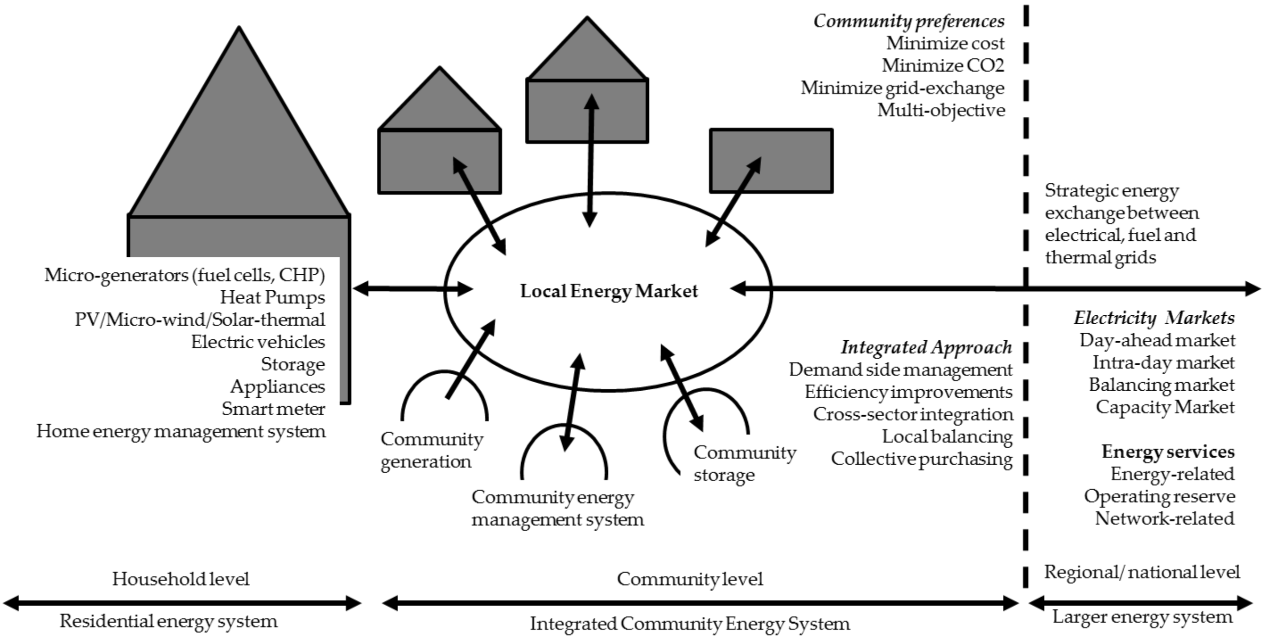
Figure 2.2. Perceived Barriers to participate in ICESs



2.6 Functions and interaction of ICESs

ICESs are expected to have interaction and coordination such as local balancing and strategic exchanges with the individual households, within the local community as well as with the neighbouring communities and the national energy system. In this process, ICESs can also provide different energy services such as ancillary and balancing services to the national energy system. ICESs enable individual households to participate in different energy markets through aggregation. Figure 2.3 summarizes different functions and interactions of ICESs within as well as with the national energy system.

Figure 2.3. Functions and interactions of an ICES



2.7 Contribution of ICESs

The contributions of ICESs for communities, system operators, and policy makers are summarized in Table 2.3. The contribution of ICESs includes reducing energy cost, CO_2 emissions, and dependence on the national grid as well as (self-) governance. ICESs help to increase penetration of intermittent renewables and bring new roles for the local communities such as flexibility and ancillary service providers [14]. ICESs might provide cost-effective solutions to local congestions and help avoid or defer grid reinforcement foreseen with increasing penetration of the local renewables.

Table 2.3. Contribution of ICESs

Community	System operators	Policy-makers
• Hedging against price fluctuations • Modular in development • Reliability • Resiliency • Economic benefits – savings and revenue generations • Grid support within ICESs • Higher efficiency • Integrated • Improved power quality • Sense of community	• Improved reliability of the energy system • Grid support - Ancillary services and flexibility • Occasional roles as service provider • Investment deferrals	• Higher energy efficiency • Higher renewables penetration • Local economic growth • Increased energy security • Environmental benefits • Sustainability

Economic benefits of ICESs might be questionable in an optimum regulatory framework, without the distortion of tariffs, since the economy of scale in the centralized energy system is more powerful. For example, installation of PV is much more expensive at household and community level. However, ICESs might bring along other benefits to the energy systems such as reduced energy losses and deferral of grid reinforcement. The economic benefits of ICESs might still be positive after consideration of all possible value streams. Moreover, it should be noted that distributed PV is less efficient because they are not always well oriented and PV is not well maintained from dust and dirt leading to sub-optimal performance.

ICESs provide opportunities for citizens and communities to decide about their energy future, ensuring strong local support and social acceptance. Other contributions of ICESs include increased awareness, reduced energy poverty, affordable energy for all as well as increased sense of community, pride, and achievement.

2.8 Key issues with implementation and adaptation

ICESs are confronted with technological, socio-economic, environmental and institutional issues during its implementation and adaptation [59]. Most of these issues drive the emergence of such systems on the premise of sustainability. Moreover, ICESs aim at maintaining energy security or striving for energy independence, tackling climate change and keeping the prices affordable. For detailed discussions on each issues, please refer to Koirala et. al. [29].

2.8.1 Technical requirements

ICESs should meet several technical requirements for the integrated operation. ICESs technologies include flexible generators such as combined heat and power, fuel cells and heat pumps; intermittent renewables generator such as solar PV and the wind turbines; energy management measures such as demand-side management and demand response, as well as storage technologies such as batteries, hydrogen, heat storage and electric vehicles. The technologies included are for generation and supply, end-use, network management with information and communication technologies as well as the storage. The main issues surrounding these systems are intermittent of local renewables generation and demand response, energy efficiency, energy storage, local balancing of supply and demand, local flexibility and impact on larger energy system as well as load and grid defection. The technical requirements of community micro-grids such as grid-connected and islanded operation, relaying and protection as well as power quality are equally applicable to ICESs [96].

Technology progress is essential for linking local energy services and making them accessible and affordable. At the same time, technologies should be continuously shaping and adapting to the local circumstances. Advancements in technologies continuously shape ICESs. Technological innovations drive these systems as they create essential links between local energy services and their accessibility, affordability and environmental compatibility.

The technical configuration of ICESs depends not only on available technologies but also on corresponding political, market and regulatory frameworks adapted [66]. Moreover, technology choices are often linked to laws and regulations that reflect community capabilities, social preferences and cultural backgrounds [74]. Technological innovations also bring down the initial costs of the energy systems, at the same time increasing their reliability what, in turn, enables citizens and communities to adopt ICESs.

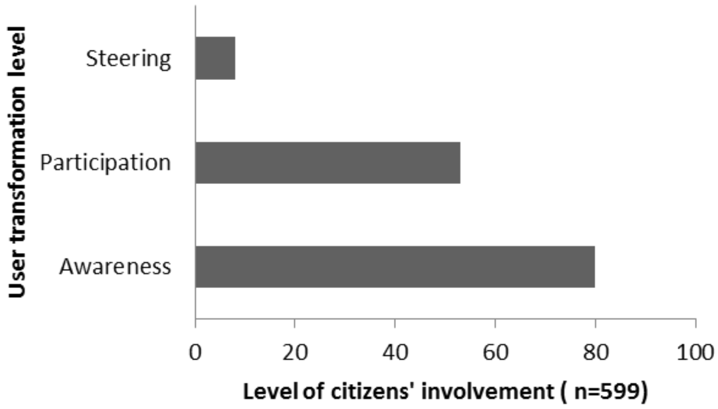
2.8.2 Socio-economic conditions

Technologies will drive the end-user activation in ICESs, yet there also remains the trickiest part of the community engagement process. A growing number of state of the art literature is increasingly concerned with the importance of more deliberative and inclusive participation of the consumers in the energy production process [87,94]. Community action on energy has increased significantly during the last decade due to rising energy costs [94]. According to the recent survey in the UK reported by DECC (2014), 42 % of the people surveyed showed their interest in taking part in the community energy development, provided it would reduce their energy bills [82].

Local energy systems such as ICESs are open and participatory as well as local and collective [21]. Accordingly, these systems have higher social acceptance and support. A strong sense of community is a prerequisite for the ICESs [60]. An emergent and self-organized community approach is expected to change the experience and outcomes of the ICESs implementation, as communities become both producers and suppliers of the energy [24,59,88].

A survey among Dutch households presented in Appendix and Figure 2.4, reveals that 80 % of the respondents are aware of the local energy initiatives such as ICESs, 53 % of the respondents are willing to participate and only 8 % are willing to take organizational responsibility to steer the system. The survey participants were also asked which organizational responsibilities they are willing to undertake to steer ICES activities. Among the respondents, 25% are not willing to participate at all, 37% are willing to participate but without organizational responsibility, 30 % are willing to participate with minor responsibility such as attending member meeting, and 8 % are willing to participate with substantial responsibility of steering the ICESs such as member of the board. Citizens' participation in the energy system helps to enhance local support. It increases acceptance of renewables and adoption of energy efficiency measures and impacts beyond the limit of the local energy project.

Figure 2.4. User transformation vs. level of citizens' engagement



Moreover, ICESs are in a better position to address the issues of energy poverty than profit driven traditional utilities. ICESs may not operate for profit. The socio-economic issues surrounding ICESs are paradigm shift through community engagement, economic incentives, willingness to pay, split-incentive problems, energy poverty, energy autonomy and security of supply as well as financing. Moreover, the question yet to be answered is how should the local exchanges in communities be organised and design of the local energy markets. As ICESs become sufficiently common, local energy markets become essential for the interaction between them.

2.8.3 Environmental constraints

The primary policy argument for implementing renewable energy technologies is the unpriced pollution externalities from burning fossil fuels [97]. Fossil fuel based centralised energy systems have externalities mainly due to the environmental damage. Together with improvement in efficiency and reliability, ICESs are considered to be an environmentally friendly alternative to a centralised power supply system as they help in increasing the penetration level of renewables [58]. Similar to distributed generation, environmental policies and awareness are the major driving force behind the surge in the implementation of ICESs [98].

ICESs are considered as an effective means to bring our energy systems in the sustainability track. For example, Harcourt et al (2012) estimated that ICESs in Canada have the potential to reduce CO_2 emissions by 5-12 % annually by 2050 [63]. Being local, these systems have higher social acceptance than their giant counterparts. Consequently, community action on energy has increased significantly during the last decade as a result of rising concerns about climate change [94]. The limited availability of private and public space for the installation of energy systems at the local level constrains the emergence of ICESs. The main environmental related issues with ICESs are emissions, waste and spatial constraints [63,99].

2.8.4 Institutional issues

The present energy system is highly institutionalized. However, these institutions did not develop with the focus on community energy initiatives such as ICESs. The existing institutional regimes hinder long-term transformation of energy systems which demands (re-) design of such institutions [83]. Accordingly, ICESs experiment with current institutional arrangements, take risks and grab opportunities, and create new institutions or, even self-organize local energy systems [59].

The institutions are comprised of regulative, normative and cultural-cognitive elements which together with associated activities and resources can provide stability and meaning to ICESs. It includes hard institutions such as legislations, capital markets, or the educational system as well as the soft institutions such as culture and social norms [100]. According to Wolsink (2012), there are five categories of institutions for the provision of low-carbon energy systems such as ICESs: (i) government policies; (ii) dominant technologies; (iii) organizational routines and relations; (iv) industry routines and relations; (v) societal expectations and preferences [58]. The community has an individual institutional order which can shape decisions on citizens' involvement as well as plant location and scale [32]. Moreover, Williamson's (2000) four levels of institutional analysis explains the characteristics, links and influences of the different institutional level such as informal institutions, formal institutions, institutional arrangements as well as actors and their strategies [80]. These characteristics and links connect ICESs with the individual households as well as the larger energy systems.

The changing local energy landscape requires reconsidering roles and responsibilities of different actors. Financial and regulatory risks can be dealt with by leaving some aspects such as economic incentives to market and regulating other aspects such as co-ordination of shared infrastructure and facilities. Opportunities such as self-regulation and self-governance emerge in local energy systems. Institutional transformations must be a critical aspect for ICESs because it is a way to effect significant and lasting social change to ensure the sustainability of these local energy initiatives.

According to Oteman et al. (2014), the institutional context of the policies, power structures and energy discourses differ among countries such as the Netherlands, Germany and Denmark [40]. For example, civil society friendly energy sector of Denmark, market-oriented energy sector of Netherlands and state-dominant energy transitions strategy of Germany, strongly influences the available institutional space for the ICESs development. Moreover, Wolsink (2012) argues that current development of local energy systems suffers from a focus only on technology, whereas social determinants are largely being neglected [58]. The institutional issues surrounding ICESs are trust, motivation and continuity, energy democracy, ownership, organizational models, locality and responsibility, support schemes and targets, (self) governance, regulatory issues, institutional (re-)design as well as changing roles and responsibilities.

Avelino et al (2014) identified four categories of challenges for self-governance of ICESs: economic and financial challenges, legal issues, socio-cultural conditions, and micro-political struggles as well as conflicts [60]. Moreover, a community energy system is largely affected by inter-personal dynamics, the intellectual capacity of community members and their long-term commitment. Often, the community energy initiatives are due to enthusiastic leaders. Yet, there are often free rider problems in such initiatives.

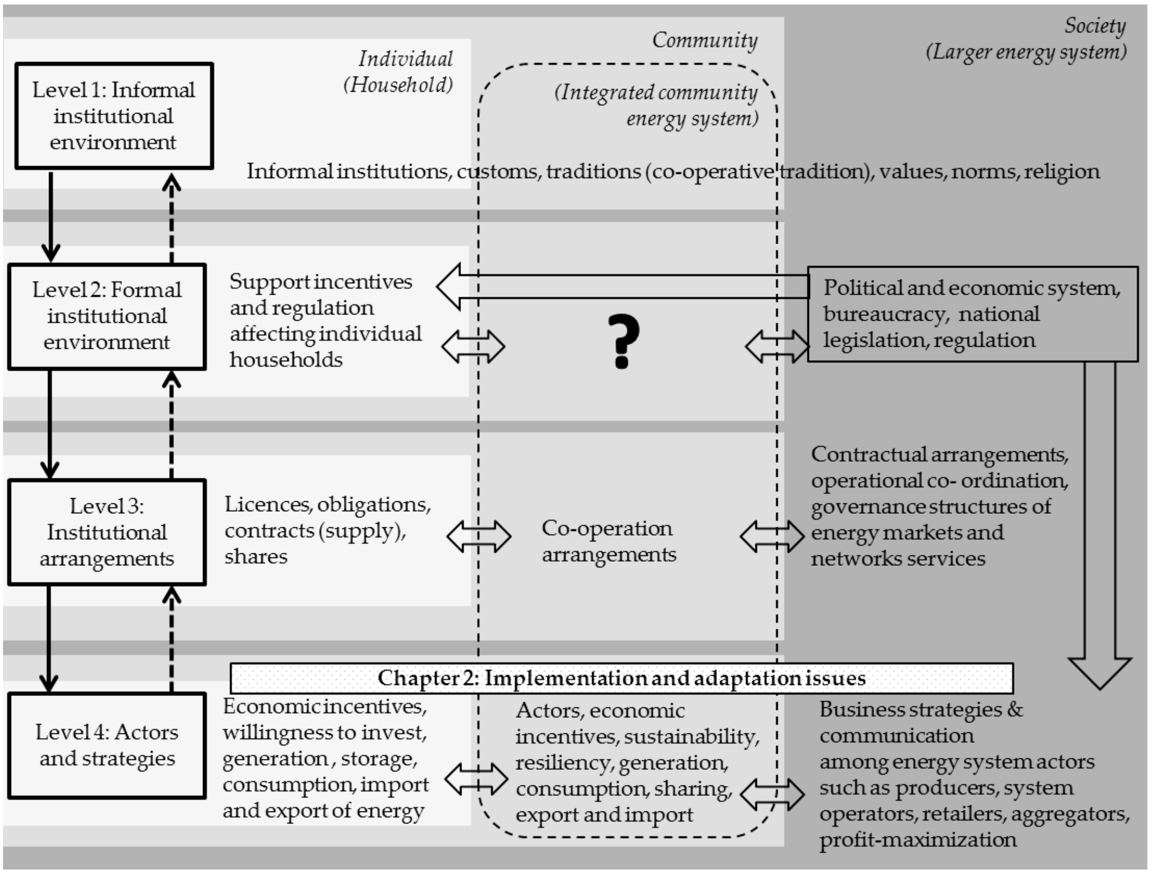
Frantzeskaki et al (2013) introduced the concept of 'beyond controlling and beyond governing' or 'invisible governance' or 'meta –governance' [59]. These concepts can be utilized for the governance of ICESs. This type of reflexive governance diagnoses paradoxes and facilitates space for self-correction and action without neglecting the roles and responsibilities of the government. This provides higher control for local communities in shaping their local energy systems.

2.9 Synthesis

The sub-research question addressed in this chapter was: *What are the technical, socio-economical, environmental and institutional dynamics and interactions of transformation towards ICESs?* This chapter reviewed the drivers, barriers, contributions of ICESs as well as the key technical requirements, socio-economic conditions, environmental constraints and institutional issues in implementation. The contributions of ICESs include sustainability as well as the security of supply, self-reliance and energy independence. Challenges in ICESs operation such as joint investment, joint decision making, and the fair allocation of costs and benefits among members, make it difficult to capture all the benefits of the ICESs. Even focus on technical, socio-economic, environmental and institutional aspects help to co-create local energy system such as ICESs bringing along user-inspired innovations. ICESs has the potential for fundamental technological, socio-cultural and institutional shifts in households and community assumptions about energy consumptions as well as new opportunities for ownership, engagement and control of the local energy system.

Figure 2.5 positions Chapter 2 in the conceptual framework. ICESs have to be embedded in the multi-level institutional environment dominated by the national energy system. Different actors of the ICESs will have important roles to steer and transform the activities of ICESs. These activities namely consumption, storage, exchange and collective purchasing are influenced by attributes of the technical world such as available technologies, grids as well as the environment, attributes of community in which actor and actions are embedded and institutions which guide and govern actors behaviour. This leads to patterns of interactions and outcomes which could cause different technical, economic, social and environmental issues in ICESs as well as the larger energy system. Accordingly, appropriate institutions should be established to overcome barriers and challenges to the design, planning, implementation and operation of ICES.

Figure 2.5. Positioning chapter 2 in the conceptual framework



Chapter 3
Modelling of Integrated Community Energy System

"If I have seen a little further than others, it is by standing on the shoulders of giants"

-Sir Issac Newton

This chapter provides the detailed modelling approach of the ICES model used in Koirala et al (2016)[3] [70]. First, the state of the art in energy system integration are presented. Then, a framework to model and assess the ICESs is presented. Finally, the model description and the relevance as well as the limitations of the modelling approach is provided.

3.1 Background

Increasing penetration of DERs is challenging the top-down architecture of the centralised energy system. In this context, sharing of energy between households in a neighbourhood is increasingly becoming relevant. The rise of DERs, bottom-up local energy initiatives and local energy exchange further complicates the planning and operation of the present energy system as well as the associated economic and environmental implications [103]. Accordingly, the problems in energy systems related to efficient planning and operation are nowadays very complex and very often a large data set is associated. Optimization techniques such as linear and non-linear programming have played important roles in the economic, secure and reliable operation of the present energy system. The goal of this chapter is to review the state of the art in literature on the system integration of DERs and community energy system as well as to develop a model for the assessment of ICESs.

3.2 State of the art energy system integration options

The key challenge of future energy systems is the integration of increasing levels of distributed energy resources. To address this challenge, several energy system integration options are being designed and implemented such as virtual power plants, energy hubs, community micro- grids, prosumers community groups, community energy systems and integrated community energy systems [18–29]. These options to energy system integration differ in their objectives and most of them are designed to adapt to an existing blueprint of a centralised energy system. For example, the aim of community micro-grids is to optimize electricity generation and demand for resiliency

[3] Koirala B, Chaves Ávila J, Gómez T, Hakvoort R, Herder P. Local Alternative for Energy Supply: Performance Assessment of Integrated Community Energy Systems. Energies 2016;9:981. doi:10.3390/en9120981.

whereas virtual power plants aim at aggregation and operation of DERs. ICESs offer a comprehensive and integrated approach for local energy system where communities can take complete control of their energy system and capture all the benefits of energy system integration. See Table 3.1 for a summary of the objectives of each energy system integration option.

Table 3.1. Overview of the energy system integration options

Options	Objective	References
Community micro-grids	Optimize electricity generation and demand for autarky and resiliency in community	[18]
Virtual power plants (VPPs)	Aggregate and manage (operate) DERs	[19]
Multi -energy hubs	Multi-carrier optimization of electricity, gas, heat and cooling within a district	[26]
Prosumer community groups	Energy exchange among prosumers having similar goals	[27]
Community energy systems	Invest and operate the local energy system	[20][21][25][24]
Integrated community energy systems (ICES)	Multi-faceted approach to supply local communities with its energy requirements through DERs, flexible loads and storage together with different carriers as well as the community engagement	[23] [22] [28]

Community microgrids: Community micro-grids comprise of locally controlled clusters of DERs which are seen as single demand or supply from both electrical and market perspectives [53]. Micro-grids can detach from the national grid and operate autonomously when needed. It enables higher penetration of DERs such as solar, wind, combined heat and power, demand response as well as storage. In this way, local resources can be used to supply local demand, thereby reducing losses and increasing the efficiency of the energy delivery systems.

Virtual power plants (VPP): Consumption and production of various households can be aggregated to form flexible capacity equivalent to that of a power plant, hence creating a virtual power plant. According to Morales et al. [48], virtual power plants are "a cluster of dispersed generating units, flexible loads and storage systems that are grouped in order to operate as a single entity". A VPP can be technical or commercial [12]. A technical VPP has location specificity attached to the flexibility, mainly within a distribution system. Differently, a commercial VPP has no location specificity; flexibility from such a VPP can be distributed and aggregated from different distribution systems. The VPP allows participation of DERs into energy markets as well as system operation support; thereby helping the gradual replacement of centralized power plants.

Energy hubs: An energy hub manages the energy flows in a district through the optimal dispatch of multiple energy carriers [13]. It includes storage, conversion and distribution technologies to supply electricity, heat, gas and other fuels to the end users. When the conversion technology is available, energy-carriers can be transformed into other forms.

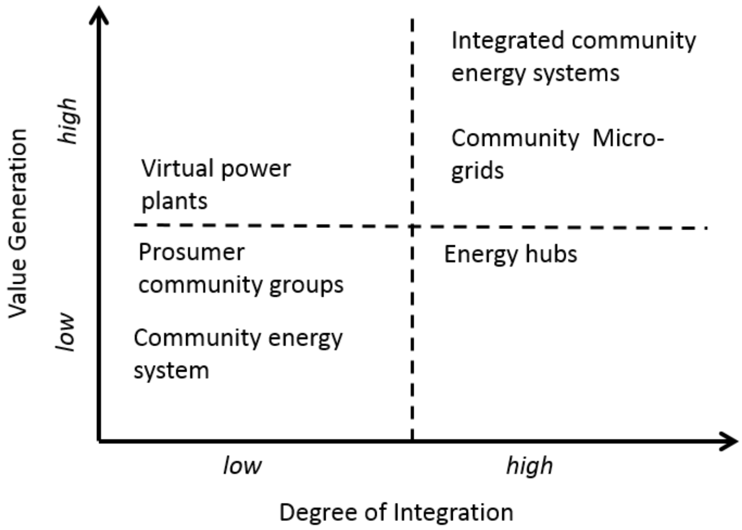
Prosumer community groups (PCGs): According to Rathnayaka et al. [14], "PCG is defined as a network of prosumers having relatively similar energy sharing behaviour and interests, which make an effort to pursue a mutual goal and jointly compete in the energy market". In fact, PCGs are designed to overcome possible inflexibility arising from micro-grids and technical VPP such as complexity to add or remove new members. PCGs virtually interconnect prosumers and may not necessarily be connected technically.

Community energy systems: According to Walker and Simcock [8], "community energy systems refer to electricity and/or heat production on a small, local scale that may be governed by or for local people or otherwise be capable of providing them with direct beneficial outcomes".

Integrated community energy systems: As elaborated in Chapter 1, ICESs capture attributes of all energy system integration option discussed above and apply them to a community level energy system. These are modern developments to re-organize the local energy systems and increase the community engagement. Mendes et al. [16] defined ICESs as a multi-faceted approach for supplying a local community with its energy requirement from high-efficiency co-generation or tri-generation as well as from renewable energy technologies coupled with innovative energy storage solutions as well as electric vehicles and demand-side measures. They aid in increasing self-consumption and matching supply and demand at the local level.

For the comparison, value generation and degree of integration are analytically plotted for different energy system integration options as presented in Figure 3.1. Value generation refers to the value for the larger energy system. It can be through collaboration and services to external systems such as other communities or larger energy system. Degree of integration refers to internal values such as self-provision and self-sufficiency. As ICESs and community micro-grids provide both energy-related services, operating reserves and network services through physical interconnection, they rank high in terms of both value generation and the degree of integration. ICESs are expected to rank slightly better than community micro-grids due to higher community engagement and integrated operation of different sectors.

Figure 3.1 Interplay between value generation and degree of integration in different energy system integration options



3.3 Choice of modelling options

After contextualizing ICESs in the energy system and the qualitative assessment, the next logical step is the quantitative modelling of ICESs. DERs integration in local communities and cities have been addressed by several studies [104–117]. Many of these studies present sophisticated optimization techniques to solve DER investment and scheduling problems. In this process, several tools such as hybrid optimization model for electric renewables (HOMER), distributed energy resources-consumer adoption model (DER-CAM) and SPLODER have been developed [104,108,118]. Mendes et al (2011) performed a review of the potential tools for the planning and analysis of ICESs [23]. Modelling tools such as MARKAL/TIMES [119], RETScreen [120], HOMER [45,108,121] and DER-CAM [104,122] has been summarized and compared. Similarly, Huang et al (2015) provide a detailed review of the methods and tools used for the community energy planning [123]. Modelling tools such as EnergyPLAN [124], Environment and energy Geographical Information System (E-GIS) [125] and Sustainable Urban Neighborhood Modelling tool (SUNtool) [126] are described. Currently, community energy planners have to manage a large set of modelling tools which are not compatible to be integrated. Furthermore, there has been limited numbers of integrated assessment models that span across multiple sectors and activities. In this section, an overview of the selected modelling options for ICESs is provided.

3.3.1 MARKAL/TIMES

For the decision support and community energy planning from the macroscopic level, tools such as MARKAL (MARKet Allocation), Energy Flow Optimization Model (EFOM) or the combination such as The Integrated MARKAL-EFOM System (TIMES) are available [119]. These tools are being developed by the Energy Technologies Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) and are one of the most widely used tools for the modelling of the integrated energy systems. These tools, however, do not offer the possibilities for detailed simulation of distributed energy resources and building energy demand. Despite its application for the governments, states and municipalities, the results are not readily available to the larger scientific community.

3.3.2 EnergyPLAN

EnergyPLAN is an advance energy system analysis tool developed and maintained by the Aalborg University [124]. It can simulate the operation of national, regional and local energy systems including the electricity, heating, cooling, industry and transport sectors. Although the model assist in the design of the national energy planning strategies through techno-economic analysis of different national energy systems and investments, it has also been applied for the analysis of the local energy systems [127].

3.3.3 HOMER

HOMER can simulate and optimize stand-alone and grid-connected power systems comprising of wind turbines, solar PV, hydro, biomass, conventional generators as well as energy storage [121]. In HOMER, investment and operation costs as well as techno-economic and emission constraints are considered for the optimal sizing of hybrid renewable energy systems and community micro-grids [108]. HOMER is originally developed by National Renewable Energy Laboratories (NREL) in 1992 and further enhanced by HOMER energy. A recent study on the grid-integrated and grid-defected operation of DERs at household level using HOMER is presented in [19]. Although HOMER is capable of modelling integrated energy systems at the community level, it has not been applied for this application yet.

3.3.4 RETScreen

The RETScreen clean energy management software is developed and maintained by Natural Resources Canada since 1996 [120]. It allows comprehensive assessment and optimization of the technical and financial viability of the renewable energy, energy efficiency and co-generation projects. Recent versions also include off-grid analysis capabilities. RETScreen allows parallel analysis of conventional and renewable technologies and can be extended to analyze variety of projects ranging from district heating systems to energy systems of institutional and commercial buildings. The limitations of RETScreen includes no operation optimization, monthly time step, unavailability for further expansion and adaptation.

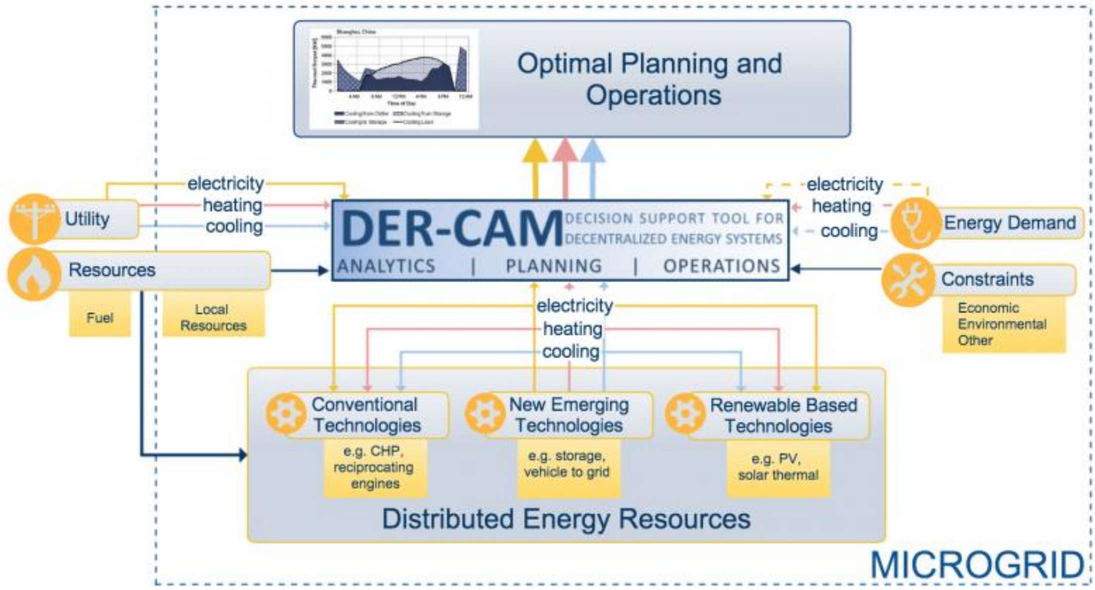
3.3.5 SPLODER

SPLODER is continuously being developed and maintained by the Institute for Research in Technology at Comillas Pontifical University. SPLODER is able to make planning and optimal operation at building, community and system level [118]. For this purpose, different versions of SPLODER such buildings, micro-grid, AMS and System are available. The version SPLODER-SYSTEM has been used in the utility of the future project [128]. Recently, many research has been conducted using this model [109,112,115]. It has real time part running round the clock in several regions in Spain.

3.3.6 DER-CAM

Distributed Energy Resources- Consumer Adoption Model (DER-CAM) is a mixed –integer optimization tool for investment and planning decision support in micro-grids [104,122]. It is continuously being developed and maintained by Lawrence Berkeley National Laboratory, since 2000. Recently, a web-based version of DER-CAM, called DERs Web Optimization Service (WebOpt), as well as DER-CAM+, is also available [122]. Figure 3.2 represent the detailed schematic of DER-CAM Model. DER-CAM is being widely used to solve DER investment and scheduling problems as well as for economic and environmental analysis of DERs [104,122].

Figure 3.2. Schematic of DER-CAM [122]



In this research, DER-CAM is used as the modelling basis due to its validated use as well as the inbuilt capability to conduct the economic and environmental analysis of the DERs. The choice of DER-CAM is due to robust and flexible optimization algorithm, hourly time step and consideration of multiple sectors as well as its proven application in modelling micro-grids [23]. Additionally, availability of the source code through the research collaboration as well as GAMS modelling environment allowed adaptation of the DER-CAM model to the ICES model. The previously one-node DER-CAM model has been adapted to the multi-node ICES model incorporating aggregated investment and operations of DERs at household and community levels .

3.4 Integrated Community Energy Systems Model

Despite the above mentioned choices of modelling options, a little has been done regarding DER investment and scheduling considering a collective and co-operative action of a group of households in local communities. The aggregation of DERs is proven to be beneficial even for relatively small groups of prosumers in comparison with individual configurations [6]. The concept of ICESs supersedes all the advantage of single or hybrid DERs, thus the advantage of aggregation and integrated operation could be considered. This work advances the study on the ICESs where a group of customers cooperates to efficiently manage their local energy systems, including DERs at individual premises as well as in the common spaces. The ICES model can determine economically and environmentally optimal community energy system, given the energy usage, system of prices and charges as well as the DER costs such as those of fuel cells, combined heat and power, solar-PV, electric vehicles as well as the energy storage system.

The main highlights of the ICES model over DER-CAM are:

a) A new set of households (H) has been added to each equation;
b) Different electricity, hot-water, space-heating and cooling demand profiles for each household are considered;
c) The simulation and optimization of DER investment and scheduling in several households simultaneously are possible;
d) In addition to individual investment in DERs, the community can also decide to invest in community-level technologies provided there are economies of scale;
e) The local exchange between the households is enabled;
f) The DER installed capacity and exchanges are constrained by the maximum line capacities;
g) Grid connected and grid-defected operation options are available.

3.4.1 Modelling framework

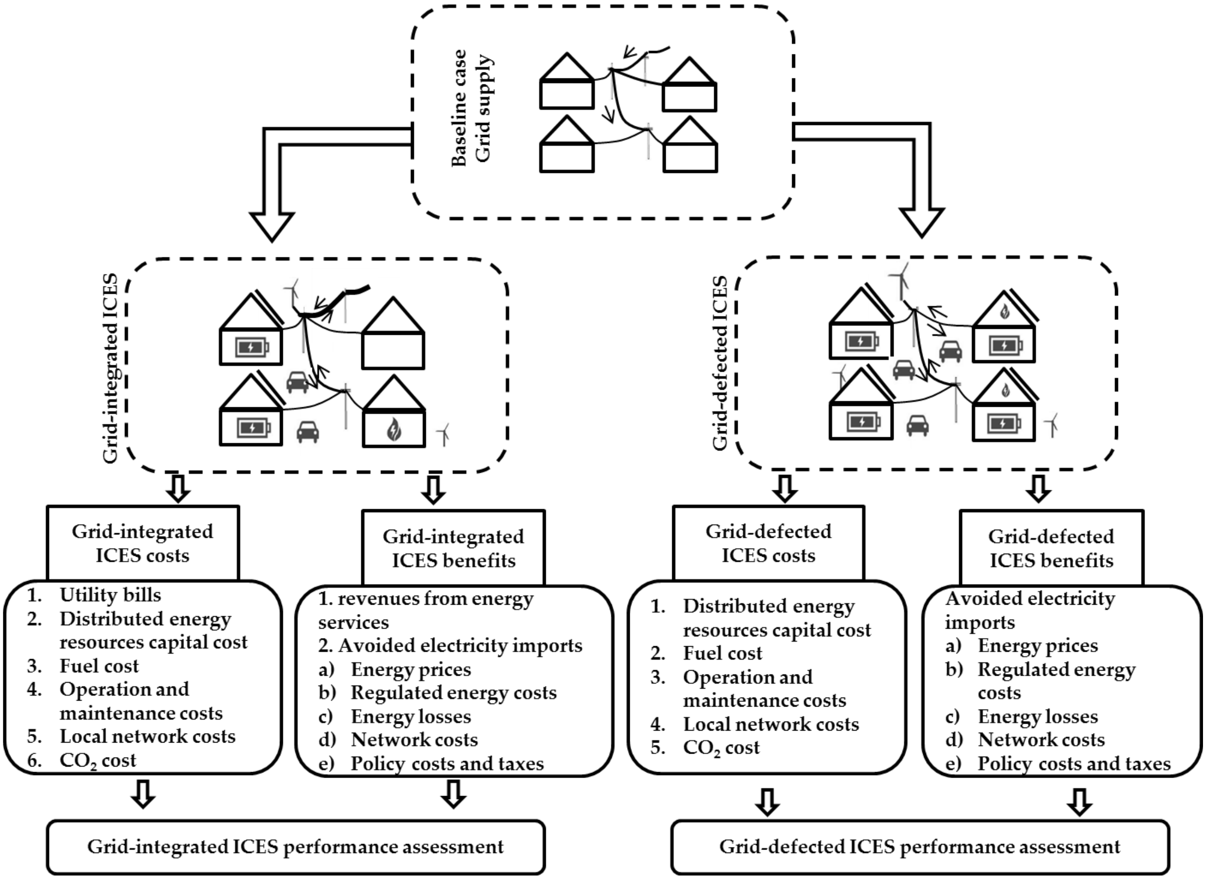
ICESs are expected to have technical, economic and environmental potential for improving the local energy systems. Yet, the modelling of complex socio-technical systems under the changing energy landscape is a tedious task. Several technological, socio-economic, environmental and institutional issues as well as emerging trends in the energy landscape as discussed in Chapter 1 and 2 shape the emergence of ICESs [29]. As the benefits and costs are understood, the added value of ICESs could also be assessed. The local aggregation in the form of ICESs may further improve the economics of DERs. The interaction and complementarities among multiple-energy carriers might also have significant value in the energy system. Critical empirical assessment of the economic and environmental value of alternative energy system organization, such as an ICES, is needed [129].

It is technically possible to have both grid-integrated and grid-defected operation of the energy system at the household level and the economic and environmental assessment and evaluation of the former system are promising [47–50]. The collective operation of a group of households in the form of ICESs can cause new interactions, dynamics and value streams in the energy system. Despite falling prices of DERs, the grid-defected system for individual households which are completely independent of the grid, on the other hand, is not yet economically attractive. Assuming the technical possibility, the aggregation of a group of local consumers in the form of ICESs might further improve these results for both grid integrated and grid-defected system. For this, economic and environmental assessment and evaluation of such local aggregation are needed.

Our modelling framework for the assessment of ICESs is presented in Figure 3.3. Households are the basic units of ICESs with different energy demand profiles. For the base case, it is assumed that households are passive consumers and do not invest in DERs. A number of households cooperate to form ICESs which can operate either in grid-integrated or in grid-defected mode. The investment and operation of DERs, as well as associated cost and benefits, are different for each case which in turn impact its economic and environmental performance.

Grid-integrated ICES costs involve utility energy bills, capital costs for DERs and the energy management system, fuel costs, operation and maintenance costs as well as network costs to interconnect households. There are many benefits of the ICES as result of the several services provided to their members and to the system. Some of these benefits create efficiency in the whole energy system, such as energy sales, avoided energy imports at lower costs than the one provided by the external system and corresponding energy losses, whereas other benefits such as saving in network charges, or policy costs and taxes might be opportunistic; for further details on efficient and opportunistic benefits of aggregation strategies in the power system, refer to [46].

Figure 3.3. Modelling framework for the grid-integrated and grid-defected ICESs.

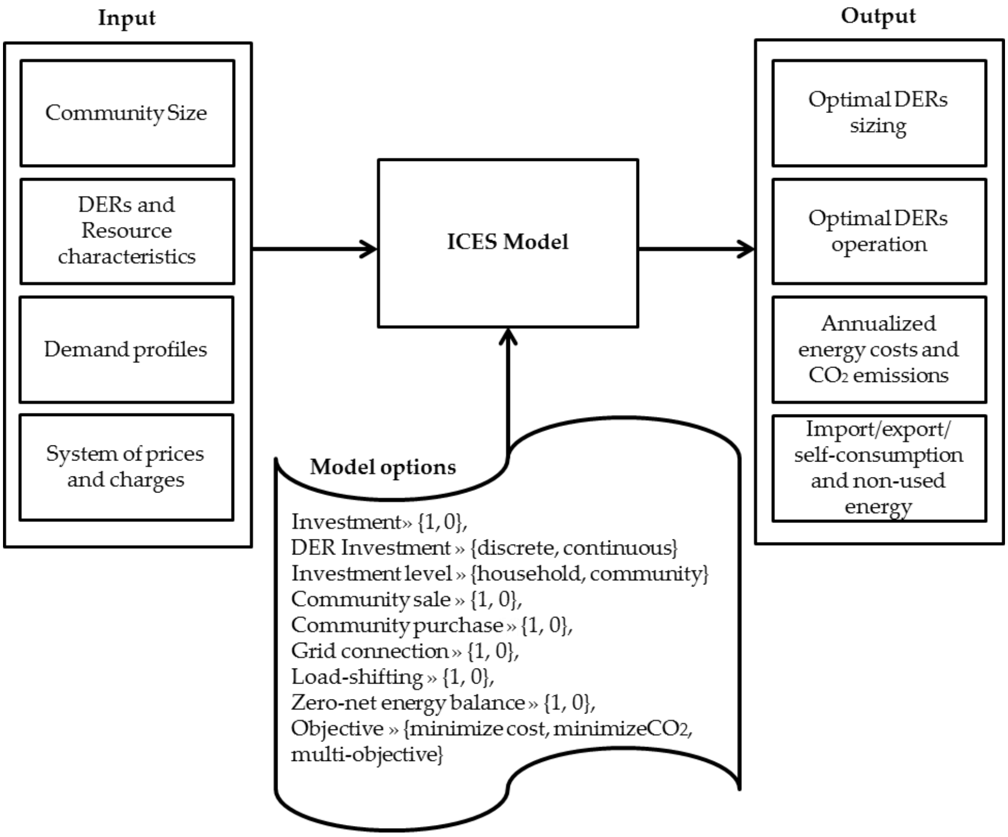


More communities are willing to take complete control of their energy systems. Some of these energy communities might decide to defect from the grid for non-economic reasons such as energy independence, emissions reduction, self-governance and other local preferences. Grid-defected ICESs costs mainly comprise of DER capital cost, operation and maintenance expenditure, network costs, CO_2 costs as well as fuel costs for the back-up system. In addition, the ICES may present system benefits, such as reduced network usage due to local balancing which can defer the need for network reinforcement. When assessing the grid-integrated and grid-defected ICES profitability, these avoided costs should also be accounted.

3.4.2 Functional model

Figure 3.4 presents the functional model of the ICES. The input modules contain demand profiles, the system of prices and charges, DERs techno-economic and resource characteristics as well as the community size. In demand profiles module, different energy carriers and end-uses are considered: electricity, hot-water, and space-heating and cooling demands for each individual household. The DERs techno-economic characteristics module consists of the techno-economic parameters of the household and community level DERs. This module also consists of energy conversion technologies. The resource data, such as temperature and solar irradiation, is also the key part of this module. The system of prices and charges module varies according to the region or country. It consists of fixed and variable costs as well as wholesale and retail prices of the energy. The community size represents the number of households that form the ICES.

Figure 3.4. Functional ICES model



Based on the community size, the consumers have the possibility to invest in DERs and perform local exchanges in order to reduce their energy bills as well as the carbon footprint. Optimal investment options are considered for both households and communities as more DERs become technologically and economically available. For the sake of simplicity, the additional community network costs for ICESs are not accounted in this thesis, instead network costs of the national grid are used as a reference. In addition, the model has different scenarios as modelling options. For example, the baseline case is represented by the modelling options with no investment. When the DER investment is an option, the model can make discrete (CHP and fuel cells) or continuous (solar PV and storage) or both investment. The investment can be at the household or community level or both level. The grid defection scenario is modelled with no community sale or purchase and no grid connection with the larger energy system. The objective function can be cost minimization, emission minimization or multi-objective.

The outputs of the model are optimal sizing and operations of DERs for both household and community level. The annualized energy costs and CO_2 emissions are used as performance metrics for economic and environmental analysis. In addition, detailed data on energy balance at household and community level such local exchange, unused or curtailed energy, import and export is also available as output.

3.4.3 Model formulation

An ICES model for local energy exchange is formulated in DER-CAM, an optimization tool for DER investment and planning. Aggregated performance of a group of households in a neighbourhood is estimated in terms of energy demand and generation from various distributed energy resources including storage and demand response. The analysis considers overall energy costs, CO_2 emissions as well as the level of energy autonomy. In addition to the model equations presented in [104], further equations have been added to the ICES model to simulate the local exchange and community level operation.

Modelling of a household

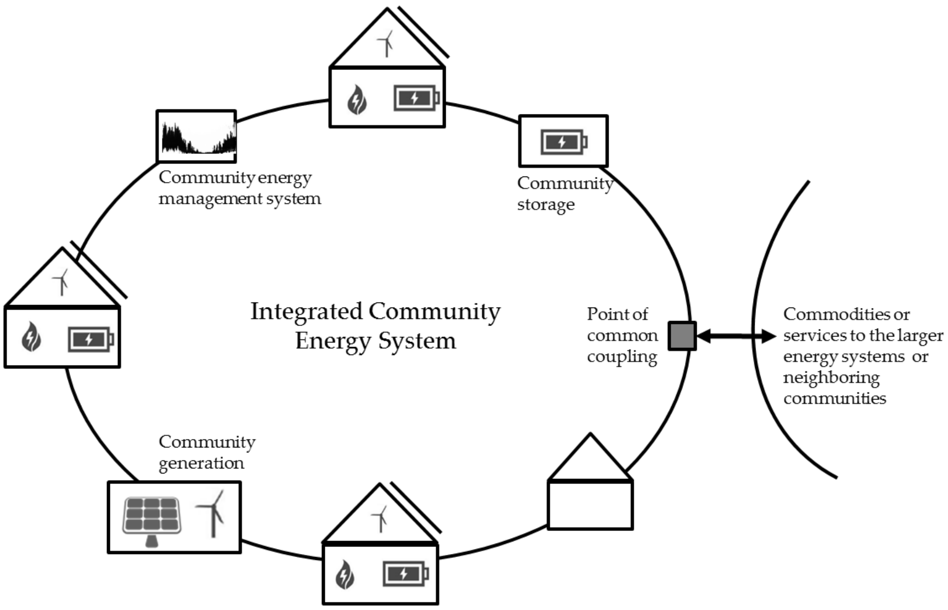
Households are the basic units of the ICES. In the changing local energy landscape, these households can invest in local generation technologies such as solar photovoltaics (PV), solar thermal, CHP, fuel cells, electric and thermal storage, electric cars and heat pumps (HPs) as well as home energy management systems to ensure effective energy balance and smart operation at household level. The households can export the surplus energy to ICES and purchase the deficit also through the ICES.

Modelling of a community

A group of consumers may join and cooperate together in the form of ICESs as presented in Figure 3.5, implying some advantages and challenges. The advantages include larger economies of scale due to common installations; multi-carrier efficiency gains from bundling different energy sources (e.g., electricity, heating, cooling); increasing reliability at lower costs; community engagement and fulfillment of community visions, such as autarky or energy independence where consumers are willing to pay higher costs for self-provided electricity within a community. Further investments are possible in community level technologies if the local community supply is not enough or it is cheaper compared to the household investment or grid-supply in the case of grid-connected systems.

The surplus generation from the households is pooled in the community energy exchange platform. The household can also purchase deficit energy from the platform. Different options exist for operating the local energy exchange platform such as peer to peer exchange, marginal or average cost-based local energy markets [40]. Due to the system perspective in this study, the transactions between the members are considered but not priced, and the energy exchanges among households are free of charge. As cost allocation of the local exchange is very important for the success of the ICES, the design of the system of prices and charges within the ICES definitely should be a future research agenda. For grid-integrated ICESs, energy deficits or surpluses at the community level can be purchased or sold to other communities or market agents through the national grid. The grid-integrated ICES can also provide different energy services for the system operators, such as balancing and flexibility, however, this is beyond the scope of this research. The grid-defected ICES, on the other hand, has to maintain the energy balance locally.

Figure 3.5: Modelling of a community in ICES model



Modelling of a household and community level DERs

As DER-CAM is the starting point for the ICES model, the existing models of household level DERs such as PV, CHP, EVs, energy storage and heat pumps from DER-CAM is used. In order to distinguish EV with stationary energy storage, EV is made available only between 10:00 and 17:00. Community level DERs are modeled and integrated into the ICES model. For further illustration, the modeling of community energy storage and community PV is presented.

Modelling of community photovoltaics

The community PV size is constrained by the available common area, Equation (3.1). The electricity generated by the community PV is constrained by the size and available solar insolation, Equation (3.2). The indices y, H, m, d, h in each equation refer to year, household, months, day types (week, peak, weekend) and hours, respectively.

$$\frac{cCPV_{CPV,y}}{p\eta PV} < ACA \tag{3.1}$$

$$eCPV_{y,m,d,h} = cCPV_{CPV,y} \times \frac{SI_{m,h}}{p\eta PV} \times \eta PV_{m,h} \tag{3.2}$$

Where,
$cCPV_{CPV,y}$ is the total capacity of community PV in year y,
$eCPV_{y,m,d,h}$ is the hourly electricity generated by the community PV,
$p\eta PV$ is peak PV efficiency,
ACA is the maximum common space available in the community in m^2,
$SI_{m,h}$ is the monthly average hourly solar insolation, and
$\eta PV_{m,h}$ is the monthly average hourly PV efficiency.

Modelling of community energy storage

The operation of storage is constrained by several storage parameters such as size, charging and discharging efficiency. The technical parameters of the community energy storage are presented in Table 3.2. The total energy stored depends on the size of the community energy storage.

Table 3.2. Community energy storage parameters

	Community energy storage
Charging efficiency (η_{CESC})	0.97
Discharging efficiency (η_{CESD})	0.97
Decay/hour (CESSD)	0.000042
Maximum charging rate (CESCR)	0.25
Maximum discharging rate (CESDR)	0.25
Maximum depth of discharge (CESDOD)	0.8

Equations (3.3)–(3.10) represent the operation of community storage.

$$CESS_{y,m,d,h} = CESS_{y,m,d,h-1} + CESI_{y,m,d,h} - CESO_{y,m,d,h} - CESL_{y,m,d,h} \tag{3.3}$$

$$CESI_{y,m,d,h} = EfCS_{y,m,d,h} \times \eta_{CESC} \tag{3.4}$$

$$EFCS_{y,m,d,h} = CESO_{y,m,d,h} \times \eta_{CESD} \tag{3.5}$$

$$CESL_{y,m,d,h} = CESS_{y,m,d,h-1} \times CESSD \tag{3.6}$$

$$CESI_{y,m,d,h} \leq CESC_{y,m} \times CESCR \tag{3.7}$$

$$CESO_{y,m,d,h} \leq CESC_{y,m} \times CESDR \tag{3.8}$$

$$CESS_{y,m,d,h} \leq CESC_{y,m} \tag{3.9}$$

$$CESS_{y,m,d,h} \geq CESC_{y,m} \times CESDoD \tag{3.10}$$

Where,

$CESS_{y,m,d,h}$ is electricity stored in community energy storage,

$CESI_{y,m,d,h}$ is community energy storage input,

$CESO_{y,m,d,h}$ is community energy storage output,

$CESL_{y,m,d,h}$ is community energy storage losses,

$EfCS_{y,m,d,h}$ is electricity for community energy storage,

$EFCS_{y,m,d,h}$ is electricity from community energy storage,

$CESC_{y,m}$ is capacity of community energy storage,

$CESSD$ is community energy storage self-discharge rate,

$CESCR$ is community energy storage maximum charging rate,

$CESDR$ is community energy storage maximum discharging rate,

$CESDoD$ is community energy storage maximum depth of discharge,

η_{CESC} is community energy storage charging efficiency, and

η_{CESD} is community energy storage discharging efficiency.

Modelling of the Local Energy Exchange

The community energy pool consists of the surplus from each household, the deficit from each household and the generation from community DER technologies. For the grid-integrated ICES option, the surplus can be exported and the deficit can be imported through the external grid. However, for the grid-defected case, there is no exchange with the external grid and all the energy demand has to be met locally. The local exchange is the net surplus from the household and the community generation which is consumed within the ICESs. Although local energy prices become increasingly important we assume the exchange of energy among members of ICESs without determining the corresponding price but fulfilling energy requirements.

$$CNE_{y,m,d,h} = \sum_{H} ES_{y,H,m,d,h} + eCPV_{y,m,d,h} + EFCS_{y,m,d,h} - EfCS_{y,m,d,h} - \sum_{H} EP_{y,H,m,d,h} \quad (3.11)$$

$$CNE_{y,m,d,h} = CES_{y,m,d,h} - CEP_{y,m,d,h} \quad (3.12)$$

Where,
$CNE_{y,m,d,h}$ is net energy exchange at community,
$ES_{y,H,m,d,h}$ is household electricity sale,
$EP_{y,H,m,d,h}$ is household electricity purchase,
$CES_{y,m,d,h}$ is community electricity sale, and
$CEP_{y,m,d,h}$ is community electricity purchase

Objective Function

The objective function of ICES model can be a cost minimization or CO_2 emissions minimization or multi-objective involving combination of cost and CO_2 minimization. The structure of the DER-CAM based ICES model, includes the main objective function to reduce cost as well as the key constraints. A mixed integer linear programming ICES optimization model is solved in the general algebraic modelling system (GAMS) environment [130]. The community annual energy costs consist of annual utility costs for electricity and gas of each household; annualized DER capital costs; operation and maintenance costs, as well as revenues from the annual electricity sales outside of the community. The detailed model formulation including the model of households and community DERs as well as local energy exchange is presented in [101].

The objective function to minimize annualized community energy costs is presented in Equation (3.11).

$$ACEC = CEC + CNGC + CDC - CAES \quad (3.13)$$

Where,
ACES is annualized community energy costs,

CEC is annualized community electric costs,
CNGC is annualized community natural gas costs
CDC is annualized community DER costs
CAES is Annual community electric sales

The community electric costs (Equation (3.14)) and community natural gas costs (Equation (3.15)) represent total utility costs for electricity and natural gas for the whole community.

$$CEC = \sum CEFC_{y,m} + \sum CETOUC_{y,m} + \sum CECO2C_{y,m} \tag{3.14}$$

$$CNGC = \sum_{m} \sum_{H} HNGC_{y,H,m} \tag{3.15}$$

Where,
$CEFC_{y,m}$ is monthly fixed costs of electricity for the community,
$CETOUC_{y,m}$ is monthly time of use costs of electricity for the community,
$CECO2C_{y,m}$ is monthly CO_2 costs of electricity for the community,
$HNGC_{y,H,m}$ is monthly natural gas costs for the household.

The community DER Costs (Equation (3.16)) are the aggregated costs of household and community level DERs and consider both capital as well as operation and maintenance costs.

$$CDC = \sum_{H} HDC_{y,H} + ACCC + \sum_{m} (FMCC_{y,m} + VMCC_{y,m}) \tag{3.16}$$

Where,
$HDC_{y,H}$ is annualized DERs cost of the household,
$ACCC$ is annualized capital cost of community DERs,
$FMCC_{y,m}$ is fixed maintenance cost of community DERs,
$VMCC_{y,m}$ is variable maintenance cost of community DERs.
The community annual energy sales (Equation (3.17)) refers to the revenue generated from the export outside of the ICES. Where, PX is the day-ahead market price input to the model and community electric sales is the hourly amount of energy export from the ICES and calculated in the energy balance equation. The import happens at retail price whereas the export is remunerated at the wholesale price.

$$CAES = \sum_{m,d,h} CES_{y,m,d,h} \times PX_{y,m,d,h} * NumberofDays_{m,d} \tag{3.17}$$

Where,
$CES_{y,m,d,h}$ is hourly electricity sales from the community in kWh
$PX_{y,m,d,h}$ is hourly day ahead wholesale market price in euros/kWh

The objective function (see Equation (3.13)) presented above is subjected to several technical, economic, and environmental constraints. Technical constraints include community and household energy balance, line capacity, generator as well as storage size. Economic constraints such as maximum payback period is considered. Environmental constraints such as available area is also taken into account. For household energy balance equations, refer [104]. For example, the household and community DER investment are constrained by the available connection line capacity which depends on conductor types.

$$CCC_{y,m} \geq CEP_{y,m,d,h} - CES_{y,m,d,h} \tag{3.18}$$

$$HES_{y,H,m,d,h} \leq HLC \tag{3.19}$$

$$CES_{y,m,d,h} \leq CLC \tag{3.20}$$

Where,

$CCC_{y,m}$ is monthly community contract capacity in kW,

$CEP_{y,m,d,h}$ is hourly electricity purchase in the community in kWh,

$HES_{y,H,m,d,h}$ is hourly electricity sales from the household to the ICESs,

HLC is maximum line capacity of the household in kW,

CLC is maximum line capacity of the community in kW,

3.4.4 Model statistics

The ICES model is run using 4 parallel threads on a 8 GB RAM computer running GAMS 24.7.3 and CPLEX solver. The maximum execution time limit is 20 hours, iteration limit 5 million, and the optimality gap is 1 %. The Table 3.3 represents the number of equations and variables according to the model options.

Table 3.3. ICES Model statistics

Model options	Equations	Variables	Discrete variables
Baseline (No investment)	2,954,569	3,919,692	279,194
Investment (household)	3,093,969	3,989,892	313,794
Investment (community)	3,097,452	3,991,647	314,659

3.4.5 Model relevance

Community energy systems are of growing interest and the ICES model offers a key tool in assessing the planning and operation including better designs and new policies for local energy system. The integrated modelling approach has very high policy relevance involving multiple sector and activities. The model is capable of analysing grid connected and grid-defected operation and the emphasis is on the synergies with the larger energy system. It includes wide ranges of household and community level DERs and can analyse the interactions between electricity, heat and transport sectors as wells as other activities such as energy efficiency and load shifting within the local communities. The model results include detailed planning and operation of DERs, local energy exchange, self-consumption, curtailments, imports and exports as well as total costs and emissions. The ICES model can simulate variety of options based on scenarios and compare them, rather than modelling one optimum solution. ICES model can potentially support community planners, policy makers, technology providers as well as entrepreneurs and businesses. Table 3.4 compares the ICES models with other existing modelling options.

Table 3.4 Comparison of ICES Model characteristics with existing modelling options

Model	Objective	Optimization	Investment	Sector	Configuration	Outputs
MARKAL/TIMES	Minimize costs	Planning	National or regional or community	Electricity, heat, industry, transportation, commercial and tertiary sector	Grid-integrated	Energy flows, energy commodity prices, emissions, capacity of technologies, and costs
EnergyPLAN	-	Operation	-	Electricity, heat, transport and industrial	Grid-integrated	Energy balances, annual generation, fuel consumption, import/exports and total revenues
HOMER	Minimize lifecycle costs	Planning and operation	Community	Electricity and heat	Grid-integrated or grid-defected	System configurations, economic parameters
RETScreen	Minimize costs	Planning	Community	Electricity and heat	Grid-integrated or grid-defected	Energy production and savings, costs, emissions, financial viability and risk
SPLODER	Multi-objective (comfort, cost, environm-ental impact and resiliency)	Planning, operation and real time operation	Building, districts, microgrids or country/ system	Residential, tertiary, industrial and policy makers	Grid integrated or grid-defected	Environmental impact, energy price (off-grid), tariffs (system level), optimal mix of DER generation, schedule and investment

DER-CAM	Minimize costs	Planning and operation	Building	Electricity, heat and transport	Grid-integrated	Total costs and emissions, import and exports
DER-CAM-ICES	Minimize costs, emissions or multi-objective	Planning and operation	Building and community	Electricity, heat and transport	Grid-integrated or grid-defected	Optimal planning and operation, Total costs and emissions, imports and exports , local energy exchange, self-consumption, curtailments

3.4.6 Model limitation

The developed model partially address the different community objectives such as cost reduction, emission reduction and higher energy independence. The model relies on exogenous model input data on energy demand. These energy demand data are either measured or simulated with other tools.

Modelling assumptions: The outputs and efficiency of the DERs are assumed constant during the lifetime. The model does not consider reliability and power quality benefits. It is a deterministic model, thus the same inputs results the same output.

Complexity: The ICES model is developed to understand a real-world system. The spatial and temporal range of the model is limited due to the complexity involved in data availability as well as computational performance. The model performed well for the annual data of 77 households with hourly time resolution. The optimization techniques used in this model attempts to consider these complexities with the option of multi-objective optimization and sensitivity analysis.

Data availability and uncertainty: The ICES model rely heavily on the input data such as energy demand, techno-economics of DERs, prices and charges as well as the weather data. In order to apply the ICESs model, defining the boundaries of the local communities can be complicated. It might be difficult to acquire the detailed energy statistics for the local communities. As more sectors are integrated into the model, the demand for the data rises further.

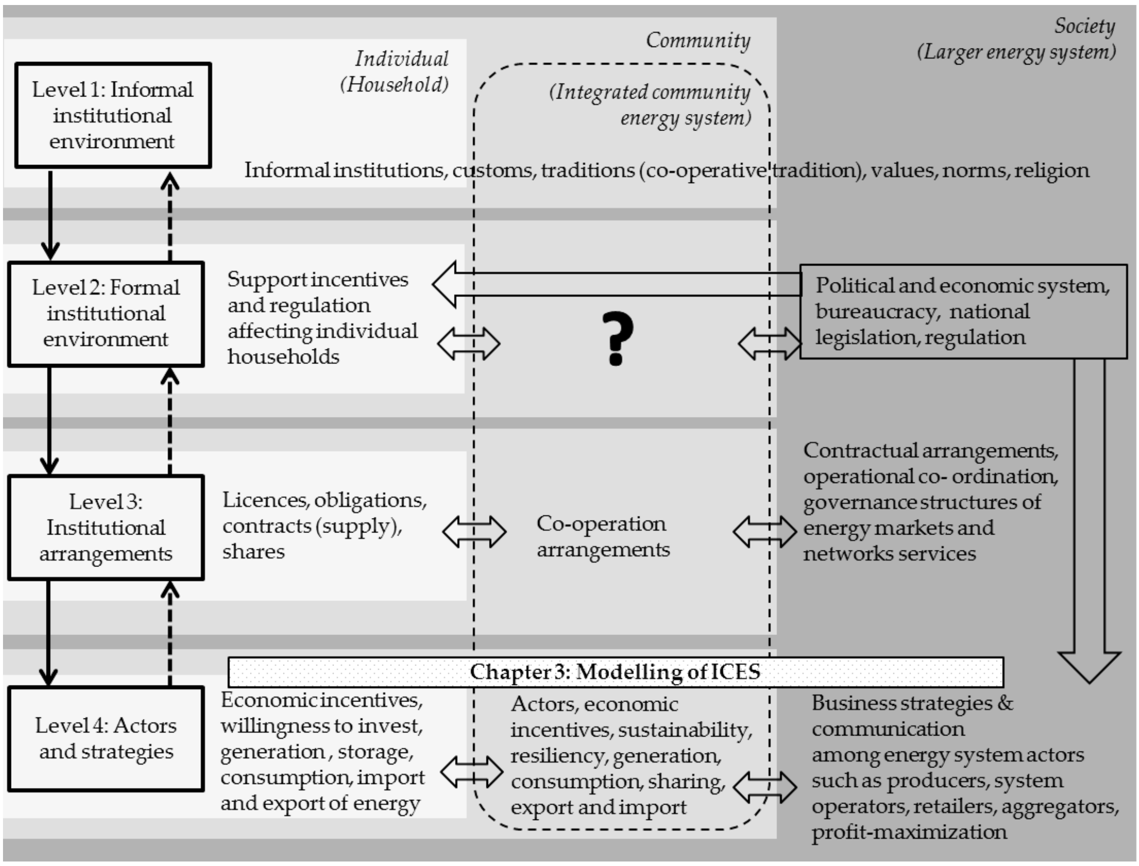
Model integration: The ICES model makes use of different models results as input. For example, the energy demand can be simulated and the weather data are obtained from external models. Further improvements are possible in improving the compatibility of these models with each other. The ICES model also attempts integrated assessment of household and community level energy system with integration of multiple sectors such as electricity, transport and heat. Further improvements are possible in the integrated operation of wider transport, heat and electricity sector.

3.5 Synthesis

The research sub-question addressed in this chapter was: *How can we assess the added value of ICESs to the individuals, local communities as well as to the larger energy system?* This chapter answers this research question by developing the model for the assessment of ICESs. The ICES model determines optimal planning and operation of ICESs for different investment and grid-connection scenarios. It also quantifies the added value of ICESs to the local communities based on economic and environmental performance indicators.

Figure 3.6 positions Chapter 3 in the conceptual framework. The modelling of ICESs cannot be done in isolation. The interaction and dynamics of the individual households, local communities and society in the form of larger energy system should be adequately considered. Households invest in household and community level technologies and strategically exchange energy with ICESs. System of prices and charges as well as technology cost developments impacts the level of investment in ICESs technologies. ICESs has been modelled as the bridge between individual households and the larger energy system. Although such interactions are directly possible in the liberalized energy markets, ICESs can further facilitate it.

Figure 3.6. Positioning Chapter 3 in the conceptual framework



Chapter 4
ICES Value Assessment

"We have things of value but we can never find them because we don't even know how to look."

- *Ally Condie*

This chapter is based on the work described in Koirala et al (2016)[4] [70]. This chapter assesses and evaluates the value of grid-integrated and grid-defected ICESs to the local communities in the context of the Netherlands. It also assesses the impact of ICESs on individual households and its potential value to the larger energy system.

4.1 Background

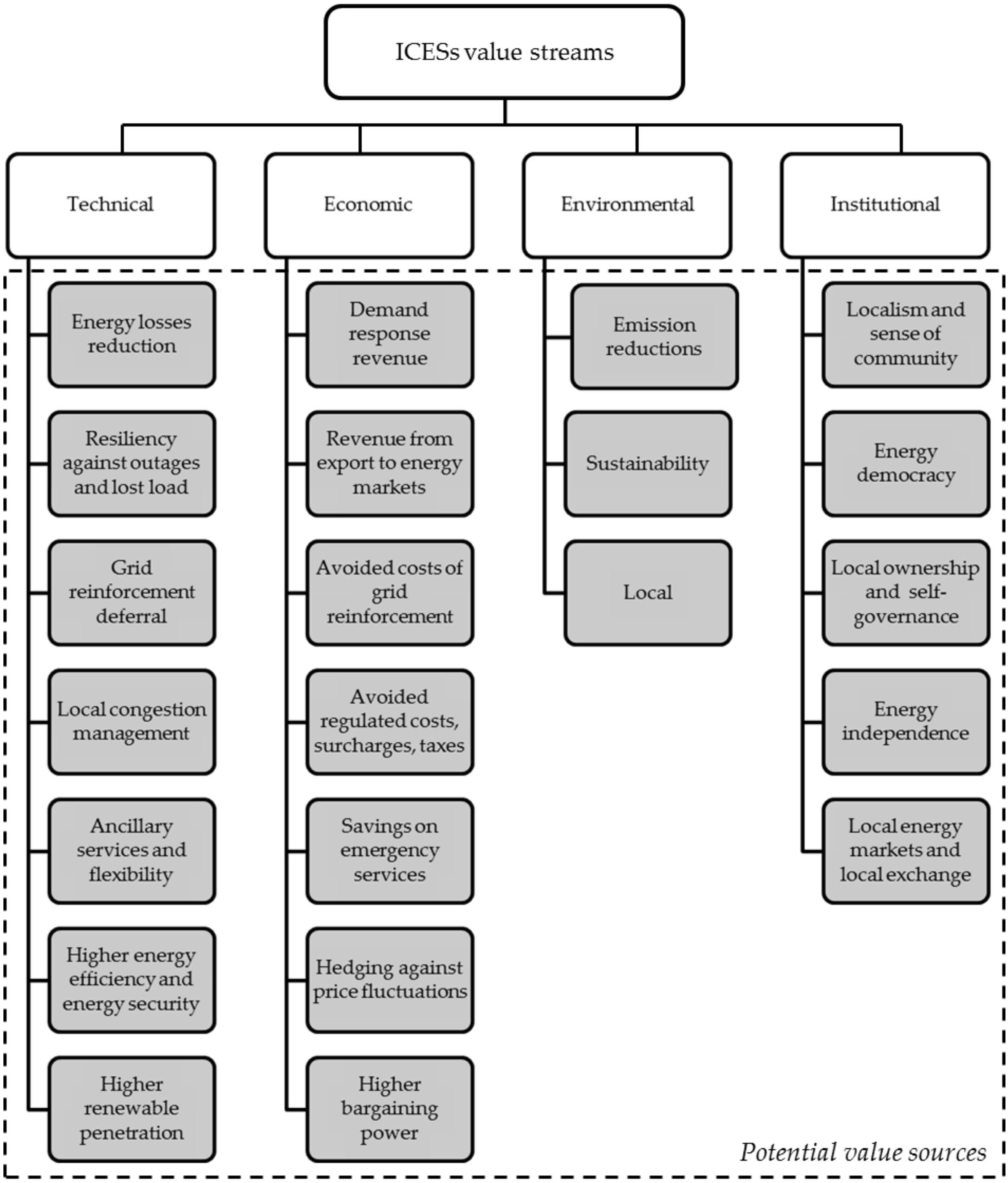
The local energy initiatives are rapidly emerging due to community objectives, such as cost and emission reductions as well as resiliency. However, assessment and evaluation are still lacking on the value that these systems can provide both to the local communities as well as to the whole energy system. A quantitative assessment with empirical data from several demonstration projects will help to determine the value of local energy initiatives such as ICESs. Such assessment is expected to increase the understanding of the impact of ICES to the different actors as well as to the larger energy system. The ICES model introduced in Chapter 3 is used to assess the value of an ICES in the Netherlands. With the aid of two case studies, the value of ICESs to the individual households and the larger energy system is also determined.

4.2 Value streams for ICESs

ICESs enable a range of technical, economic, environmental and institutional values to the households, local communities and society at large. ICESs may facilitate additional economic value streams which can compensate the increased cost and improve the economic feasibility of the ICESs implementation [96]. Figure 4.1 summarizes the key value streams identified in this research and their sources. In this research, the focus is on ranges of economic and environmental values of ICESs on the local communities. The value of ICESs to the individual households in assessed in terms of costs and emissions reductions as well as energy autonomy. In the case of the ICESs values to the larger energy system, the value of flexibility provision from ICESs is considered.

[4] Koirala B, Chaves Ávila J, Gómez T, Hakvoort R, Herder P. Local Alternative for Energy Supply: Performance Assessment of Integrated Community Energy Systems. Energies 2016;9:981. doi:10.3390/en9120981.

Figure 4.1. Value streams of ICESs and their potential sources



4.3 Case I: ICESs in the Netherlands

To assess the value of ICESs to the local communities, a 20 household energy community in the Netherlands is analysed as ICESs. The annual electricity, hot-water, space heating and cooling demand are 71.2 MWh, 167.4 MWh, 67.7 MWh and 0 MWh, respectively. The total annualized energy cost is 33,459 € and total annual CO_2 emission is 84.5 tons. The individual hourly metered data for both electricity and gas are obtained from the Liander open data platform [131]. The demand profile varies depending on household types, occupants and their behaviour. The hourly solar irradiance, wind speed and temperature data are obtained from [132].

The Dutch electricity and gas prices and charges for 2015 are used as the starting point and are presented in Table 4.1 [133]. The Netherlands uses a mix of volumetric and fixed charges for the electricity and gas supply services. The network tariffs and suppliers' margins are a fixed cost per month per household; wholesale energy prices are passed-through and sustainable energy surcharges (SDE) as well as regulated energy taxes are volumetric (€/MWh). Although, the Netherlands has a net metering policy (*saldering*) in place for annual energy balance, we do not consider it in this study as it is not favorable for ICESs. According to the *Postcoderoos* regulation to promote DER penetration and local balancing, renewable electricity could be generated and sold to consumers in the same postcode area. Participants get discount in energy tax which is financed by increasing the energy prices to the rest of the consumers. This regulation allows implementation of ICESs. Furthermore, for household electricity consumers, annual tax reduction is applied. ICESs as entities with higher consumption are subjected to lower tax regimes as presented in Table 4.1 . Therefore, it is assumed that ICESs consumers do not benefit from annual tax reduction.

Table 4.1. Dutch system of prices and charges for electricity and gas in 2015.

Components	Electricity	Gas
Electricity procurement and supply costs		
Wholesale energy price	Amsterdam power exchange (APX)	Title transfer facility (TTF)
Suppliers margin	3.25 €/month	3.25 €/month
Network tariffs	19.22 €/month	12.34 €/month
State-introduced price components		
Sustainable energy surcharges (SDE)		
0–10,000 kWh	0.0036 €/kWh	0.0074 €/m^3
10,000–50,000 kWh	0.0046 €/kWh	(up to 170,000 m^3)
50,000–10 million kWh	0.0012 €/kWh	-
Regulated energy tax		
0–10,000 kWh	0.1196 €/kWh	0.1911 €/m^3
10,000–50,000 kWh	0.0469 €/kWh	(up to 170,000 m^3)
50,000–10 million kWh	0.0125 €/kWh	-
Tax reduction	312 €/year/house	-
Value added tax (VAT)	21%	21%

The ICES model can invest in household and community level DERs. The techno-economic data for the household and community level DERs as presented in Table 4.2 are provided as input to the model. The techno-economic parameters of the considered DERs are predefined. The economic parameters considered for each technology are capital cost, operation and maintenance costs and lifetime. In addition, fixed costs of 2000 € and 10,000 € per storage unit is assumed for household and community storage units respectively, for the cost associated with the battery management systems and bi-directional inverters. The fixed costs for charging infrastructure for electric vehicles is assumed to be 1071 € per vehicle [134]. Similarly, the fixed costs for absolute chillers, ground source HP and heat storage is assumed to be 1000 €, 2286 € and 1000 € respectively. The economies of scale effect are evident in the case of community investment. The cost of capital is assumed 5% and the maximum payback period for the investment is limited to 10 years. The CO_2 emissions from natural gas is 0.18 kg CO_2/kWh. The emissions per kWh of electricity consumed are based on the national average, for example, for the Dutch grid, it is 0.44 kg CO_2/kWh [135]. The CO_2 tax is assumed to be 8 €/ton.

Table 4.2. Techno-economic data for household and community level DERs.

Level	DERs	Capital Cost (€/kW(h))	Operation and Maintenance Costs (€/kW(h)/Year)	Life-Time (Year)	Reference
Household	Solar PV	1280	6	30	[136]
	Electric Storage	300	1.3	10	[137,138]
	Heat Storage	100	0	17	[139]
	Absolute chillers	525	22.6	20	[139]
	ASHP	558	6	30	[140]
	Ground-source HP	1076	27.6	30	[140]
	Solar thermal	500	5	20	[139]
	Electric vehicles	130	1.3	10	[134,141]
	Micro-CHP	8000 (1 kW) – 4000 (3 kW)	0.021/kWh	20	[142]
Community	Community PV	1000	5	30	[136]
	Community Storage	250	1.2	10	[137,138]

4.3.1 Grid-integrated ICESs

In this case, the households within ICESs perform similarly to the case of individual DER investment but also contribute towards the local energy exchange. Hence, the prosumer households can optimize their self-consumption and feed electricity into the community pool based on techno-economic and environmental criteria. The economic benefits include, among others, avoided energy purchase costs and revenues from selling energy surplus at the community level. The community can also collectively decide to invest in community DERs, such as community PV and storage. In the latter case, further cost savings are expected in capital costs as well as in operation and maintenance costs of DERs. Based on this distinction, we identify two cases of ICES, namely an ICES with individual investment and ICESs with individual and community investment.

The results based on objectives to reduce total energy costs are presented in Table 4.3 for the baseline, the individual DER investment, the ICES with individual investment and the ICES with individual plus community investment cases. For the grid supply and the individual DER investment cases each household has its connection point to the grid. In the remaining ICES cases with the individual DER investment as well as the individual and community DER investment common point of coupling is assumed. ICES implementation leads to further savings in terms of total energy costs as well as CO_2 emissions due to local energy exchange, community engagement through load shifting, and lower tax regimes for larger consumers and economies of scale. Although the major energy cost saving comes from the technological change from natural gas-based heating systems to HPs and self-consumption, savings in policy costs and taxes are also significant. As the Dutch system of prices and charges uses fixed costs for network costs and suppliers' margins, no savings are possible in these categories through the implementation of a grid-integrated ICES. The DER costs are a major cost component in a grid-integrated ICES.

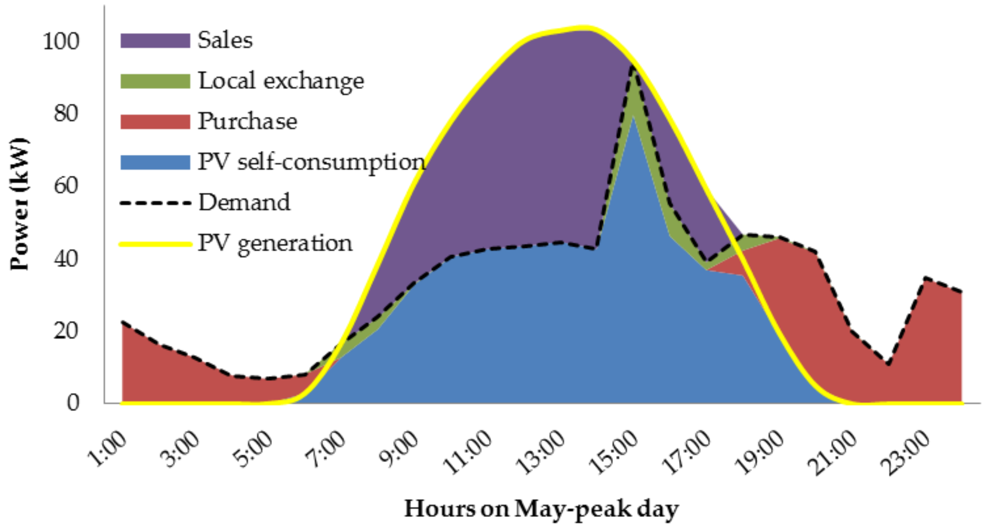
Table 4.3. Annualized costs and emissions of Grid-integrated ICESs.

Cases	**Annualized Total Energy Costs (€)**	**Annual CO_2 Emissions (tons)**
Grid supply (baseline)	33,459	84.5
Individual DER investment	28,615	43.9
Individual DER investment (ICES)	26,872	32.9
Individual plus Community DER investment (ICES)	23,951	32.9

Figure 4.2 illustrates the hourly energy balance at the ICES with the individual investment case. PV generation refers to aggregated profiles of 20 households whereas PV self-consumption represents aggregated self-consumption of PV generation at each household. The surplus from each household is first pooled to manage the local deficit. As PV is the only generation and each household has solar PV installed, the local exchange on this representative day has a small share (37 kWh) but it is expected to

increase with the diversification of DERs. Ultimately, the remaining surplus is traded to the energy market directly or through intermediaries.

Figure 4.2. Energy balance for May-peak day for the grid-integrated ICES.

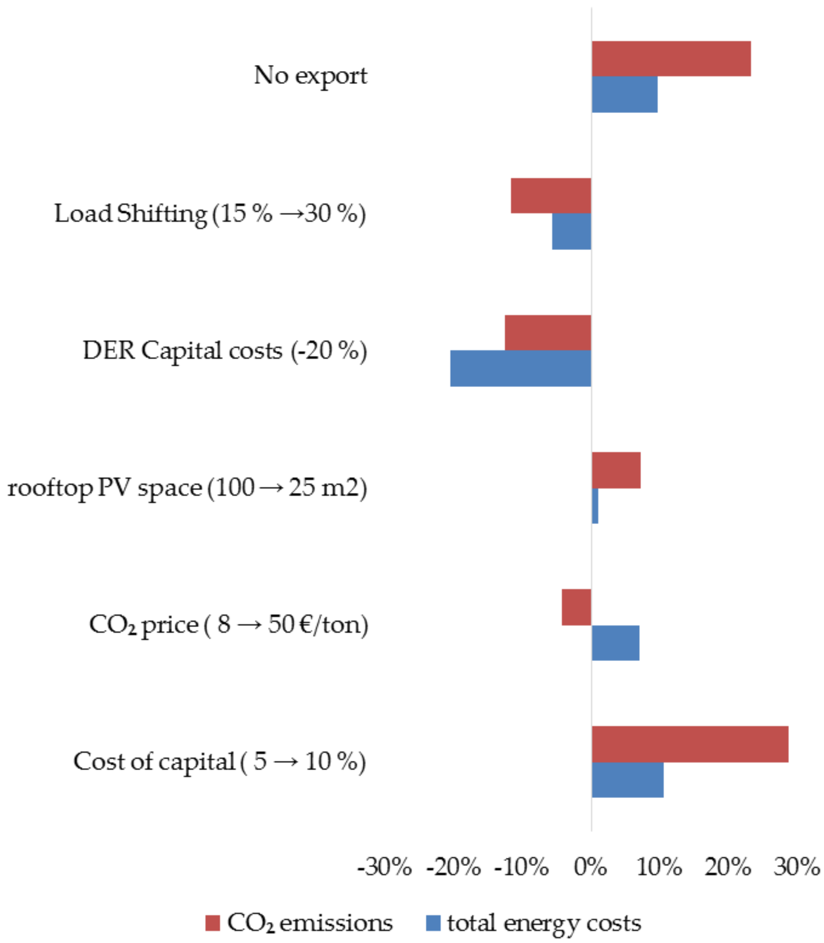


Sensitivity analysis

The present energy landscape is changing [29,47,143]. The customers are expected to be more flexible in the future [91,144,145]. The capital costs of DERs, especially solar PV and electric storage are falling more rapidly [47,136]. The CO_2 prices are expected to increase [146]. Moreover, in urban areas, limited space is available for the DERs installation. To address the changing energy landscape, a sensitivity analysis on some of the parameters assumed in this research is performed. For illustration, a grid-integrated ICES with individual DER investments case is further analysed. Figure 4.3 shows the result of a sensitivity analysis in terms of percentage deviations in annualized energy costs and CO_2 emissions.

The total energy costs and CO_2 emissions are found to be more sensitive to the input parameters which directly impact the optimal size of the DERs installed in the ICES, such as DERs capital costs, the cost of capital and possibility to sell excess energy. The diversity of demand, as well as generation profiles among the households within the ICES, leads to the increased local exchanges reducing energy losses in comparison to importing energy from the system.

Figure 4.3. sensitivity of input parameters on energy costs and CO_2 emissions



The decrease in capital costs has more impact than performing the load shifting, as the former reduces both the import and increases the export of energy whereas the latter only reduces the energy cost by less import during peak hours and more local energy exchange. Moreover, among the considered parameters in this analysis, the performance metrics are more sensitive to input parameters such as DER capital costs, the cost of capital and export options as these parameters can directly impact the amount of DERs invested in the ICES.

4.3.2. Grid-defected ICESs

In the case of grid defection, all the community energy demand has to be met locally. Therefore, more and diverse technologies are invested in the grid-defected ICES compared to the grid-integrated ICES case. In the grid-integrated case the DERs invested are community PV (168 kW) and air-source HPs (0.24–1.1 kWe) whereas in the case of the grid defection, the DERs invested are community PV (1274 kW), household and community storage (1660 kWh), air-source HPs (0.4–1.5 kWe) as well as electric vehicles (16–38 kWh). The electric vehicles are used in this case as an alternative form of energy storage and the driving behaviour is not considered.

Table 4.4 presents total energy costs and CO_2 emissions for the grid-integrated and the grid-defected ICES case with individual plus community DER investment. Under current DER economics, the grid-defected case is 8.3 times more expensive than the grid-integrated case. This is very dependent on storage of 1660 kWh, so if cost of storage falls the economics of grid-defected ICESs improve further. Moreover, further CO_2 emission reduction of 58% is achieved in the grid-defected case compared to the grid connected case.

Table 4.4. Energy costs and CO_2 emissions for grid-integrated and grid-defected ICES cases

Case	Annualized Total Energy Costs (€)	Annual CO_2 Emissions (tons)
Grid-integrated	23,951	32.9
Grid defected	198,762	14

The grid-defected ICES implies an oversized and rather expensive local energy system with long periods of unused energy from renewable sources to be curtailed. For example, in this particular case, 400298 kWh of unused electricity has to be curtailed annually which is 6.6 times higher than the annual electricity demand for the whole community. However, this situation can change with a more diverse and flexible technology-mix. Inefficient and opportunistic grid-defection should be avoided through regulation such as *exit-charge*. Such charge should cover avoided regulated costs, taxes, network costs and other surcharges.

Grid-defected ICESs are not yet economically rational. The grid defection might still make economic sense if there is a network connection or reinforcement costs and lower investment costs for the energy storage. For grid-defected ICESs to be economically feasible, they might have to be connected back to the grid so that the unused or curtailed energy can be marketed to the neighbouring communities and the energy markets or used to provide system services for the whole energy system [47]. In this case, the system will be self-sufficient on the demand side but will still depend on the network to transfer the surplus energy. The energy community in Feldheim, Germany is a prime example of this case. The Feldheim energy community is self-sufficient in terms of demand and only consumes 1% of total generated energy, selling 99% of the energy to other market parties [147]. The community also provides ancillary services to a transmission system operator.

4.4 Case II: Impact of ICESs on the individual households

This case study is based on the research presented in van de Hil (2015) [97]. To study the impact of the ICESs on the individual households, an energy community consisting of 8 households is considered. A bottom-up modelling approach consisting different demand profiles and local generation technologies at the household level is used. The four household-types considered are one adult, two adult, family and pensioner household. First, the model is capable of selecting optimal technology mix for each household based on objectives to reduce energy cost, reduce CO_2 emissions or increase energy autonomy. Then, the modelled households with their optimal technology-mix are connected together to form an ICESs. The performance of households and ICESs are measured based on three indicators: energy price, CO_2 emissions and energy autonomy.

ICESs enable energy sharing among the households. ICESs lower energy costs, increase the energy autonomy at the ICES level and reduce the carbon foot-print of the individual households, figure 4.4 – 4.6. In addition, ICESs increase the collective bargaining power of individual households on technologies and service contracts. Households can participate in the energy market through ICESs.

Figure 4.4. Impact of ICESs on total energy costs of individual households

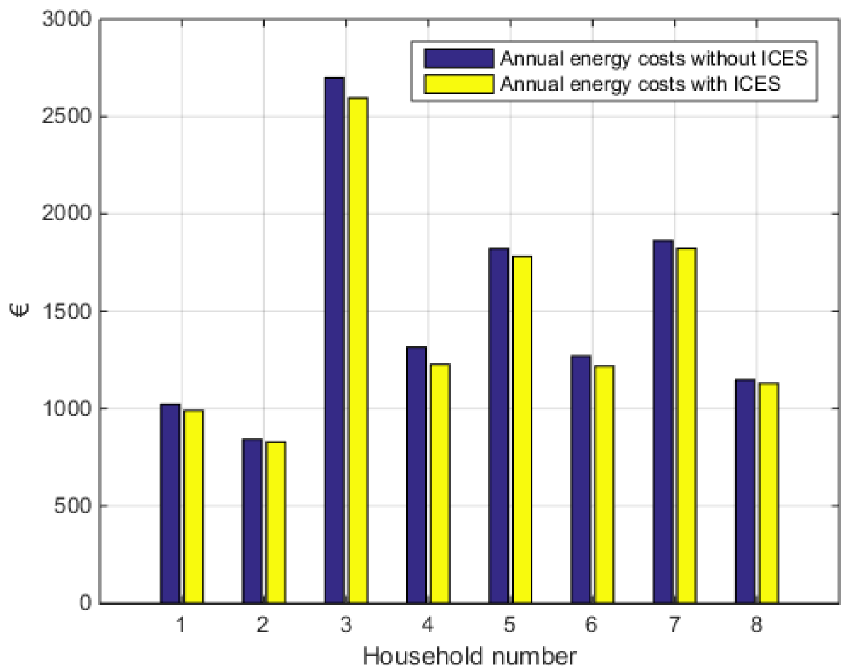


Figure 4.5. Impact of ICESs on CO_2 emissions of individual households

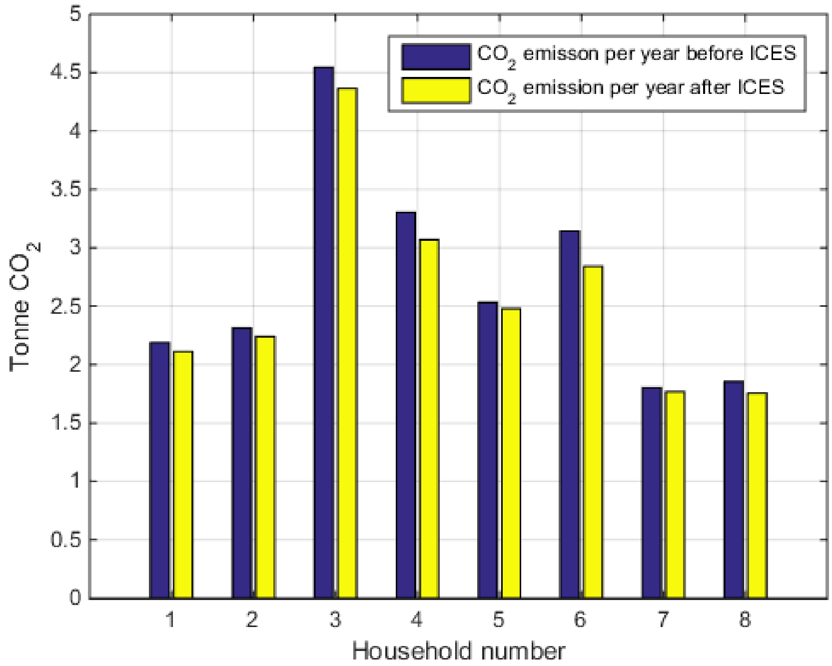
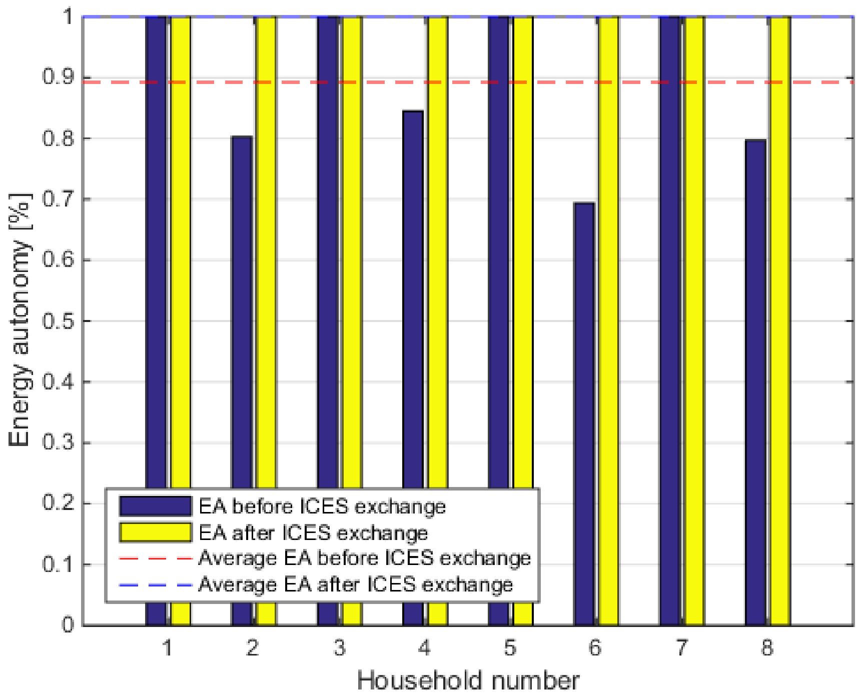


Figure 4.6. Impact of ICESs on energy autonomy of individual households



4.5 Case III: Flexibility from residential prosumers

A pilot project to determine flexibility from residential prosumption was conducted in 203 households of Heerhugowaard, the Netherlands [150]. This project was implemented jointly by companies, consumers and the government and offers an example that different energy system actors can work together for a sustainable and decentralized energy future. The technologies implemented and actors involved in this project are summarized in table 4.5.

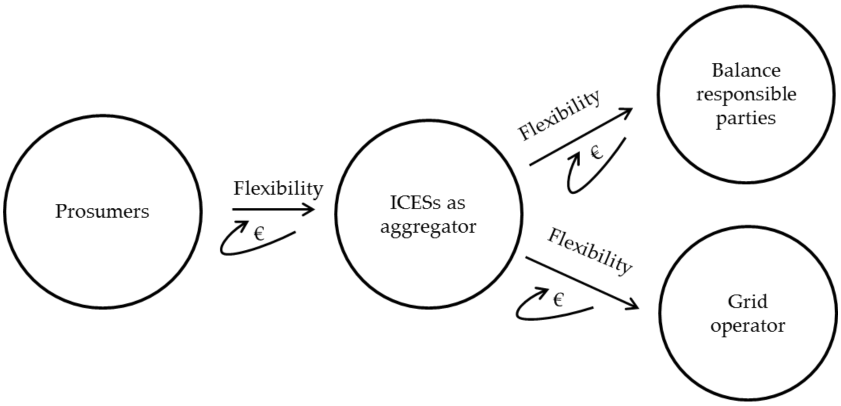
Table 4.5: Technologies and actors of smart energy collective, Heerhugowaard

Technologies	**Actors**
183 roof-top solar PV 95 PV-switch 49 heat pumps 45 electric boiler 14 fuel cells	203 households System operator (Alliander) Energy supplier (Essent) Technology providers (IBM, ICT Group) Municipality of Heerhugowaard Dutch Ministry of Economic affairs (Innovation programme intelligent grids)

The pilot project was conducted for a year between August 2015 to July 2016. During this period, the supply and demand of flexibility were balanced for the group of 203 households for 20 % of the time, 1752 hours. This has been achieved through trading in average 0.92 kWh of flexibility per day per household. In terms of operation, the boilers were automatically switched-on for 613 hours, the heat-pumps were automatically switched-off for 701 hours, the solar panels were automatically switched-off for 350 hours and the fuel cells were automatically controlled for 3066 hours, annually.

As illustrated in Figure 4.7, this project demonstrated that the flexibility from local prosumers can be collected by a local aggregator such as ICESs and offered to a distribution system operator or the balance responsible party through a separate market for flexibility. In this way, the flexibility from local prosumers can provide value to different actors in the energy system. Through the aggregation of individual households, ICESs can have new roles of ‘flexibility provider’ in the future energy system. In addition, ICESs can curtail both demand and supply peaks and defer the need for grid reinforcement.

Figure 4.7. ICESs unlocking decentralized flexibility from local communities



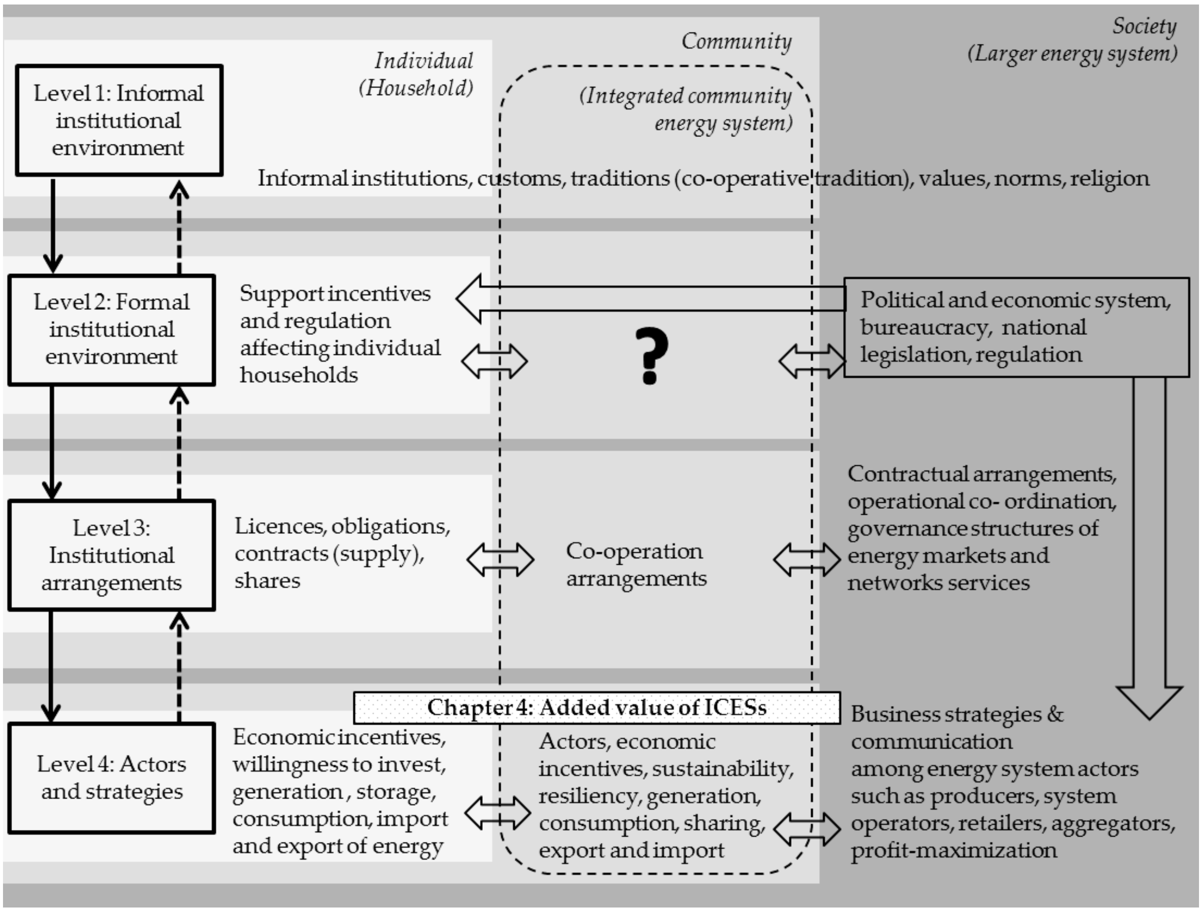
4.6 Synthesis

The sub-research question addressed in this chapter was: *How can we assess the added value of ICESs to the individuals, local communities as well as to the larger energy system?* The analysis in this chapter has demonstrated the added value of ICESs to the individual households, to the local communities as well as to the larger energy systems. In ICESs, optimal planning and operation of DERs as well as energy sharing among the member households is possible, thereby reducing energy costs, CO_2 emissions and increasing the energy autonomy. ICESs offers strategic choices for households and communities to transform their energy system and become active prosumers and play more active role in the energy system. These choices could be potentially interesting in the context of 'van gas los' discussions in the Netherlands. Local communities do not always have to rely on the government to transform their energy system. The local communities could build or lease heat and electricity network and exploit different locally available distributed energy resources and storage options based on techno-economic, temporal and spatial conditions. In contrast to the local initiatives, government initiatives often involve larger time frames. Households and communities can perform self-consumption and local energy balance strategically. ICESs contribute towards sustainability and energy security locally. The larger energy system benefits from the aggregation of the households as ICESs. The surplus energy can be procured to provide flexibility as well as other system services.

Under current energy prices and charges, it is more likely to have grid-integrated communities than grid-defected communities. Moreover, the benefits of the grid-integrated ICES are highly subjected to the system of prices and charges as well as institutional settings available for their operation. With decreasing costs of DERs, increasing electricity tariffs and the technical viability of the grid defection, ICESs will have a progressively important role in the future as they keep the grid intact or enable off-grid options when desired. Higher reliability and permanent local energy balance needs lead to a more diverse but over-sized grid-defected ICESs with a very high unused energy to be curtailed. A detailed assessment on a grid defection alternative should be performed for cases requiring a significant network connection or re-enforcement costs.

Figure 4.7 positions this chapter with respect to the conceptual framework introduced in Chapter 1. The added-value of ICESs cannot be determined in isolation and its interaction with individual households, local communities and the society should be adequately considered. With the aid of this framework, it is demonstrated that ICESs has added value not only to the local communities but also to the individual households and the larger energy system. ICESs as a bridge between the local households and the larger energy system could have important role in realizing these added-values. ICESs can meet the expectations of individual households on the energy system they wish for and also offer possibilities for the transition of the centralized energy system through energy service provisions.

Figure 4.7. Positioning Chapter 4 in the conceptual framework



Chapter 5
Institutional Design

"Change is inevitable, but transformation is by conscious choice"

– Heather Ash Amara

This chapter is based on the work published in Koirala & Hakvoort (2017)[5]. This chapter first identifies necessary institutional precursors for ICESs. Then, institutional design recommendations for the emergence of ICESs are provided based on the techno-economic and institutional perspectives.

5.1 Background

In the previous chapters, the added value of ICESs to the households, local communities and larger energy system is demonstrated. The value of ICESs, however, is not only impacted by the local consumption patterns and weather conditions as discussed in chapter 3 of this thesis but also by the institutional settings both internal and external to the system. Although the technologies to realize ICESs are wide-spread, the institutions to govern these energy systems are still lagging behind. The current centralized institutional arrangement does not always provide enough incentives for ICESs as the latter were not foreseen during the development of these institutions.

The term institutional design has a different meaning in different disciplines. For example, in the field of law, it only deals with regulations and established institutions. In the context of this thesis, institutional design is defined as deliberate attempt to change set of rules that structure interactions and dynamics of the emergence of ICESs within the present energy system [83]. A wider definition of institutional design is adopted so as to cover market design, self-governance as well as contracts and partnerships aspects.

In the context of ICESs, new institutions should be established and existing institutions should be (re-)designed or adapted, to enforce the necessary roles, responsibilities, control and intervention. New institutional arrangements are needed to co-ordinate

[5] Koirala, B. P.; Hakvoort, R. A. Integrated community-based energy systems: Aligning technology, incentives and regulations, *Innovation & disruption at the Grid's Edge*, edited by Fereidoon Sioshansi, Academic Press, 2017

and shape ICESs activities, thereby leading to further innovation [83]. Several local solutions should be examined. For example, new models of partnerships between the energy distribution networks, utilities, private developers, and communities might be needed. In addition, performance expectations such as sustainability, flexibility, and cost minimization also play an important role in shaping technologies and institutions in ICESs.

5.2 Institutional precursors for ICESs

5.2.1 Regulation

Current energy laws and policies around the world are developed for the centralized energy systems. Accordingly, there are legal barriers to the implementation of local, decentralised and bottom-up energy systems such as ICESs. One of the most prominent ones is the EU energy market legislation, the third energy package [151]. According to this package, generation, distribution, and retail should be unbundled. With the engagement of citizens and community, ICESs are likely to control the local energy system and take over several roles as a single entity, demanding re-bundling [152].

Moreover, current energy regulations do not provide the equal level playing field for ICESs. For example, in Germany, after 2014 amendment to the renewable energy law (EEG), small and medium-sized producers have to compete with large producers [153]. In the Netherlands, there are similar obligations to both small and large producers in terms of the license of supply [60]. The recent self-consumption regulation in Spain discourages self-generation as well as aggregation such as ICESs [154]. Moreover, administrative hurdles for renewable energy installation, legislative uncertainty, dis-incentive for self-consumption and production as well as ineffective unbundling of integrated energy companies inhibit ICESs implementation in Spain. Similarly, in Portugal, the *Decreto Lei n. 153/2014,* a net-metering law despite allowing self-consumption and trading with 10% contribution going to network maintenance, still does not encourage local energy exchange.

The EU 2016 winter package attempts to address some of these issues. For example, the proposal foresees active and central role of consumers in the energy system with the possibility to produce and sell own electricity [85]. Furthermore, local energy communities are entitled to own, establish, or lease and manage community energy network. The energy communities such as ICESs can access all the energy markets directly or through aggregators. Moreover, they can take a different role of consumers, generators, distribution system operators or aggregators, simultaneously.

For the emergence of ICESs, space for innovation, often introduced by new actors is a necessary precondition. As ICESs might take different forms based on local conditions, the legislation should keep open space and options for the development of local models. There should be freedom to organize ICESs to the local requirements. Experiments should be encouraged so that the effects of the different models can be assessed. Laws and regulations should create space for the actors to experiment with different organizational models to determine their viability to specific local conditions. Legal frameworks should promote a wide range of models for community ownership, participation and investment in ICESs. By analysing the implications of these models in the short and long term, it will become clearer how the ICES can emerge and in what areas further legislation is possible or desirable.

Example: Spanish self-consumption regulation
This case study is based on the work published in Koirala et al (2016)[6] [102].

In October 2015, Spain introduced a new regulation on self-consumption, royal decree 900/2015) [154]. The main aim of this regulation is to ensure the same contribution from consumers with onsite generation to system costs as the consumers without DERs. For this purpose, a new charge called self-generated energy charge is introduced in order to recover regulated costs and system costs that otherwise would be avoided and is recovered through volumetric charges. In addition, onsite generation cannot reduce the established contracted capacity charges and associated costs. It also prevents local exchanges among households.

To illustrate the effect of this regulation on the economics of ICESs, a block of 10 Spanish households with solar PV plus battery storage system is considered. The hourly demand profiles for electricity for the 8 households (H1-H8), ranging from 3149 to 7961 kWh, are generated using the load profile generator tool considering household types, occupants behaviour and geographical location [155]. The demand profiles of the remaining two households (H9-H10), with the annual electricity demand of 4510 and 3639 kWh, are obtained from the smart-meter data from Guadalajara city near Madrid, Spain [156]. These profiles are processed to represent the three typical demand profiles, week, peak and weekend, for each month for each household.

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[6] Koirala, B. P.; Chaves-Ávila, J. P.; Hakvoort, R. A.; Gomez, T. Assessment of integrated community energy systems. *International Conference on European Energy Markets.* 2016, Porto, Portugal.

The hourly solar irradiance and temperature data are obtained from [132] for the Madrid area. The hourly wholesale and retail electricity prices Spanish data for the year 2015 are obtained from [157]. The retail electricity prices include wholesale price and the regulated costs such as surcharges and taxes. A contracted capacity charge mainly covers the network costs.

A further distinction is made between the cases: baseline case with grid supply, Case I, ideal conditions from the local communities' perspective, which is closer to situations in countries like Germany where no self-generation charge is applied and contracted capacity costs can be reduced with ICESs, and Case II, the Spanish case following current self-consumption regulation. In case I, there is no regulatory barriers and ICES can import and export from the national grid without any restriction. For the latter case, we assume that interconnection of household in the form of ICES is allowed according to Royal Decree 56/2016, assuming all other regulation as per Royal Decree 900/2015 including self-generated energy charges [154,158]. In this analysis, it is assumed that in the baseline case with grid supply and Case II, each household is connected to the grid. In Case I, the ICES is connected to the grid through a common point of coupling.

For case I, the ICES model introduced in chapter 3 invests in 4 kW PV in each household constrained by rooftop area of 25 m^2. Regarding storage, 1 kWh is invested in household H4 and H10, 2 kWh in household H5 and H9, respectively. Alternatively, in case II, the solar PV investment in households reduces. Solar PV of 4 kW is installed in household H1, H2 and H4, 1.8 kW in H9. At the same time, an electric storage capacity of 1 kWh is invested in household H1, H5, H8, H9 and H10 and 2 kWh in household H7.

Figure 5.1 shows energy demand, PV generation, wholesale and retail price as well as storage operation for the July-peak day for H10. Figure 5.2 represents the hourly net local energy exchange among households, net-import and export from the ICES. The local energy exchange is limited due to PV installation in each households. A more diverse set of DERs might lead to better local energy exchange within ICESs.

Figure 5.1. Energy balance in house H9 for July-peak day

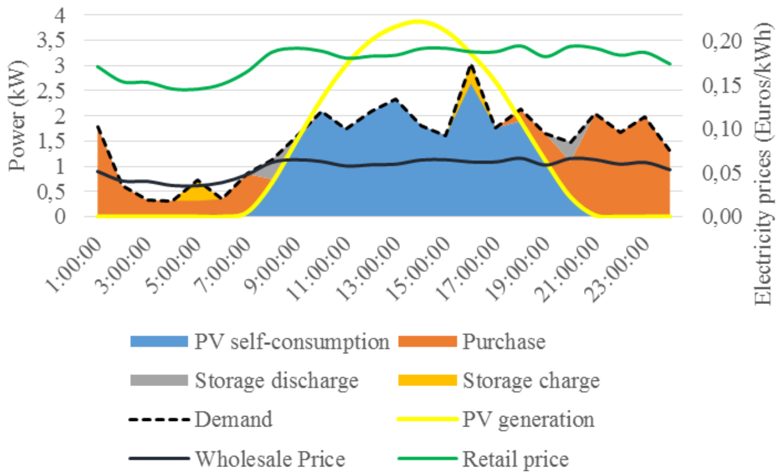
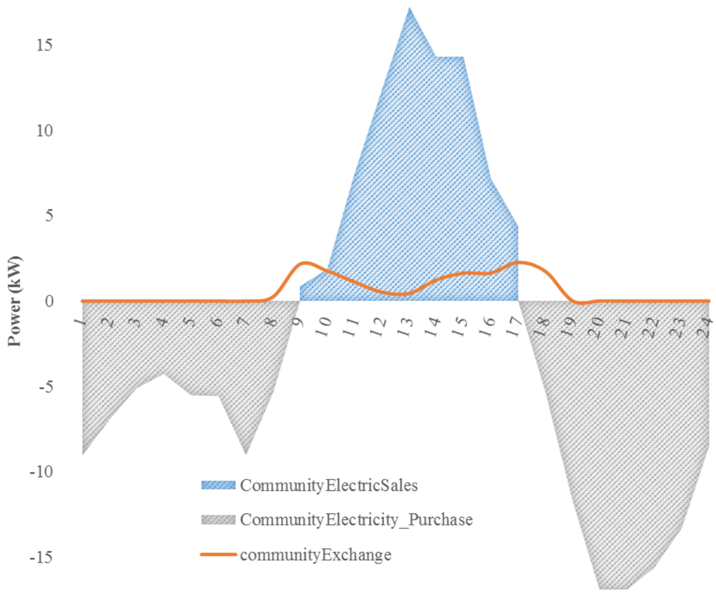


Figure 5.2. Net community exchange for July-peak day



The annualized benefits and costs of ICES are presented in Table 5.1 for the baseline case, case I and case II. Cost reduction in the case I is mainly from avoided electricity imports and thereby associated energy losses charge, network regulated cost, policy cost and taxes as well as revenue from the electricity imports. In case II, the benefit mainly comes from avoided energy prices and energy losses charges for on-site generation. Both cases are feasible under current market conditions without any additional support.

Table 5.1. Annualized costs and benefits of ICES

Total cost and revenue (in euros)	Baseline Case	Case I: Ideal conditions	Case II: Spanish self-consumption regulation
Electricity import cost	*9254.28*	*4073.00*	*5650.58*
Self-generated energy charge	*0.00*	*0.00*	*779.93*
DER investment cost	*0.00*	*3818.92*	*1426.15*
Contract capacity cost	*1231.82*	*940.02*	*1416.85*
Revenue from electricity export	*0.00*	*-2642.69*	*0.00*
Total cost	*10824.59*	*6189.25*	*9273.51*

Under both case I and case II situations, ICES is beneficial over current energy system in Spain by 43 % and 14 %, respectively. The recent self-consumption regulation in Spain makes the ICESs less profitable. The benefits of ICESs are highly subjected to the system of prices and charges as well as mix of technologies, as demonstrated in these cases.

5.2.2 Support incentives

Several countries in the world such as Germany, Denmark, The Netherlands, the UK, and the USA already have support incentives to promote community-based energy systems. Few examples of the support incentives addressing community-based energy systems are postcode regulation for local energy exchange in the Netherlands, community net-metering in New York, priority access to the grid in Germany, government grants in Germany, UK and Scotland as well as low-interest loans in Germany. In the US, several states, such as New York through reforming the energy vision (REV), California through its community-based renewable energy self-generation program (SB 843) as well as several other states are pushing all sorts of opportunities for community energy [159,160]. Similarly, Australia is also expecting high shares of community solar [161].

The implementation and success of these support incentives differ among countries which again is affected by several institutional factors. Rather than a one-size-fits-all approach, support schemes designed and tailored to local conditions might prove beneficial in long-run. As the focus is shifting to auction/tendering process to support future renewable energy development, the community participation therein should nevertheless be safeguarded. In order to speed up low-carbon transition, ICESs should also be given access to national support policies for renewable energy mainly designed for households and large investors such as feed-in tariffs, tax-incentives, grants, low-interest loans, grid access, guaranteed power purchase and virtual net metering [128].

5.2.3 Grid access and local balancing

There can be resistance from the incumbent grid-operator to transfer the ownership, sell or lease the energy network to the community as seen in Feldheim and Schönau in Germany [147,162]. Feldheim had to build a parallel grid and Schönau had to buy back the local grid to realize the local energy system. As private utilities are often biased towards incumbent energy suppliers, increasing number of formally privatized distribution grids in Germany, including Hamburg, are re-municipalized and further 20% are planning such a step [122, 123].

Moreover, local energy exchange among ICESs members should be enabled and incentivized. The local energy exchange might not always be straightforward. It might involve changing the point of delivery of energy, building a physical interconnection between households across the street or utilizing higher level network infrastructure. In each case, the rules for access to technologies and networks should be well-defined to prevent the opportunistic behaviour.

Incentives to follow load or to integrate renewables might improve local balancing and reduce stress on the grid during hours of peak generation. Moreover, although *time–based energy balance* of the local generation through net-metering has proven beneficial for the Dutch households as well as the higher penetration of DERs, it might be counter-productive for the operation of ICESs. *Location-based netting* promotes co-operation among households through local exchange and might be beneficial for the emergence of ICESs. Moreover, ICESs should be provided with right incentives to collaborate with system operator on storage, energy management and grid issues.

5.2.4 Intermediary organizations for facilitation

Support and mentoring of these local energy initiatives through dedicated intermediary organizations have been proven successful in the UK and Scotland [165,166]. At the European level, the European Federation of Renewable Energy Co-operatives (RESCOOP) is playing this role through networking and knowledge exchange among European renewable energy co-operatives [167]. Similarly, establishing knowledge-exchange platform could also be beneficial for these initiatives as they can learn from each other. One such example is Hydro Empowerment Network which is knowledge exchange platform for community micro-hydro in South and South East Asia [168].

5.3 Institutional design recommendations

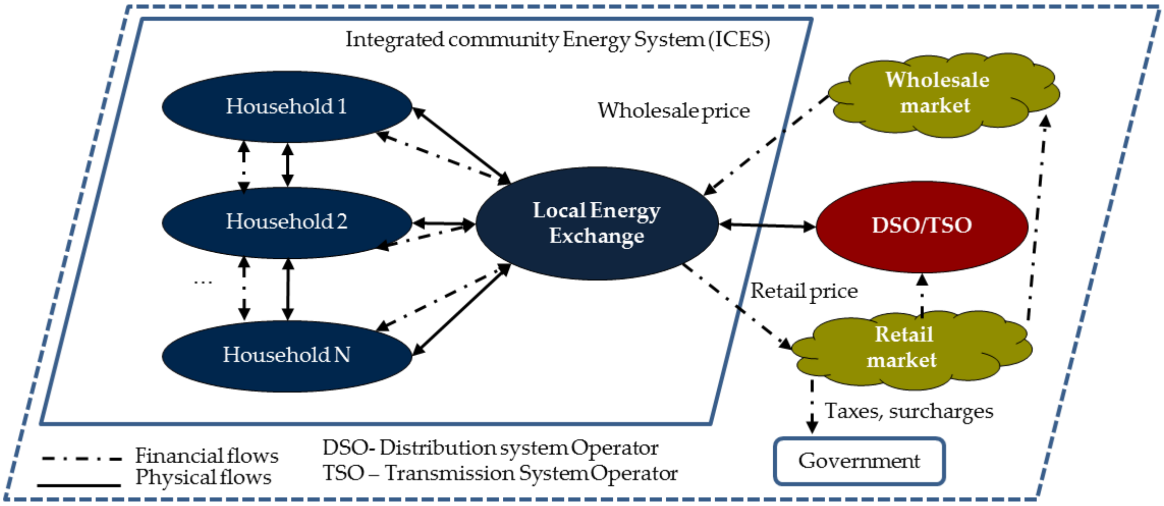
New energy systems such as ICESs have many technical and operational challenges, as discussed in chapter 2 of this thesis, which is often solved by technical and market design. The technical design ensures commodity flow through reliable and robust system whereas market design ensures monetary flow through the efficient allocation of goods and services according to the community needs [71]. These two basic design approaches, although complementary, may sometimes be at odds. An additional comprehensive design, called institutional design, is necessary which combines the techno-economic and institutional perspectives in the design of institutions for ICESs. However, due to the involvement of multiple stakeholders and technologies, the institutional design of ICES is complex. For example, collective decisions have to be made to meet the individual needs. Different institutional arrangements for physical and financial administration are necessary for well-functioning of these systems. Below different institutional design recommendations for the implementation of ICESs are provided.

5.3.1 Design and co-ordination of local exchange

Local energy exchange is one of the most important attributes of ICES. Figure 5.3 illustrates the architecture for such local energy exchange. Households can exchange energy locally through local buying and selling prices. The local energy price should reflect all the capital costs, operation costs as well as local network costs. Suitable institutional arrangements should be designed to prevent local energy exchange from being a monopolist. The commodities and suppliers should be well defined, ensuring efficiency, fair allocation of costs and benefits, right prices for participation and preventing the opportunistic behaviour.

The grid connection to the larger energy system(s) can also have a strategic exchange with different energy markets or neighbouring communities. For example, the excess energy can be sold to the wholesale market at wholesale prices. It can also be used to provide flexibility to the system operators or balance responsible parties. The supply to cover residual demand can be purchased at retail prices. In the case of autonomous ICES, total demand should be met locally.

Figure 5.3. Local energy exchange in ICES



There is no single best organizational model applicable for the local energy exchange in ICESs but it should be based on the available resources, types of participants as well as their needs and expertise. The technical and operational complexity of ICESs might require the involvement of the service provider. The service provider could be energy service companies (ESCOs), distribution system operators (DSOs) or private company with expertise in ICESs.

The local energy exchange in ICESs could be operated through service or co-operative model. In the cooperative model, the actors jointly find the local planning and coordination site, operate the facility together lifting the separation between production and use. The complex technical operation can be handled by the service provider, however, the ICESs remains in control of the local co-operative. In the service model, the social desire for local utility with a wide range of services is reflected with a great emphasis on the development of energy service companies (ESCOs).

The local exchange can take several forms such as peer-peer exchange and prosumer community groups [27,61,169]. Using a well-known blockchain technology, a new community micro-grid project in Brooklyn, New York is providing a platform of peer-peer, transactive energy trading among neighbours in a local neighbourhood [169]. Another such mechanism for local energy exchange is PowerMatcher® concept developed in the Netherlands [170,171]. It utilizes available electricity consuming and producing devices from households to derive system operation that optimally matches supply and demand maximizing individual household benefit. For such systems to prevail, appropriate technology integration is crucial.

5.3.2 Flexibility provision

In recent years, technological change has enabled households and businesses to fine tune their energy consumption as well as higher penetration of renewables and disruptive technologies such as electric vehicles and energy storage. The variations in electricity demand and supply can be forecasted but an unexpected mismatch might still occur and the system must ensure that supply and demand are always equal [172]. This feature of an energy system is called *flexibility* [173]. Flexibility is a very broad concept with different temporal dimensions: from very short-term (seconds), short-term (minutes to hours) and longer term (days, weeks, months).

Technologies and methods employed for increasing ICES flexibility include co-generation, fuel cells, heat pumps, electric vehicles and energy storage as well as demand response. The excess PV generation could be stored as heat through heat-pumps or in the electricity storage. There are technologies available for seasonal storage of the heat such as Ecovat®, however, long-term storage of electricity is still technically challenging [174]. Similarly, when electricity demand is higher, combined heat and power units can continue to produce electricity storing the excess heat in thermal storage. At the same time, members of ICESs are more energy cautious allowing higher demand side flexibility. The technical and socio-economic integration make ICESs more flexible.

Significant benefits are associated with an increase in the flexibility of local energy systems [13,68]. ICESs are capable of decreasing or aligning the production and consumption depending on the requirement of the larger energy system. Increasing flexibility allows a higher penetration of intermittent renewables within local energy systems and opens new possibilities to trade energy with neighbouring communities and the national grid. Lund and Muenster (2006) demonstrated the potential of integrated energy system to increase the share of wind energy in the Danish energy mix from 20% to 40% without causing significant imbalance issues [68]. The higher is the renewable energy penetration in a system, the higher is the expected value of ICES flexibility. The value of flexibility from ICESs, however, can be different for different actors such as communities, energy suppliers, grid operators and aggregators. Moreover, ICESs can contribute to system services such as capacity and ancillary services needed to operate the grid [14,175].

The flexibility provision, however, should be carefully designed to incorporate multiple households and communities. A clear, transparent and reliable flexibility market such as the one proposed by Universal Smart Energy Framework (USEF), for the trading of flexibility might be beneficial [176]. The energy markets itself should also be more flexible allowing trade closer to the real-time.

5.3.3 Energy storage

Energy storage is not only the great source of flexibility but also the enabler of integrated operation as illustrated in Table 5.2. Energy storage is vital to balance supply and demand at household and community level. Storage type and size differ based on seasonal, weekly, daily or hourly demand to store energy. Similar to flexibility provision, long-term energy storage is still technologically challenging. Moreover, integrated operation of heat and electricity storage is desirable. The energy storage can enable location-based netting, ensuring local energy balance and overall higher energy system performance.

Table 5.2. Different functionalities of storage in ICESs

Functionalities	Community-level storage	Household-level storage
Balancing demand and supply	Seasonal/weekly/daily and hourly variations, peak shaving, integrated electricity and heat storage	Managing daily variations, peak saving, integrated operation of electricity and heat storage
Grid management	Voltage and frequency regulation, ancillary services, participation in balancing markets	Aggregation of household storage for grid services such as voltage and frequency regulation
Energy efficiency	Demand side management, better efficiency of ICESs minimize energy losses	Local production and consumption, behaviour change to match supply, demand and storage, increase value of local generation, integrated operation

Local energy systems are likely to change with the introduction of plug-in electric, hybrid and vehicle to grid technologies [58]. Rising penetration of electric vehicles will yield higher load as well as storage capacity for ICESs. Electric vehicle flexibility is expected to bring added benefits such as stability and reliability to the local grid as well as flexible back-up for intermittent renewable energy. Based on where the storage systems are installed (i.e. household level and community level or a combination of both), it might help ICESs to withstand peaks in demand as well as to achieve power balance. Additionally, storage allows the flexible generators to run at rated power and higher efficiency. It can also avoid curtailment of intermittent renewables.

Hadjipaschalis (2009) recommends studying the network environment as well as available storage devices specifications before making decisions on the specific storage technology [177]. Accordingly, storage solutions are very tailored and system specific. Moreover, the rules for the access and control of energy storage are essential for the operation of ICESs.

5.3.4 Energy service provision

The increasing penetration of intermittent renewables and DERs in the energy systems is forcing a debate on new energy services as well as their pricing and provision [175]. According to Perez-Arriaga et al., energy services refer to "activities or products with commercial value that are procured directly for, or on behalf of electricity consumers" [175]. As presented in Table 5.3, these energy services will also be relevant for ICESs, some of these services are internal to ICESs whereas others are system services. For electricity, these services can be further categorized into energy-related services, operating reserve and network related services. Energy-related services include the provision of electrical energy. In addition, secondary services such as medium and long term contracts, power exchanges can be derived from these primary services. Operating reserves service consist of primary, secondary and tertiary reserve as well as firm capacity to ensure the reliability of the system. Network related services include the network connection, voltage control, congestion management and energy loss reduction. For more details on energy and network related services of the energy systems, see [175]. These services differ slightly for other energy carriers such as heat and gas and should be defined accordingly. Moreover, when multiple carriers are involved additional services emerge. Monetization of these energy services is important for the emergence of ICESs.

Table 5.3. Energy services within ICESs and to the larger energy system

	Services	Description
Energy-related services	Electrical energy	Electricity sold or purchased at given location and time within the ICESs and to the system
	Flexibility	Upward and downward flexibility to the system
	Operating reserve	Primary- immediate, automatic, decentralized response to system imbalances stabilizing system frequency. For example, Feldheim energy community in Germany provides primary reserves for TSOs through its 10 MWh storage [147] Secondary- up or down regulation service to accommodate normal, random variations in system frequency, and normal variability and uncertainty of load and generation balance
	Firm Capacity	A guaranteed amount of installed capacity that is committed to producing when called upon under system-stress conditions

	Black-start capability	The availability of resources to restore ICESs to normal conditions after black out
Network-related Services	Network connection	Physical connection between the households, to the electricity distribution network and access to the associated services
	Voltage control	Maintenance of voltage within regulated limits throughout ICESs
	Power Quality	Minimum voltage disturbance in delivered power
	Congestion management	Overcoming local congestion through network reconfiguration, re-dispatch/utilization of generators, modifications to load or generation, utilization of flexibility from ICES members
	Energy loss reduction	Local consumption reduces energy losses

5.3.5 Autarkic design

ICESs fit very well into the ideas of self-reliance and independence [60]. Many communities around the globe are concerned with the security of supply and are planning to achieve energy self-sufficiency through dedicated renewable energy, energy efficiency and emissions reduction targets. The expansion of energy systems from residential to community level helps to achieve higher energy and power balance. With larger areas, more primary energy is locally available and generation profiles from intermittent renewables can be absorbed within the local system. The decreasing costs of DERs and the rising retail prices are creating an enabling environment for customers to optimize the planning and operation of the local energy system with the national grid or to get out of the national grid to manage their own local grid [46]. This increases the cost for those customers that remain connected to the grid and do not have means to install DERs.

Accordingly, ICESs can take different architecture: grid integrated and grid-defected or autarkic ICESs. The most optimal solution is the hybrid system with a combination of the grid and the ICES. Such system can also be islanded during emergency situations to provide critical community functions. The driving forces for the grid defection are independence from the national grid, CO_2 emissions reduction at higher levels than the centralized system, self-governance, and other local preferences. The cost of the grid-defected system might be higher because of the limited resource availability at the local level.

ICESs might redefine the relation between production and consumption as they enable resiliency through co-production. ICESs might enable a power balance through smart local consumption, community energy storage, and flexible micro-generation units such as CHPs, fuel cells and heat-pumps as well as hydrogen or ammonia production. This helps to reduce or substitute the industrial production of energy at centralized power plants by decentralized local production. The excess energy can be sold directly to the grid. The residual demand should be met by the industrial production until large scale storage become financially viable.

However, as more communities attempt to achieve energy balance at the local level, the national energy systems might have negative rebound effects if peak demand of many ICESs coincides, in turn leading to higher electricity prices during peak hours. As heating, cooling, and transport sectors are being increasingly electrified, it remains an open question if ICESs can cover future local demand. On the other hand, if all of this demand has to be met from the national grid, distribution grids will need substantial reinforcement to avoid local congestion. Alternatively, a significant portion of this demand could be met locally with the help of ICESs.

Case study: Grid defection

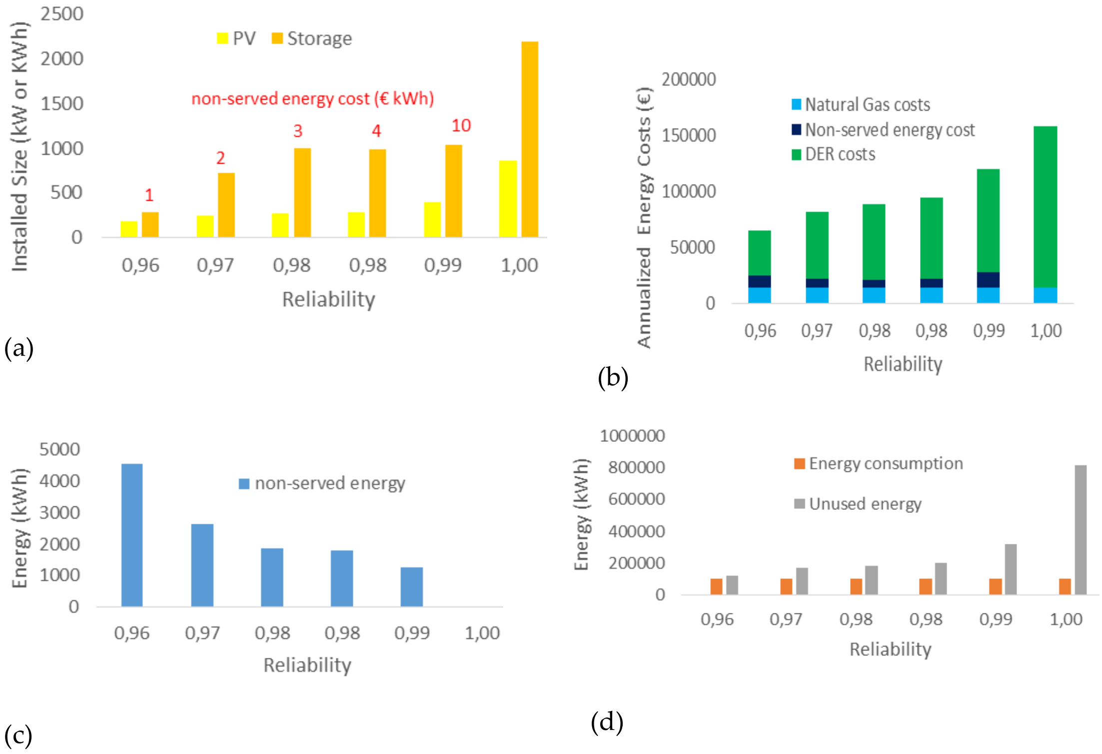
To illustrate the grid-defected ICESs, an energy community in Spain consisting 12 households with community PV and storage is simulated. The demand profiles for the 12 households are based on the household size and their affordances and is generated using Load profile generator [178]. Demand and weather data correspond to Madrid, Spain [132].

The *reliability* is defined here as the ratio of supplied energy to the total demand. The *non-served energy* refers to the amount of energy demand not met by the ICESs whereas the *unused energy* refers to surplus energy not absorbed within ICESs and has to be curtailed as exporting to neighbouring communities or national grid is not an option due to the absence of physical connection. The simulated cost of non-supplied energy for obtaining different levels of reliability vary from 1 to 10 €/kWh.

Figure 5.4 presents the results for community PV and storage sizing, annualized energy costs, non-served energy and unused energy as a function of reliability. For higher reliability needs, the grid-defected system should be significantly oversized which translates into the higher total energy costs. For example, while increasing the reliability of the ICES from 96% to 99.99%, the total energy costs rises more than 3 times. The oversized system also means the higher amount of non-used energy to be curtailed. Marketing such excess energy to different markets/services could further improve the economics of grid-defected ICESs.

Under current Spanish system of prices and charges and DER economics, grid defection is not economically rationale. The diversity of demand as well as generation profiles among the households within ICES would make community grid defection less costly than individual grid defection. However, higher reliability needs lead to an over-sized grid-defected system with a very high unused energy. This unused energy if could be used to provide energy and other system services such as balancing and ancillary services would improve the economics of grid-defected systems leading to a grid-connected configuration.

Figure 5.4. Grid defection through community PV-Storage system. a) Installed community PV and storage size b) annualized energy costs c) non-served energy d) Consumed and unused energy as a function of reliability



5.3.6 Financing and business case for ICESs

Each ICESs projects will require a customized approach for financing considering both costs and revenue streams. ICESs may acquire funding from a variety of sources such as individuals, municipalities, local co-operatives and banks. Although there are funds available and favourable conditions in loan packages in many countries, risk aversion of banks concerning loans for communities is a major barrier to financing ICESs [59].

The willingness to invest in local energy initiatives again depends on several institutional factors and local conditions. ICESs can bring much-needed investment and financing to the local energy system through citizens' engagement. For example, with long traditions of local energy and opposition to the nuclear energy, German citizens exhibit higher willingness to invest in local energy projects [179]. ICESs mobilize private capital of households, enabling investment in local generation technologies. Braun and Hazelroth (2015) has stressed for the national, state and local policy to mobilize local money for local energy, capturing and optimizing local economic benefits [180].

As the main technologies for ICESs such as DERs, storage, and energy management systems are gaining maturity, the next step is to create the enabling environment for business model innovation through flexibility in regulation as well as energy policy. The success of ICESs depends on the business model adopted and its flexibility. These alternative business model should reflect self-provision of energy, energy storage, local exchange as well as different energy services to the system.

ICESs can have several value streams as discussed in section 4.2. The main challenge is to tap these different value streams into a functional business model. Accordingly, business case for ICESs is not always straightforward [181] [182]. For example, in developed countries, these systems could provide different energy services for the members as well as to the neighbouring ICESs or larger energy systems. The same is not possible for ICES implemented in the rural areas of developing countries. Therefore, ICESs in developing countries have to solely depend on revenue from self-provision. Therefore, the design of the appropriate business model will determine the success of ICESs.

5.3.7 Changing roles and responsibilities

As the citizens and communities start to become prosumers, new actors and roles will emerge in energy systems. In this respect, growing numbers of literature has advocated the adaptation of roles and responsibilities of different actors in the context of ICESs [59,60,87]. Actor interests change and evolve over time; as new developments take place, new technologies become available or new market mechanisms get established. In ICESs, the role and responsibilities of the actors will change as summarized in Table 5.4. ICESs imply new roles for communities as they might have to be actively involved in energy production and sharing. Roles of communities in ICESs, further depend on institutional arrangements of ownership and control of the production units and distribution grids [87].

Table 5.4. Changing roles and responsibilities in ICESs

	Actors	Roles and Responsibilities	
Competitive parties		*Current system*	*ICES*
	Households	Consumption, payments	Consumption, payment investment, generation, energy management
	Communities	Passive and inactive individual consumption	Local energy exchange platform, accounting and billing, flexibility
	Energy suppliers	Electricity, gas and heat supply, billing, energy procurement	Supply the deficit, management of local energy systems, flexibility and energy procurement
	ESCOs	Financing, supply and installation of energy efficient equipment, building refurbishment	Management of local generation fleets; financing, supply and installation of energy efficient equipment, building refurbishment
	Technology providers	Provide energy efficient and Distributed generation technologies	Technologies for local generation, energy efficiency, energy management system
	Aggregators	-	Aggregate the flexibility from the local community
Regulated parties	*DSOs*	Grid operation, reinforcement	Grid operation, local congestion management
	TSOs	System balance	Use flexibility for system balance
	Government, policy makers and regulators	Ensure sustainable energy supply, subsidies	Investment and subsidies for ICES, policies, Reduce barriers, shape local markets
	Balance responsible parties	Balance responsibility	Incorporate flexibility in portfolio

However, as energy infrastructures are extremely complex, it would be impossible for communities alone to manage the entire energy systems. Therefore, the traditional companies need to be adapted to establish a partnership with the local communities for the management and operation of ICESs. The function of 'aggregators' which is so far only exercised by the suppliers can also be performed by ICESs through aggregation of small consumers. In this way, ICESs can have new roles as *flexibility provider*. Installers can finance as well as operate the installations themselves as service provider ensuring consumers 'comfort'. The community will have collective responsibilities in formalizing business models as well as local balancing arrangements. Distribution system operators have to adapt the system operation as per the ICESs needs and vice versa. These developments challenge the governance and traditional business structures [60]. The emergence of new roles and new interpretation of existing functions can ensure efficient development of ICESs.

5.3.8 Ownership and (self-)governance

ICESs promote commons-based energy supply. In a liberalized market, it is possible to establish local prosumer – consumer energy commons. Different actors can be enabled to co-create a smart local energy system. ICES could be 100% community owned or may be developed together with private or public sector under co-ownership arrangement [20]. ICESs advocate a combination of locally owned production and consumption of energy.

Ownership refers to a source of control rights over a resource or property and power to exercise control when the contract is incomplete such as excluding the non-owners from access, selling and transferring resources as well as appropriately streaming the economic flows from use and investments [183] [184]. The ownership in energy systems such as ICESs is affected by the financing requirements, social welfare issues as well as risk preferences [20,185]. ICESs can have locally owned and controlled community ownership, utility ownership, private ownership and public – private ownership, Table 5.5. Governance refers to a structure to practice economic and administrative authority such as rules of collective decision-making among actors [60,186].

Table 5.5. Ownership and governance model for ICESs

Ownership	(Self-)Governance
Community	All costs and benefits are covered by ICESs. Co-operative structure for the management and operation can be outsourced to the service provider.
Utility (DSO)	Utilities remain relevant in ICESs as owner, service provider or grid connection enabler or a combination of these roles. ICESs can benefit from its technical and financial capability. The utility can decide independently and level of community engagement is subjected to the utility.
Private	Private expert companies own and operate ICESs. Incorporating social and economic objectives of the local communities requires negotiation and bargaining.

Public-private (hybrid)	Joint decision making and planning through the engagement of local communities and private expert companies Private expert companies can hedge against future uncertainty.

The development of ICESs challenges existing energy-structures and creates opportunities for self-governance [60]. In the context of ICESs, (self-)governance refers a group of people that exercise the control over themselves by self-ruling or autonomy. There are good examples of common pool resources managed by communities. Ostrom (2005) has demonstrated the robustness of self-governance in socio-ecological systems where government and markets could not do better [187]. Cayford and Scholten (2014) have analysed the viability of self-governance in community energy system and reported that it depends on communities' abilities to be adaptive to co-ordinate with different governance circles [188]. Self-governance in ICESs may even take different forms according to its social and technical complexity.

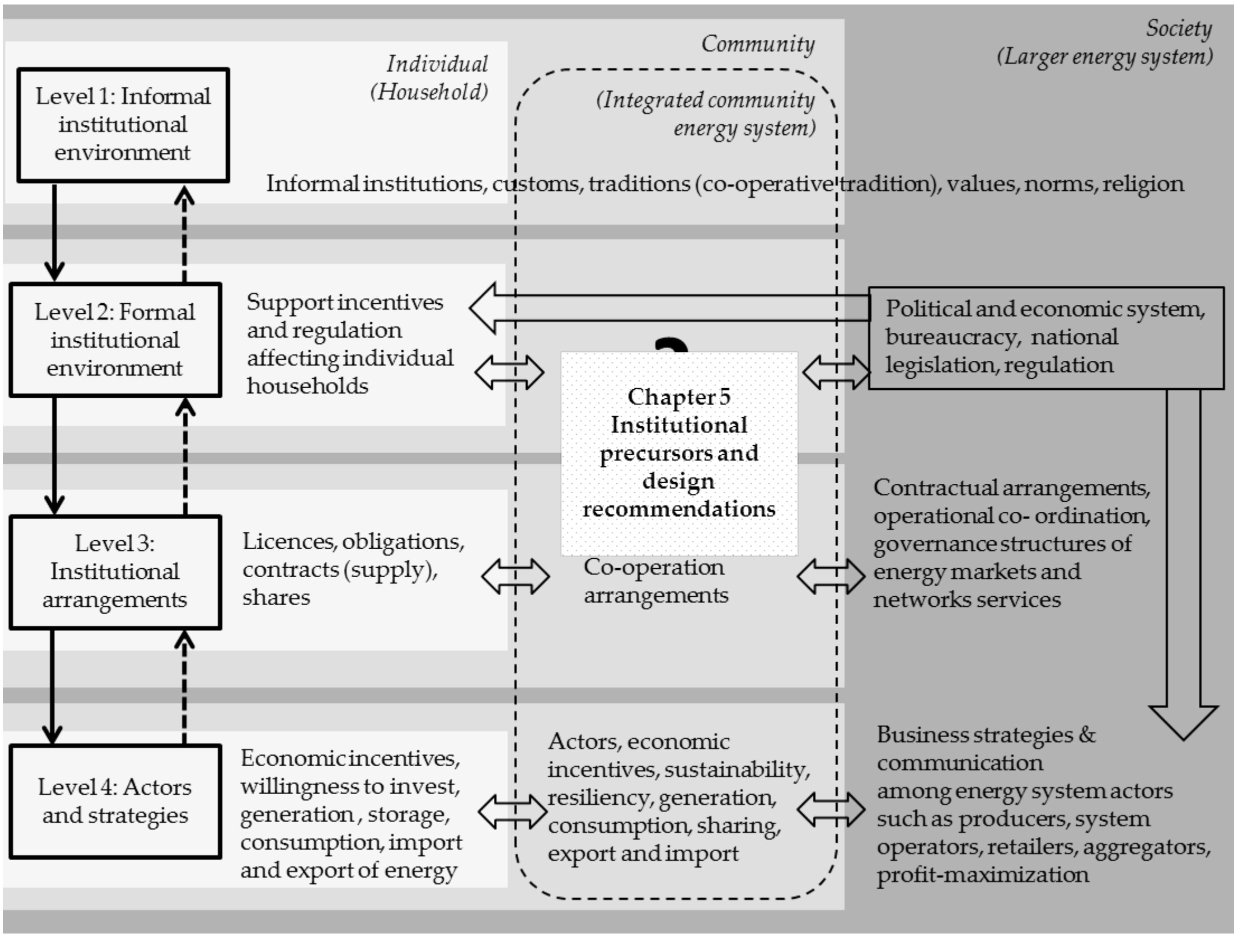
5.4 Synthesis

The research sub-question addressed in this chapter was: *What requirements exist from the techno-economic and institutional design perspective for the integration of ICESs in the energy system?* This chapter has highlighted several institutional precursors for the emergence of ICESs such as regulation, support incentives, grid access and local balancing as well as the alignment of technologies and institutions.

Figure 5.6 positions this chapter with respect to the conceptual framework. ICESs requires supportive formal and informal institutional environment as well as institutional arrangements for integrated operation as well as interactions among different actors. For example, unbundling should be relaxed for the long-term financial viability of ICES and re-bundling is required for local ownership of energy generation and supply infrastructure. The local energy exchange platform is essential to ensure energy sharing among members of ICES.

Several institutional design recommendations for ICES based on techno-economic perspectives are provided. Technical perspectives considered are the provision of energy services to the larger energy system as well as the autarkic design of grid-integrated and grid defected ICESs. Collective financing and new business cases involving flexibility provision and ancillary services as well as hedging against price fluctuations are important. The clear understanding of the changing roles and responsibilities, community ownership and self-governance, design and co-ordination of local energy exchange as well as the fair allocation of cost and benefits are important institutional settings for the success of ICESs. These institutional settings need to continuously adapt to the changing energy landscape.

Figure 5.6. Positioning Chapter 5 in the conceptual framework



Chapter 6
Conclusions and Discussions

"The only way to know how a complex system will behave after you modify it is to modify it and see how it behaves"

- George E.P. Box

This chapter provides answers to the research questions posed in the introduction chapter and outlines the conclusion of this thesis. Then, discussions on the research framework, recommendations for the policy makers and the direction for future research is provided.

6.1 Conclusions

This thesis conceptualizes ICESs as modern development in the changing energy landscape which has potential to deal effectively with the issues of energy system integration and community engagement. ICESs have to emerge in an environment designed for the centralized energy system and are being shaped by technological, socio-economic, environmental and institutional issues as well as current trends in the energy landscape. With this background, the main research question of this research was: *How can integrated community energy systems contribute to enhance the energy transition?* In the next four sub-section, the answers to the three sub-questions and the main research question presented in Chapter 1 are provided.

6.1.1 Dynamics and interactions of transformation to ICESs

The first research sub-question was: *What are the technical, socio-economic, environmental and institutional dynamics and interactions of transformation towards ICESs?* ICESs are complex socio-technical systems emerging through the changes in the local energy landscape. Bottom-up energy initiatives such as ICESs in a present centralized energy system cause multitudes of technical, socio-economic, environmental and institutional dynamics and interactions in the different level of the society. Accordingly, ICESs need to overcome the dominant culture, structure and practices from the centralized energy system. ICESs involve a diverse set of institutions and actors; the operation of such systems lie at the interface of community, policy and institutions. The roles and responsibilities of different actors of the energy system also changes with the emergence of ICESs.

ICESs provides new roles and responsibilities for the local communities in the energy system. With the active engagement of the local communities in the energy system, ICESs will impact different actors both directly and indirectly as the local and system-wide exchanges and interactions take place. In contrast to the traditional role of households in consuming energy, households and communities will have new roles in ICESs such as consumption, operation, storage, exchange, aggregation and collective purchasing. Accordingly, ICESs face tensions, controversies and institutional problems due to these new roles and responsibilities. At the same time, new technical and socio-economic developments are expected as different actors of the energy system attempt to align their incentives with those of ICESs. This leads to patterns of interactions and outcomes that not only affect the emergence of ICESs but also bring along changes in the energy system. These developments will reshape operational roles and responsibilities, local energy markets, the behaviour of different actors, business models for energy services as well as corresponding institutional arrangements.

The topology and architecture of ICESs depend largely on the community objectives to reduce energy costs, CO_2 emissions and dependency on the national grid. The local communities can operate ICESs in a grid-connected or grid-defected mode. At the local level, various new energy technologies will change the existing energy mix and further enhance the integrated operation. ICESs are influenced by the attributes of the technical world such as available technologies and networks as well as the attributes of community in which actor and actions are embedded and institutions which guide and govern actors behaviour.

Local communities can optimize their energy system based on onsite conditions, energy prices, and available DER technologies. In ICESs, local communities will play a significant role in energy production, consumption as well as distribution. The ICESs result in effective engagement of the local households and communities by means of collective purchasing, community ownership, co-operative operation and maintenance arrangements as well as through the integration of different sectors such as electricity, heating, cooling, gas and transportation. These arrangements also make citizens more energy conscious, contributing to energy efficiency improvements as well as emissions reduction. Moreover, ICESs promotes an array of benefits inclusive of sustainability, security of supply, self-reliance and energy independence. In this process, ICESs might also face barriers such as lack of technical expertise in system operation, grid access issues, financing, allocation of cost and benefits, leadership and co-ordination issues, lack of community participation, as well as not equal level playing field in the centralized energy system.

Increasing environmental concerns and renewed attention on universal energy access are the main drivers for the surge in the progress of local energy communities in both developed and developing countries, respectively. ICESs have potential to transform the local energy systems. Irrespective of where implemented, these systems might be a significant component in future energy systems of developed and developing countries alike.

6.1.2 Assessment of the added-value of ICESs

The second research sub-question was: *How can we assess the added value of ICESs to the individuals, local communities as well as to the larger energy system?* As presented in Chapter 3 and 4, ICESs have range of technical, economic, environmental and institutional values to the individual households, local communities as well as to the society. These tangible and non-tangible values necessitate both qualitative and quantitative methods for the value assessment. In this research, the value to the local communities is determined using optimization model for planning and operation of ICESs. The focus is on economic and environmental performance metrics. The value to the individual households is determined using a case study involving quantitative assessment. Finally, the value to the larger energy system is determined by a case study based on a pilot project for flexibility provisions from the individual households to the larger energy system.

For the considered community size, technology-mix and local conditions, grid-connected ICESs are found to be a beneficial alternative to solely being supplied by the national grid both in terms of total energy costs and CO_2 emissions. In other words, grid-connected ICESs are a viable alternative for the local energy supply without additional subsidies. The grid-defected systems, despite performing very well in terms of CO_2 emission reduction, are still rather expensive. Integrating multiple local generation, storage, energy efficiency and demand side management systems not only provides higher economic benefits for ICESs but also would enable them to play a more active role in achieving the low-carbon transition.

Added-value to the households: Through ICESs, the households can reduce their energy costs and emissions and improve their energy autonomy. Energy system integration of DERs and community engagement enable ICESs as an effective and cost-efficient way to reach citizens' expectation regarding the energy system. Regarding the prosumer households, ICESs can act as an aggregator, enabling their participation in the energy markets.

Added-value to the community: Local communities benefit from ICESs in terms of reducing total energy costs and emissions. Through aggregation of group of households, ICESs have the potential to reduce community dependence on the national energy systems. ICESs provide a platform to share energy among neighbours. In this way, ICESs helps to keep local money within the local economy. Therefore, the added-value of ICESs might go beyond the benefits derived from the energy service provisions alone. ICESs provide opportunities for communities to choose their energy future, thereby ensuring strong local support and social acceptance. ICESs increase awareness, reduce energy poverty through affordable energy for all as well as increase sense of community, pride, and achievement.

Added-value to the larger energy system/society: The widespread availability of flexible generation, flexible load and energy storage facilities as well as integrated operation will enable ICESs to provide flexibility and other system services to the larger energy system. ICESs can also provide these services to the neighbouring communities. ICESs can also help to defer new investments in power lines with the help of system peak reduction through the local generation and demand side management. Through community investment and flexible integrated operation, it might help to achieve higher penetration of renewables in the energy system. As increasing number of local communities implement ICESs, it might help to achieve energy and climate policy goals of the society.

6.1.3 Institutional precursors and design recommendations

The third research sub-question was: *What requirements exist from the techno-economic and institutional design perspective for the integration of ICESs in the energy system?* ICESs have to emerge in the system designed for centralized energy system. In contrast to present energy system, ICESs member households produce, consume and share energy between each other within geographically defined boundaries and may operate in both grid-connected or grid-defected mode. A platform for local energy and knowledge exchange, effective integration of different sectors and engagement of local communities as well as equal level playing field with respect to market participation and grid access are the necessary preconditions for ICESs implementation.

Policies, incentives and support schemes should provide a level playing field for enabling the collective action such as ICESs. For example, ICESs should be able to participate in different energy markets and provide different energy services. Policies should incentivize higher self-consumption and persuade local households to invest in ICESs technologies when it is economically efficient for the overall system. Through re-bundling, ICESs should be allowed to perform different roles as a single entity such as generators, consumers, distributors and system operators. ICESs can have new roles in the energy system through creating an enabling environment for the market participation and creating a decentralized market for flexibility.

Techno-economic and institutional perspectives help in the comprehensive institutional design of ICESs. The techno-economic perspectives include means for strategic interactions with the larger energy systems such as flexibility, energy storage, energy services, autarkic design, collective financing as well as business models. Grid-connected ICESs services and value streams should complement and be in synergy with the requirements of the larger energy system. The clear understanding of the changing roles and responsibilities, community ownership and self-governance, design and co-ordination of local energy exchange as well as the fair allocation of cost and benefits are important institutional aspects to be considered. It is important that in ICESs, costs and benefits are shared fairly amongst the stakeholders involved. Institutions and business models as well as the regulatory framework need to be adapted to provide equal level playing field for ICESs. In addition, alternative business models such as local balancing and ancillary services are needed to sustain these initiatives and have meaningful contribution to the larger energy system.

6.1.4 Overall conclusion

The previous three sub-sections provide the foundation to answer the main research question of this thesis: *How can integrated community energy systems contribute to enhance the energy transition?* Bottom-up energy initiatives such as ICESs can enhance energy transition by providing effective means for energy system integration and community engagement. ICESs can act as the bridge between bottom-up local energy initiatives and the centralised energy system thereby encouraging the low-carbon transformation of the overall energy system. An ICES offers more than the low-carbon transition; it improves efficiency, strengthens the security of supply and empowers the local customers. In addition, ICESs helps to achieve climate and energy policy objectives of the society.

Among the ICESs discussed in Section 2.2, not all types may contribute to enhance the energy transition. For example, ICESs which depends solely on conventional generation or demand aggregation for collective purchasing despite providing economic benefits to the local communities may not enhance energy transition significantly. ICESs with renewable generation are expected to contribute towards energy system transformation.

As discussed in Chapter 1 and 5, complex socio-technical systems such as ICESs have to adapt and operate in the changing energy landscape where new technologies will become available, new institutions will emerge and roles and responsibilities of the actors change continuously. In this context, the contributions of ICESs to the energy transition should be assessed not in isolation but in terms of its interactions, dynamics and strategic exchanges with the individual households, local communities and the larger energy system.

ICESs contribute to reducing energy cost, CO_2 emissions, and dependence on the national grid as well as improve (self-) governance. This way ICESs help to increase penetration of intermittent renewables and bring new roles for the local communities in the energy systems such as aggregators and flexibility as well as ancillary service providers. ICESs might also provide cost-effective solutions to local congestions and help avoid or defer grid reinforcement foreseen with increasing penetration of the local renewables. ICESs provide opportunities for citizens and communities to decide about their energy future, thereby ensuring strong local support and social acceptance. These aspects help in a smooth transitioning of the overall energy system.

ICESs contribute towards sustainability and energy security locally. For example, ICESs can provide flexibility and system services to the neighbouring energy communities and larger energy system and defer the new grid reinforcement. ICESs have an important role in engaging consumers, thereby bringing in the private investment in the energy system. Integrated operation of different sectors, demand side measures, energy efficiency as well as citizens' engagement in ICESs lead to a higher flexibility. ICESs aggregate individual households and several ICESs can co-operate together to improve their positions further among the market players of the larger energy system. ICESs have added-value not only to the local communities but also to the individual households and the society.

A comprehensive institutional design considering techno-economic and institutional perspective is necessary to ensure effective contribution of ICESs in the energy transition. Such institutional design should not only focus on the internal structure of the ICESs but also on external linkages, synergies and strategic exchanges with the larger energy system. ICESs should be open for new interactions and experiments to allow further technological and social innovation and to adapt to the changing energy landscape. Although community objectives to reduce energy costs and CO_2 emissions as well as to increase energy autonomy are sufficient reasons to initiate ICESs, innovative value streams in synergy with the requirements of the larger energy system are required for ICESs to have significant contribution in enhancing ongoing energy transition.

6.2 Policy recommendations

This thesis provides following insights for local, national and regional policy makers to design suitable policies for ICESs with potential impact on energy transition.

Higher flexibility through integrated operation: As highlighted in chapter 3 and 4, integrated operation leads to flexible local energy systems. ICESs can facilitate uptake of new DERs, different consumption patterns, energy efficiency measures as well as smart grids and demand-side management in an integrated way. It can also facilitate integrated operation of different energy sectors.

Addressing energy poverty: As discussed in Section 2.6.2, the primary focus of ICESs should be affordable energy provision to its members rather than profit-making. ICESs are better positioned with regard to vulnerable members under energy poverty both in terms of their energy provisions and participation.

Local aggregation and grid access: ICESs act as local aggregators, enabling household consumers to participate in the energy market. ICESs should be allowed to be connected to the larger energy system through a single point of coupling without entry barriers. For further discussion on grid access and local balancing refer to Section 5.2.3.

Ownership: As discussed in Section 5.3.8, ICESs should be able to own or lease energy generation and storage infrastructures, energy management systems and community energy networks.

End-user engagement: End-user engagement is essential for the success of ICESs as illustrated in Section 2.6.2. Through energy democracy and local ownership, ICESs should contribute in enhancing customer engagement in the energy systems. The European policy on end-users engagement are still based on the traditional and centralized energy systems focusing on individual consumers-suppliers relations and undermines the possibility of collective action through the local energy initiatives. Policy makers should focus on removing the perceived barriers discussed in chapter 2 through empowerment of local communities and incentivizing citizens to participate and steer such local energy systems. Increasing citizens' participation in ICESs will transform it from a niche to a more mainstream system with higher relevance for the whole energy system. The EU winter packages propose some promising proposals with respect to end-user engagement through local energy communities [85].

Autarkic design as a policy option: As investigated in Section 5.3.5, ICESs should be designed to provide essential emergency services and effective balance between supply and demand. These essential emergency services should be monetized. ICESs could have an important role in the energy security and resiliency, if the autarkic design is considered as a policy option.

Load and grid-defection: The impact of grid and load defection, as defined in Chapter 1 and further investigated in Chapter 4 should be minimized through right policy measures. To prevent inefficient grid defection, network and sunk system costs recovery should be carefully addressed through a solution such as *exit-charge*, as discussed in Chapter 4. Such charge should consist of avoided regulated policy costs, contribution towards sunk network costs as well as avoided taxes.

In future, with an increasing need for flexibility in the whole energy system, surplus energy from both grid-integrated or grid-defected ICESs might be traded in different energy markets or used in providing different energy services. This is expected to positively affect the economics of both grid-integrated and grid-defected ICESs. This emphasizes the important role of the grid in enabling future energy systems, such as ICESs. Further improvement in the value of the ICES can be expected, as the energy storage costs decrease, more storage technologies become available, and their different energy services are utilized.

Energy services and flexibility provision: ICESs can have new roles in the energy system as energy services and flexibility provider if an enabling environment for the market participation as well as the decentralized market for flexibility is created. ICESs have important roles in providing flexibility as well as smoothening the energy system operation through effective engagement of local communities. For further details on energy services and flexibility provision, refer to Section and Section, respectively.

Economics of grid-defected ICESs: As investigated in Section, grid-defected ICESs are often oversized and might have very high amount of unused energy to be curtailed. The unused energy in the grid-defected ICESs if marketed to the neighbouring communities and to the energy markets or if used to provide system services for the whole energy system, can enhance the economics of these systems. In this case, the system could be self-sufficient on the demand side but will still depend on the network to transfer the surplus energy. The energy community in Feldheim, Germany is a very good example for this particular case [147].

Time-based vs. location-based energy balance: While time-based energy balance at individual households in the form of '*Saldering*' was successful at increasing uptake of DERs in the Netherlands, the location-based energy balance is needed for ICESs. The location-based energy balance enables higher self-consumption and energy sharing within local communities as discussed in Section 5.2.3.

Minimizing opportunistic behaviour: The growth of DERs in general and the ICES in particular might affect all actors of the energy system alike. There could be a spill-over effect of the ICES savings on the remaining customers of the whole energy system, such as paying fewer taxes and policy surcharges. At the same time, these communities contribution toward energy policy goals through local investment should be adequately considered. It is important to prevent opportunistic aggregation and free rider behaviours that avoid paying system costs which otherwise should be recovered through other market agents.

Support schemes: As highlighted in Section 5.2.2, the support schemes should be tailored to the specificities of the local conditions where the ICESs is implemented. ICESs should have equal access to support incentives available for individual households as well as utility scale renewables deployment. Policy makers should steer right transformation of ICESs through suitable policies, incentives and support schemes.

Demonstration projects: The added technical, socio-economic and environmental values of ICESs as discussed in Chapter 3 should be demonstrated through pilot implementation. Policy makers should promote energy systems which are more sustainable. Policy makers should take effective action at the local level through planning, regulation, provision of services and ensuring citizens participation.

6.3 Discussions

In this research, an attempt has been made to answer the main research question. *How can integrated community energy systems contribute to enhance the energy transition?* We are now convinced that the contribution of ICESs, which are deeply embedded in the energy system, cannot be determined in isolation and the role of individual households, local communities as well as whole energy system should be adequately considered. The potential role of individual households and local communities in determining the more sustainable energy future cannot be neglected. The engagement of individual households and local communities in the energy system through local energy initiatives such as ICESs is essential for the transformation of the whole energy system. In the rest of this section we critically reflect on the conceptual framework adopted in this research and discuss on the barriers in practice, direction for future research, ICESs in developing countries and the roadmap for the sustainable future.

6.3.1 Significance and contribution

This thesis analyses how the sustainability of the local energy system be increased by integrating different energy sectors and engaging local communities. ICESs are modern development in the energy system with significant potential for energy system integration and engagement of local communities. As more and more local communities are attempting to take complete control of their energy system disrupting the utility business model, this thesis analyses different technical, socio-economic, environmental and institutional aspects associated with ICESs. In the recent clean energy package, the European Commission has recognized the important roles of community energy systems and renewable energy co-operatives in energy system transformation [85]. This research has highlighted the potential of ICESs in decarbonisation of the local energy systems and meeting the climate and renewable energy objectives.

The main contributions of this thesis are:

Contextualization of ICESs in the present changing energy landscape: This thesis has contextualised ICESs in the present energy system with the aid of research framework consisting of three societal level and four institutional level.

Conceptualization of ICESs as complex socio-technical system: In this thesis, ICESs are conceptualized as a complex socio-technical systems emerging through the changes in the local energy landscape. ICESs have to overcome multitudes of technical, socio-economic, environmental and institutional dynamics and interactions in the different level of the society as well as dominant culture, structure and practices from the centralized energy system. This thesis has identified a diverse set of technologies, institutions and actors for ICESs as well as roles and responsibilities of different actors of the energy system for the emergence of ICESs. Another important contribution of this thesis is the categorization of ICESs based on different sizes, activities, topologies, location, grid configuration in Table 2.1.

The ICES Model: The modelling of complex socio-technical systems such as ICESs under the changing energy landscape is a tedious task. Several technological, socio-economic, environmental and institutional issues as well as emerging trends in the energy landscape as discussed in Chapter 1 and 2 shape the emergence of ICESs. This thesis provides a modelling framework for ICESs and the ICES model in Chapter 3. The ICES model determines the optimal planning and operation of households and community level DERs in ICESs. The focus is on economic and environmental performance metrics.

Value assessment of ICES: With the aid of the ICES model and case studies, a range of technical, economic, environmental and institutional values of ICESs to the household, local communities and the larger energy system is assessed in Chapter 4.

Institutional precursors for ICESs: ICESs have to emerge in the centralized energy system. Institutional precursors for successful implementation and adaptation of ICESs is provided in Section 5.2.

Institutional design recommendations: A comprehensive design, called institutional design, combines the techno-economic and institutional perspectives in the design of institutions for ICESs. However, due to the involvement of multiple stakeholders and technologies, the institutional design of ICES is very complex. For example, collective decisions have to be made to meet the individual needs. In Section 5.3, institutional design recommendations for the implementation of ICESs are provided.

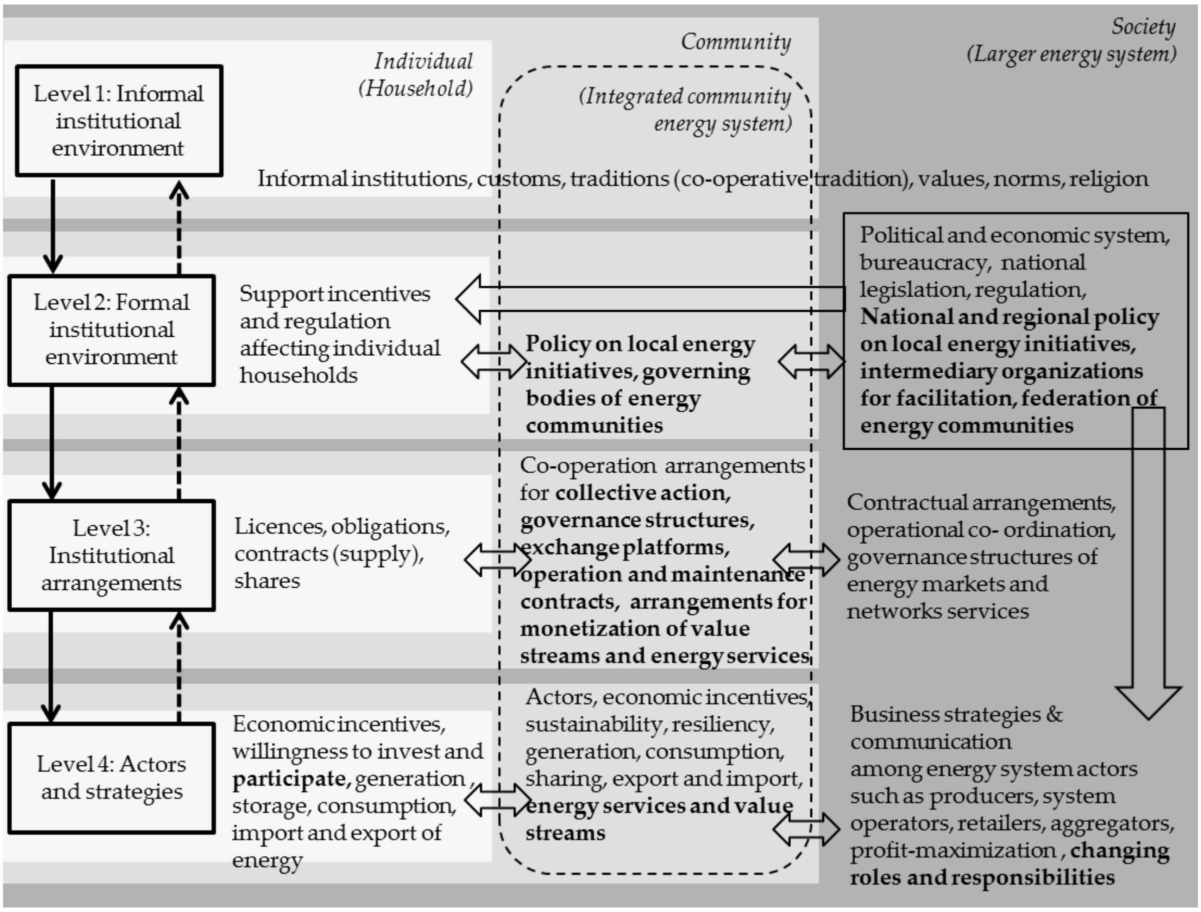
Policy recommendations: In Section 6.2, ICESs related policy recommendations are provided for the local, national and regional policy makers with potential impact on energy transition.

6.3.2 Discussions on the conceptual framework

The conceptual framework introduced in Chapter 1, based on four institutional level and three societal level, was broad enough to guide this research and to support the explanation of multiple research framework and literature, as well as the scientific and societal context of this thesis. The institutional level helped in capturing the top-down influence of different institutions in ICESs which is dominant in present centralized energy system whereas the societal level captured the bottom-up organization of ICESs, thereby the important role of individual households and local communities. The interactions between institutional level and societal level lead to the understanding of the interrelations and linkages both within and outside of ICESs. It also helped to identify the coherence between different technical and socio-economic practices and necessary institutional arrangements as well as the tensions and synergies with the larger energy system. Although positioning of different chapters within the framework was challenging, the framework provided solid lenses to conduct this research.

In Figure 6.1, the conceptual framework is further adapted based on the outcomes of this research. Before this research, the role of households and society was well-understood but the new roles of local communities in the energy system was relatively under-investigated. The policy recommendations as discussed in Section 6.2, proposed in the fourth energy package of the EU and other national and regional policies on local energy initiatives should also be an integral part of the conceptual framework. In addition, the organizational structures of the governing bodies for managing these energy communities such as energy co-operative and trust form an important part of the formal institutional environment at the community level. With respect to the institutional arrangement at the community level, (self-) governance structure for collective action and exchange platforms, arrangements for monetization of value streams and energy services as well as operation and maintenance contracts with the service providers are essential. At the societal level, roles and responsibilities of the energy system actors are expected to change. Moreover, national and regional policy on local energy initiatives as well as intermediary organizations for facilitation and federation of energy communities might emerge. The conceptual framework should be continuously adapted to these changes in the energy landscape.

Figure 6.1. Reflection and adaptation of the conceptual framework



Overall, this research established that the Williamson's four institutional level in combination with three societal level provide an useful framework to study interaction and dynamics, added-value as well as institutional analysis of systemic effects of the emergence of local energy initiatives such as ICESs.

6.3.3 Barriers in practice

This research has demonstrated that ICESs have technical, socio-economic and environmental benefits as well as significant potential to enhance energy transition. However, the implementation of ICESs in practice is not straightforward and has to face several barriers. One of the significant barrier is not equal level playing field due to traditional utilities dominated centralized energy system. Below the implementation challenges of ICESs are discussed.

Centralized energy system: The present energy system and the policies are designed for the centralized energy system and do not offer a level playing field for the bottom-up initiatives such as ICESs. Recently, utilities are starting to realize the potential of DERs to fundamentally impact the energy system.

Financing: DERs and energy management system in ICESs have high upfront capital cost. Despite the potential of ICESs to activate the private capital of the local communities, there are significant limitations in financing these local energy initiatives.

Business models: This research has demonstrated an array of value streams for ICESs. It is a significant challenge to pool all these revenue streams together to have an ICES with a reasonable payback period.

Robustness and Flexibility: Experimenting, evaluating as well as learning by doing activities in ICESs depends on cohesion and social co-operation among the members. ICESs have to adapt with new technologies, information and changes as they become available. At the same time, robust regulations and institutions might be needed to provide stability to ICESs.

Citizens' participation: Despite the large share of the population in local energy initiatives such as ICESs, the research also showed that the share of citizens' involvement diminishes from participation to steering. As the survey was mainly focused on the intention of citizens to participate in ICESs, the share of citizens could be even lower in actual ICES implementation.

Legal: There are several legal barriers for implementation of ICES. One of the most prominent ones is EU market legislation, the third energy package. According to this package, generation, distribution and retail should be unbundled which inhibits ICESs. Living off-grids is a still remote possibility in EU. There are regulatory barriers for local balancing and energy exchange among household is not possible due to lack of technical infrastructure and associated regulatory barriers. For example, self-consumption in local communities has to pay network fees in Germany. Moreover, in Spain, there are administrative hurdles for DERs installation, legislative uncertainty, dis-incentives for self-consumption and production, ineffective unbundling of integrated energy companies and obligation for property to have a connection to the electricity grid [189]. The fourth energy package proposals offer solutions to some of these legal issues [85].

Technology: ICESs should meet the technical requirements and standards for the integrated operation. The success of ICESs depends on technical and economic maturity as well as the timely availability of its technologies. Technology progress is essential for linking local energy services and making them accessible and affordable. At the same time, technologies should be continuously shaped and adapted to the local circumstances and the changing energy landscape.

Grid access: There can be resistance from the incumbent grid-operator to transfer the ownership, sell or lease the energy network to the ICES. Fair and cost-reflective access to the grid is often challenging.

Local energy exchange: Although the local energy exchange is the key attribute of ICESs, it might not be straightforward in practice. There can be resistance from incumbent utilities and it might often involve changing the point of delivery of energy, building a physical interconnection between households across the street or utilizing higher level network infrastructure. In each case, the rules for access to technologies and networks should be well-defined to prevent the opportunistic behaviour.

Entry and exit rules: In order to enhance competition in the energy markets, freedom to the choice of supply has been promoted. However, this can affect the sustainability of local energy initiatives such as ICESs.

6.3.4 Direction for the future research

Various aspects of interest related to ICESs have not been addressed adequately in this thesis, resulting in the following direction for the future research:

Commercial and industrial consumers: This thesis only considered the aggregation of residential consumers and their collective action in the form of ICESs. Future research could also consider the impact of adding commercial and industrial consumers to ICESs. Such research might be particularly interesting provided the different consumption patterns of the residential and commercial/industrial consumers.

Heat exchange: This thesis assumed electricity exchange between members and with the larger energy system and heat autonomy at the household level. Future research could investigate the impact of heat exchange among members through community heating network in enhancing the flexibility of the local energy system.

Time horizon and step: The model developed in this research uses a time horizon of one year and the step of one hour. Future work can consider the longer time horizon and shorter time steps.

Participation in different energy markets: This thesis assumed the participation of ICESs only in the day-ahead market. Future research could consider the ICESs participation in intra-day and balancing energy markets.

ICESs as price makers: This thesis assumed ICESs as price takers and no distortion in energy markets is expected due to its early stage in the development and adoption. However, with increasing number of the local energy initiatives, the impact of the emergence of ICESs on the electricity prices, especially at the local level can be significant. The research on future energy market design could pay attention to these aspects.

Local energy market: With the surge in the shared economy and advancement in the blockchain technology, the design of local energy market offers an relevant research agenda for the future. Such markets will provide platforms for interactions between ICESs.

Research Methods: The analyses in this thesis are based on system optimization model, survey, statistical analysis and desk research. More insights on interaction and dynamics of ICESs can be expected through agent-based and system dynamics models. On the one hand, the application of top-down system dynamics model could help to further understand interaction and dynamics as well as the systemic effects of ICESs implementation. On the other hand, agent-based models help to simulate the interactions among many members of ICESs. In addition, pilot ICESs implementation tailored to the local conditions with dedicated focus groups, shadowing and deep unstructured interviews helps to understand the dynamics of ICESs implementation in practice.

6.3.5 ICESs in the developing countries

ICESs differ between developed and developing countries due to different objectives, technical conditions and socio-economic features. For example, in developed countries, these systems are primarily initiated with the objective of climate change mitigation and energy autonomy as well as economic incentives such as available subsidies for local energy sources, whereas in developing countries their main purpose is to provide energy access. Moreover in terms of technical conditions, the number and types of energy carriers as well as technology status also differ among developed and developing countries. Particularly, in developed countries electricity, gas and heat networks already exist, whereas in developing countries the grids are mostly electricity-only and often have to be developed from scratch. There are many initiatives all around the world for energy access in developing countries where ICESs might play a significant role.

Based on the research conducted in this thesis, following outlook for ICESs in the developing countries can be provided:

a) Developing countries can leap-frog to ICESs. There are already some initiatives in this direction. For example, swarm-electrification in Bangladesh and interconnected mini-grids in Nepal [190] [191].
b) As most energy systems in developing countries are developed from scratch, the engagement of local communities from the beginning of the project is pivotal for the sustainability of the local energy project.
c) Based on evidence from community micro-hydro and community forest, community-based energy systems such as ICESs are likely to be successful in developing countries [168].
d) The complex technical functions of ICESs are performed by expert energy service companies in the developed countries. In developing countries, the technology providers could provide training for the local system operators to perform these functions.
e) The reliable energy access through ICESs can help to improve socio-economics of local communities through engagement in productive end-use. It might help to control migration to the urban areas or abroad.
f) Grid-defected ICESs in the developing countries could be developed considering the national grid expansion planning as well as isolated systems.
g) ICESs allow the support of the local economy; an attribute that becomes increasingly important in developing countries to improve living standards and control migration towards urban areas.

6.3.6 Roadmap for sustainable future

As an innovative way to organize the local energy system, collective action in the form of ICESs is still at the initial stage of the development and our research provides better understanding of the potential interaction and dynamics of the implementation of

ICESs as well as their potential contribution to energy transition. ICESs emerge in the changing energy landscape making use of and adapting existing infrastructure and market organization. The technologies and institutions should be continuously aligned and tailored to the local specificity. ICESs might contribute to improve energy performance and economic competitiveness and enhance quality of life in the local communities. In this way, ICESs can significantly contribute to the achievement of local, national as well as regional renewable energy, energy efficiency and climate change targets.

This research has highlighted the synergies of ICESs to the larger energy system. ICESs could work as the bridge between bottom-up local energy initiatives and the larger energy system. The success of ICESs depends on the collaboration between individual households, local communities and the society. Policies and programs discussed in Section 6.2 should be developed to support progress towards sustainable communities. ICESs can be accepted by different actors such as local governments, communities, energy suppliers and system operators as an effective means to achieve sustainability and thereby will have significant roles in transitioning the energy systems.

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Acronyms

APX: Amsterdam Power Exchange

ASHP: Air Source Heat Pump

BRPs: Balance Responsible Parties

CHP: Combined Heat and Power

CO_2: Carbon dioxide

DECC: Department of Energy and Climate Change

DERs: Distributed Energy Resources

DER-CAM: Distributed Energy Resources – Consumer Adoption Model

DSOs: Distribution System Operators

EA: Energy Autonomy

EEG: German Renewable Energy Law

EFOM: Energy Flow Optimization Model

E-GIS: Environment and Energy Geographical Information System

ESCOs: Energy Service Companies

ETSAP: Energy Technology System Analysis Programme

EU: European Union

EV: Electric Vehicles

GAMS: General Algebraic Modelling System

GSHP: Ground Source Heat pump

HOMER: Hybrid Optimization Model for Electric Renewables

HP: Heat Pump

HPNET: Hydro Empowerment Network

ICESs: Integrated Community Energy Systems

ICTs: Information and Communication Technologies

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

JCR: Journal Citation Report

kW: Kilowatt

kWe: Kilowatt Electric

kWh: Kilowatt Hours

MARKAL: MARKet ALlocation

MV- Medium Voltage

MWh: Megawatt Hours

NREL: National Renewable Energy Laboratory

O&M: Operation and Maintenance

PCGs: Prosumer Community Groups

PV: Photovoltaics

PX: Power Exchange

RAM: Random Access Memory

RESCOOPs: European Federation of Renewable Energy Co-operatives

REV: Reforming the Energy Vision, New York

SDE: Sustainable Energy surcharges

SUNTool: Sustainable Urban Neighbourhood Modelling Tool

TIMES: The Integrated MARKAL-EFOM System

TTF: Title Transfer Facility

TSOs: Transmission System Operators

UK: United Kingdom

USEF: Universal Smart Energy Framework

VPPs: Virtual Power Plants

WebOpt: Web Optimization Services

ZNEB: Zero Net Energy Balance

List of publications

Peer-reviewed journal articles

Koirala, B. P.; Koliou, E.; Friege, J.; Hakvoort, R. A.; Herder, P. M. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renew. Sustain. Energy Rev.* 2016, *56*, 722–744

Koirala B, Chaves Ávila J P, Gómez T, Hakvoort R, Herder P. Local Alternative for Energy Supply: Performance Assessment of Integrated Community Energy Systems. Energies 2016;9:981

Eid C, Bollinger LA, **Koirala B**, Scholten D, Facchinetti E, Lilliestam J. Market integration of local energy systems: Is local energy management compatible with European regulation for retail competition? Energy 2016;114:913–22.

Under review

Koirala, B. P.; Araghi, Y.; Kroesen, M.; Ghorbani, A.; Hakvoort, R. A.; Herder P. Willingness to participate in integrated community energy systems, Energy Research and Social science, 2017

Book chapter

Koirala, B. P.; Hakvoort, R. A. Integrated community-based energy systems: Aligning technology, incentives and regulations, *Innovation & disruption at the Grid's Edge*, edited by Fereidoon Sioshansi, Academic Press, 2017, 363-387

Conference proceedings

Koirala, B. P.; Chaves-Ávila, J. P.; Hakvoort, R. A.; Gomez, T. Assessment of integrated community energy systems. *International Conference on European Energy Markets.* 2016, Porto, Portugal.

Binod Prasad Koirala, Dipti Vaghela, Mitavachan Hiremath, Raveen Kulenthran: Opportunities and Challenges of Community Energy Systems: Analysis of Community Micro-Hydro Systems in South and South-East Asia (SSEA). MES - BREG 2014: Innovating Energy Access for Remote Areas: Discovering Untapped Resources, University of California, Berkeley; 04/2014

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Mavrokapnidou M.; **Koirala B.P.**; Hakvoort R.A.; Herder P. Interplay between storage and flexibility in the power system, International energy storage conference, 2015, Dusseldorf, Germany

Curriculum vitae

Binod Prasad Koirala was born on 30 October 1985 in Kavre, Nepal where he also received his basic education. In 2005, he was awarded Nepal Aid Fund Scholarship by the government of India. He obtained Bachelor of Technology in Electrical Engineering from Malaviya National Institute of Technology Jaipur, India in 2009. With the scholarship from Rosa Luxembourg Foundation, he finished Master of Science in Renewable Energy Management from University of Freiburg in 2011.

Binod has worked at reputed organizations such as Indian Institute of Technology, Kanpur (2007), Institute for Solar Energy Technology, Kassel (2008), Fraunhofer Institute for Wind and Energy Systems, Kassel (2009) and Fraunhofer Institute of solar energy systems in Freiburg, Germany (2009 – 2013).

Since September 2013, Binod is an Erasmus Mundus Joint Doctorate candidate in sustainable energy technologies and strategies(SETS) at Faculty of Technology, Policy and Management at TU Delft. As a part of the SETS program, he spent a year in Institute for Research in Technology, Comillas Pontifical University, Madrid. During the SETS PhD research, Binod has published four journal papers, one book chapters, several international conference papers, as well as collaborated with other researchers and supervised several master thesis projects.

Since June 2017, Binod is a postdoctoral researcher at University of Twente. His current research interests include energy systems integration, community energy systems and universal energy access.

Appendix: Published papers

Renewable and Sustainable Energy Reviews 56 (2016) 722–744

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems

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ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form
26 November 2015
Accepted 30 November 2015
Available online 18 December 2015

Keywords:
Distributed energy resources
Local energy systems
Energy systems integration
Self-organized energy communities
Smart grids
Flexibility

ABSTRACT

Energy systems across the globe are going through a radical transformation as a result of technological and institutional changes, depletion of fossil fuel resources, and climate change. At the local level, increasing distributed energy resources requires that the centralized energy systems be re-organized. In this paper, the concept of Integrated community energy systems (ICESs) is presented as a modern development to re-organize local energy systems to integrate distributed energy resources and engage local communities. Local energy systems such as ICESs not only ensure self-provision of energy but also provide essential system services to the larger energy system. In this regard, a comparison of different energy system integration option is provided. We review the current energy trends and the associated technological, socio-economic, environmental and institutional issues shaping the development of ICESs. These systems can be applied to both developed and developing countries, however, their objectives, business models as well as composition differs. ICESs can be accepted by different actors such as local governments, communities, energy suppliers and system operators as an effective means to achieve sustainability and thereby will have significant roles in future energy systems.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.11.080
1364-0321/

1. Introduction

1.1. Background

A recent surge of interest in local communities generating and supplying energy as well as the parallel development in the smart grids has attracted the attention of many in the implementation of local energy systems. Local communities in both developing and developed countries are being transformed by challenging their traditional identity as passive consumers to active prosumers who both consume and produce [1]. Local energy systems can potentially contribute to the overall energy and climate objectives, helping reverse energy consumption and emissions trends worldwide. Several energy and climate policies promote and support these systems to reach energy and climate targets (e.g., EU 2030 framework [2], UK community energy strategy [3], U.S. Intended Nationally Determined Contribution (INDC) [4]). Local communities are well-placed to identify local energy needs, take proper initiatives and bring people together to achieve common goals such as the reduction of energy costs, CO_2 emissions and dependence on the national grid. Local energy projects also lead to job creation and economic growth. These initiatives can further the transition to a low-carbon energy system, help build consumer engagement and trust as well as provide valuable flexibility in the market.

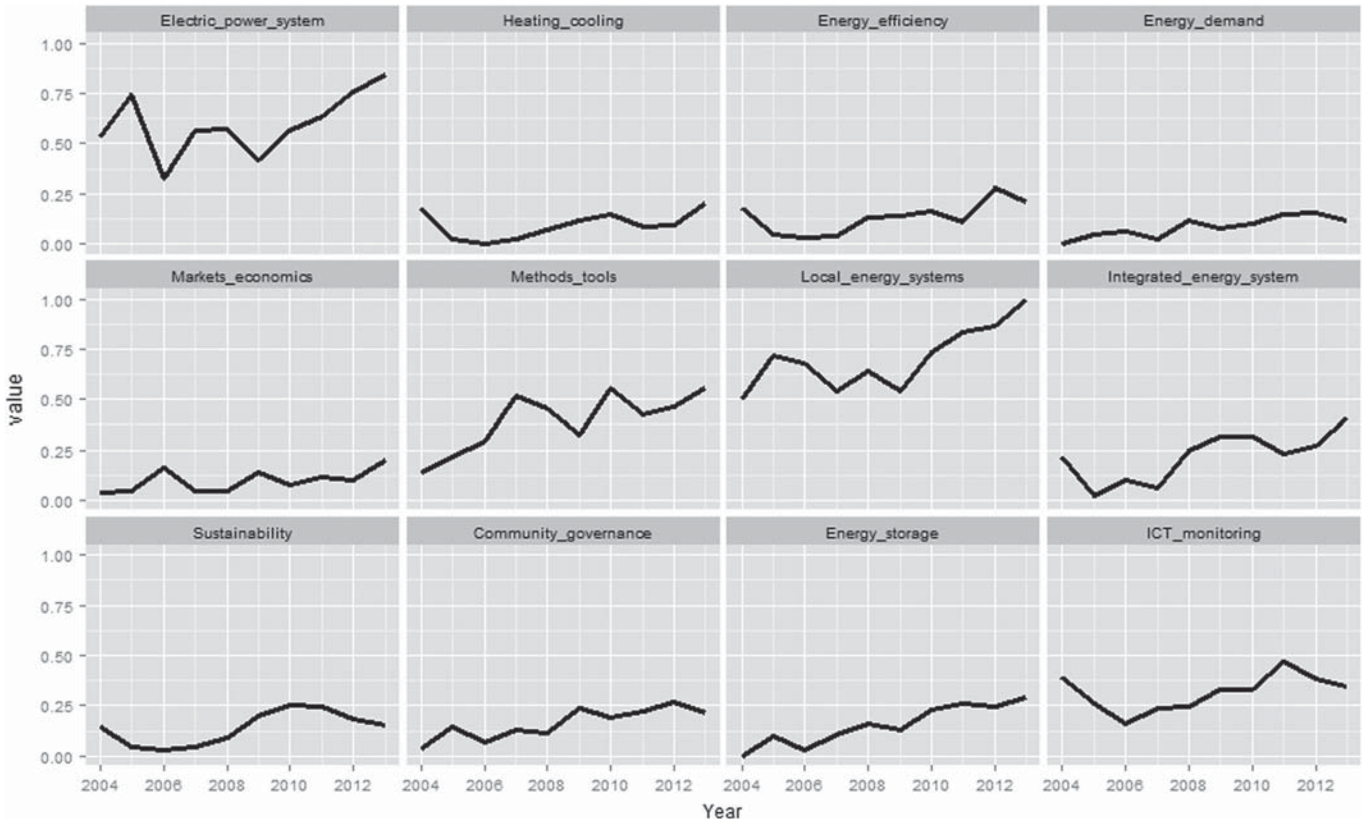

Fig. 1. Research trends in local energy systems.

Although centralized energy systems are economically attractive, local energy systems are important for self-sufficiency and sustainability. Research on such systems has increased significantly in recent years [5–9]. These studies often focus on individual technologies and issues related to implementation but often lack a comprehensive and integrated approach for local energy systems. Specifically, assessment and evaluation is lacking on the role households and communities play in the existing system architecture and the resulting impact they might have in a smart grid. Numerous technologies, actors, institutions available as well as market mechanisms further complicate the implementation of integrated local energy systems. Such complexity demands new instruments and institutional arrangements to optimally integrate generation and demand at a local level. Various approaches are available for energy system integration such as Micro-grids [10], Integrated Energy Systems [11], Virtual Power Plants [11,12], Energy Hubs [13] and Prosumer Community Groups [14]. These approaches, however, are designed to adapt to an existing blueprint of a centralized energy system. A more bottom–up solution which can capture all the benefits of distributed energy resources and increase the global welfare is still lacking. A comprehensive and integrated approach for local energy systems where communities can take complete control of their energy system and capture all the benefits of different integration options is needed.

Integrated community energy systems (ICESs) are a modern development for dealing with a changing local energy landscape. ICESs represent locally and collectively organized energy systems and combine the concept of sustainable energy communities [15], community energy systems [8], community micro-grids [16], and peer-to-peer energy [17]. ICESs are capable of effectively integrating energy systems through a variety of local generation of heat and electricity, flexible demand as well as energy storage. Cross-sector integration at the local level helps in the efficient use of available energy. Integrating smart-grid technologies and demand side management facilitate an increase in reliability and efficiency of such local energy systems.

The main purpose of ICESs is to fulfill the energy requirements of local communities through better synergies among different energy carriers. ICESs aim not only at the self-provision for the local communities but also provide system services to neighboring systems such as balancing and ancillary services. Therefore, ICESs differ from other forms of energy system integration as a result of an integrated approach.

1.2. Research framework

1.2.1. Research trends

The main research trends in local energy system are identified through a keyword analysis in Scopus[1] for 2004 to 2013 [18]. Search terms ‘Community Energy Systems OR local energy systems’ and ‘community energy AND Institutions’ were used to cover technical as well as institutional dimensions, yielding a total of 1285 publications for analysis.

The keywords from each article are ranked by occurrence with a script used in Friege et al. [19]. After this, similar keywords are clustered into 12 main themes (see Fig. 1). Normalized values are obtained for each theme by dividing the total number of keywords for each year by the total publications in that year. The resulting value is further divided by the maximum to get a normalized value. All identified themes have increasing research trends while some appear to receive more attention than others.

[1] As the largest abstract and citation database of peer-reviewed literature, Scopus delivers a comprehensive overview of research output in various fields along with features for analysis and visualization.

1.2.2. Analytical framework

ICESs are conceptualized as multi-source multi-product, complex socio-technical systems consisting of different decision making entities and technological artefacts governed by energy policy in a multi-level institutional space [20]. ICESs have a strong degree of complementarity that is enabled via physical and social network relationships [20]. ICESs encompass a combination of technical elements, characteristics and active links. Such characteristics consists of a pattern of social practices and thinking referred to as 'institutions' [21]. Current energy systems are highly institutionalized, however, these institutions did not develop with the focus on ICESs. Yet, current trends in the energy system affect these institutions. Therefore, ICESs as well as other forms of local energy systems are shaped by new trends in the energy landscape. Transformational energy systems such as ICESs are also influenced by technological, socio-economic, environmental and institutional issues and interactions (see Fig. 2) [22]. As a result, these trends and issues influence the emergence of ICESs. In the changing local energy landscape these issues and trends are considered accordingly for a comprehensive assessment of ICESs.

1.2.3. Research approach

This research assumes that ICESs are shaped by current trends and issues in the energy system. First, the trends in the current energy landscape are reviewed, followed by an elaboration on different energy system integration options. ICESs are conceptualized as a comprehensive approach towards integrated energy systems together with engagement of the local communities. Different technologies, actors, characteristics, categories as well as drivers and barriers of ICES are reviewed. Technological, socio-economic, environmental and institutional issues related to the implementation of ICESs are highlighted. A business model canvas for ICESs is also presented. Finally, the application of ICESs in developed, and developing economies are highlighted with case examples.

1.3. Research structure

This paper presents a review of keys issues and trends in the energy landscape which are shaping the development of ICESs. The work begins with an analysis of current trends, followed by a review of energy system integration options in Section 3, which bring the focus to ICES. Specifically, the local level emphasis is elaborated in detail in Section 4, which conceptualizes ICESs, presenting the technologies as well as actors involved. Section 5 examines the key technological, socio-economic, environmental and institutional issues affecting the implementation of ICESs. In Section 6, a business model canvas as well as sample cases of ICES application are presented.

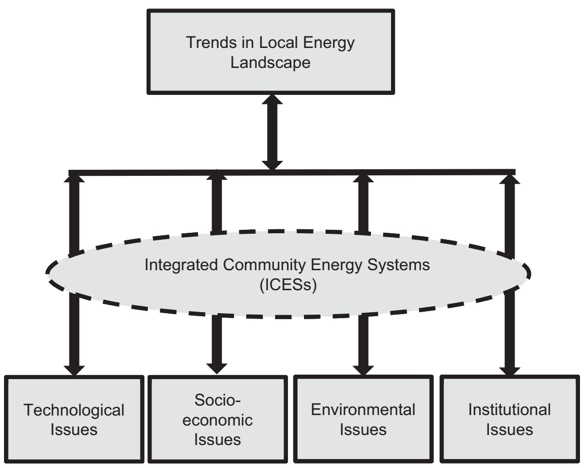

Fig. 2. Analytical framework considering issues and trends in changing local energy landscape.

2. Trends shaping the energy landscape

Restructuring and liberalization of the energy sector both in developed and developing countries is facilitating the energy transition [23]. The energy landscape is transforming towards decentralized low-carbon energy systems. Such developments are engaging a multitude of actors to deliver new and innovative solutions. Utilities are adapting their business models and new energy services are emerging. In this context, new roles for local communities are emerging, transitioning them from passive consumers to active prosumers with local generation, demand response and energy efficiency measures. Demand response refers to programs which provide incentives for consumers to modify their consumption patterns [24,25]. The shift towards renewable-based production for energy consumption and increasing electrification of different sectors requires local generation to be integrated and coordinated.

2.1. Increasing electrification

The world energy demand is expected to increase at the rate of 2.2% per annum between 2012 and 2035; 90% of this growth will occur in the building and industrial sectors [26]. The energy demand growth has been stabilized for OECD countries since 2005, whereas the rest of the world is still experiencing ongoing incremental energy growth. The IEA predicts a continuation of this pattern until 2040 [26].

Evidence indicates that the built environment is responsible for most of the energy consumption and CO_2 emissions worldwide. For example, 70% of energy demand worldwide comes from cities which will increase further with rapid urbanization. In the European Union (EU), the building sector alone is responsible for 40% of total CO_2 emissions [27]. In order to improve overall energy efficiency as well as reduce CO_2 emissions, specific focus on cities and local communities is required.

According to the EU 2050 Roadmap, electricity will have a more predominant role on the final energy consumption by almost doubling its share by 2050 in comparison to 2005 [28]. This is due to the de-carbonization of the transportation and heating as well as cooling sectors. Residential electricity demand is expected to increase significantly with the adoption of electric vehicles and heat pumps [29]. Consequently, increasing electricity demand resulting from electrification may contribute to escalating congestion problems on local grids. Until now, the solution has been grid reinforcement, which is costly and path dependent. Distributed local generation will become more prevalent with the increasing electrification of different sectors.

2.2. Rising distributed energy resources

Distributed Energy Resources (DERs) include distributed generation, storage as well as controllable loads [10]. Distributed generation refers to electric power generation within a distribution network or on the customer side of the meter [30]. More recent definitions of distributed generation include local generation such as electricity and heat [31]. DERs are becoming increasingly common in the local energy landscape and are playing an essential role in the global energy system. Currently, one-quarter of electricity generation worldwide is attributed to distributed generation [32,33].

In smart grid systems, end-users are expected to utilize distributed generation and storage technology in their homes (e.g., TESLA Powerwall [34]) as well as at the community level (e.g., community energy storage [35]). This enables local communities to take energy-related matters into their own hands. Electric storage has also experienced significant cost reductions in the last decade and costs are also expected to further decline in the next decade. Moreover, demand side management can be stimulated as well through price based and incentive-based schemes. This is enabling bidirectional balancing in the power system i.e., both on the supply and demand side.

2.3. Towards a carbon-neutral energy mix

The energy transition from fossil-fuel based centralized energy systems towards renewables-based decentralized energy systems is high on the energy policy agenda for a low-carbon future (e.g., EU 2030 [2], American Recovery and Reinvestment Act of 2009 [36], and Renewable Portfolio Standards [37]). Relatively inflexible conventional power plants such as coal and nuclear are being replaced by more flexible systems that can accommodate a high share of intermittent renewables [38]. Renewable energy systems are being incentivized in the form of grants for research and development, subsidy on initial capital cost as well as through direct renewable generation support schemes. This has increased the share of renewables such as solar and wind in the energy mix of several countries in Europe and elsewhere. For example, the installed solar PV capacity of 38.5 GW in Germany in 2014 exceeded all other types of power plants.

Increasing penetration of intermittent renewables in the energy systems leads to various issues and raises capacity and ancillary service costs [39,40]. Such issues are becoming increasingly common not only on the transmission systems but also on local distribution systems. Moreover, renewable generation at the local level raise new balancing and congestion challenges. This demands flexibility from all the actors in the electricity value chain including customers [39]. In other words, all the market players are expected to be *"balance responsible"*. Balance responsibility refers to the responsibility of connected users at every node on the grid to draw up for them their programs for production, transport and consumption of electricity. Balance responsible parties are expected to act in accordance with these programs which they provide to the system operator; if connected users do not comply with their submitted schedules they face penalties [41]. The need for imbalance management will rise in the future, as it will reflect the real cost of balancing intermittent renewables. Along these lines, there is a rising demand for new flexibility sources such as storage and other innovative measures to balance the rising variability of renewable energy production.

2.4. Changing utility business models

With the rise of distributed generation, individuals and communities have higher control of generation and consumption of energy. For example, more than half of Germany's remarkable RES installation is owned by citizens, whereas the share of the four big incumbents, namely E.ON, RWE, Vattenfall and EnBW, is only 6.5% [42]. The increasing share of RES is affecting the capacity factor and economics of large power plants. This is distorting the business case and incumbents are reporting losses to the tune of millions of euros.

Accordingly, incumbents are also starting to change roles and strategies in energy systems. In September 2013, RWE, Germany's largest power producer, decided to radically depart from its traditional business model based on large-scale thermal power production to become an energy service company [43]. Similarly, E.ON announced at the end of 2014 that it is spinning-off conventional power plants to focus on RES, distribution network and customer solutions [44]. RWE and E.ON are the representative example of undergoing transformation in the energy system.

2.5. Increasing customer engagement

Many local communities have expressed their goal to become self-sufficient and carbon-neutral in energy. For example, in the Netherlands there are more than 500 initiatives for energy neutral, zero-emission or low carbon communities [1]. Several others are engaged in local generation as a business case to sell electricity to the national grid [45]. Similarly, there are more than 900 energy co-operatives in Germany. In either case, decentralized co-ordination is an emerging phenomenon in the local energy landscape.

Household level energy conversion, storage and exchange technologies are expected to permeate future energy infrastructures [46]. The integration of distributed generation, however, is a challenge. If managed properly it brings a lot of opportunities such as local jobs and improves energy efficiency. For this to happen, the traditional system designed to fit centralized energy infrastructure and institutions has to be adapted. This will help to utilize the maximum potential of decentralized energy systems through the use of local resources and wider engagement of local communities. The energy system becomes more flexible and decentralized if different energy sectors such as electricity, heating, cooling and transportation are increasingly integrated at the local level. Such integrated approaches bring energy generation closer to consumers, thereby reducing all the complexity, cost and inefficiencies associated with a centralized energy system [16]. Hence, decentralized co-ordination is required for both engaging customers and integrating sectors.

3. State of the art energy system integration options

The key challenge of future energy systems is the integration of increasing levels of distributed energy resources. Several energy system integration options are designed to meet this challenge such as virtual power plants, energy hubs, community micro-grids, prosumers community groups, community energy systems and integrated community energy systems.

3.1. Energy system integration

These options to energy system integration differ in their objectives. For example, the aim of community micro-grids is to

Table 1
Overview of energy system integration options.

Options	Objective	References
Community micro-grids	Optimize electricity generation and demand for autarky and resiliency in community	[47]
Virtual power plants (VPPs)	Aggregate and manage (operate and dispatch) DERs	[48]
Energy hubs	Multi-carrier optimization of electricity, gas, heat and cooling within a district	[13]
Prosumer Community Groups	Energy exchange among prosumers having similar goals	[14]
Community energy systems	Invest and operate local energy system	[49,50,8,6]
Integrated community energy systems (ICES)	Multi-faceted approach for supplying local communities with its energy requirements through DERs, flexible loads and storage together with different carriers	[16,51,52]

optimize electricity generation and demand for resiliency whereas virtual power plants aim at aggregation and operation of DERs. See Table 1 for a summary of the objectives of each energy system integration option.

3.1.1. Community micro-grids

Community micro-grids comprise of locally controlled clusters of DERs which are seen as single demand or supply from both electrical and market perspectives [53]. Micro-grids can detach from the national grid and operate autonomously when needed. It enables higher penetration of DERs such as solar, wind, combined heat and power, demand response as well as storage. In this way, local resources can be used to supply local demand, thereby reducing losses and increasing the efficiency of the energy delivery systems.

3.1.2. Virtual power plants (VPP)

Consumption and production of various households can be aggregated to form flexibility capacity equivalent to that of a power plant, hence creating a type of virtual energy plant (VPP). According to Morales et al. [48], virtual power plants are “a cluster of dispersed generating units, flexible loads and storage systems that are grouped in order to operate as a single entity”. A VPP can be technical or commercial [12]. A technical VPP has location specificity attached to the flexibility, mainly within a distribution system. Differently, a commercial VPP has no location specificity; flexibility from such a VPP can be distributed and aggregated from different distribution systems. The VPP allows participation of DERs into energy markets as well as system operation support; thereby helping the gradual replacement of centralized power plants.

3.1.3. Energy hubs

An energy hub manages the energy flows in a district through optimal dispatch of multiple energy carrier [13]. It includes storage, conversion and distribution technologies to supply electricity, heat, gas and other fuels to the end users. When the conversion technology is available, energy-carriers can be transformed to other forms.

3.1.4. Prosumer Community Groups (PCG)

According to Rathnayaka et al. [14], “PCG is defined as a network of prosumers having relatively similar energy sharing behavior and interests, which make an effort to pursue a mutual goal and jointly compete in the energy market”. In fact, PCGs are designed to overcome possible inflexibility arising from micro-grids and technical VPP such as complexity to add or remove new members. PCGs virtually interconnect prosumers and may not necessarily be connected technically.

3.1.5. Community energy systems

According to Walker and Simcock [8], “community energy systems refer to electricity and/or heat production on a small, local scale that may be governed by or for local people or otherwise be capable of providing them with direct beneficial outcomes”.

3.1.6. Integrated community energy systems

ICESs capture attributes of all energy system integration option and apply them to a community level energy system. These are modern developments to re-organize local energy systems. Mendes et al. [16] defined ICESs as a multi-faceted approach for supplying a local community with its energy requirement from high-efficiency co-generation or tri-generation as well as from renewable energy technologies coupled with innovative energy storage solutions as well as electric vehicles and demand-side measures. They aid in increasing self-consumption and matching supply and demand at the local level. ICESs are further elaborated in detail in Section 4.

3.2. Energy services

According to Perez-Arriaga et al. [54], energy services refer to “activities or products with commercial value that are procured directly for, or on behalf of electricity consumers.” Some of these services are internal whereas others are system services. For electricity, these services can be further categorized into energy-related services, operating reserve and network related services (see Fig. 3). Energy-related services include the provision of electrical energy. In addition, secondary services such as medium and long term contracts, power exchanges can be derived from these primary services. Operating reserves service consist of primary, secondary and tertiary reserve as well as firm capacity to ensure reliability of the system. Network related services include network connection, voltage control, congestion management and energy loss reduction. For more detailed elaboration on electrical energy services, see Perez-Arriaga et al. [54]. These services differ slightly for other energy carriers such as heat and gas, and should be defined accordingly. Moreover, when multiple carriers are involved additional services emerge. For example, over-production from DERs can be balanced in heating or power to gas conversion.

3.3. Comparative analysis

Value generation and degree of integration is analytically plotted for different energy system integration options (see Fig. 4). Value generation refers to the value for other energy system. It can be through collaboration and services to external systems such as other communities or larger energy system. Degree of integration refers to internal values such as self-provision and self-sufficiency. As ICESs and community micro-grids provide both energy-related services, operating reserves and network services through physical interconnection, they rank high in terms of both value generation and degree of integration. ICESs are expected to rank slightly better than community micro-grids due to superior community engagement.

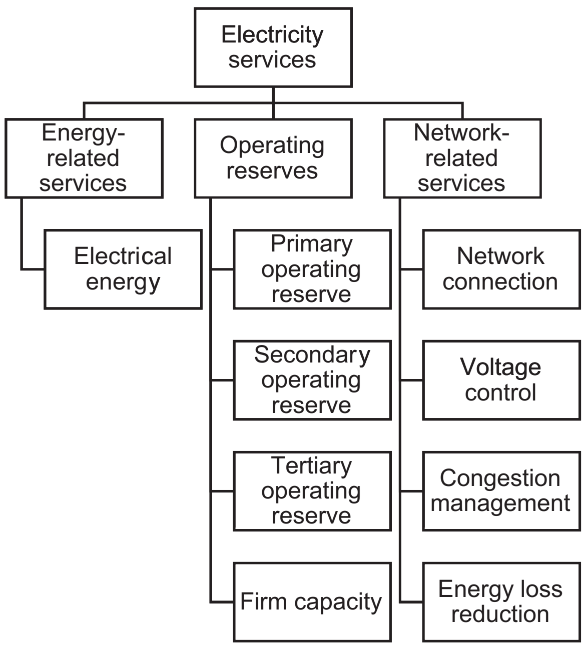

Fig. 3. Electricity services.

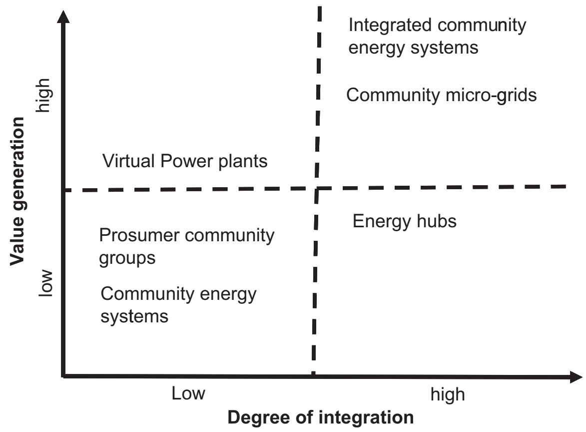

Fig. 4. Interplay between value generation and degree of integration in different energy system integration options.

Despite many benefits and being frequently mentioned in energy policy documentation [3], local energy systems integration options such as ICESs, however, have not gained enough momentum in Europe and elsewhere. This can be attributed to missing active engagement from local communities as well as existing regulatory barriers. This paper further analyzes the justification behind such a hindrance by plunging into the complexity associated with such systems, accordingly investigating main energy trends and key issues in the implementation of ICESs. Specifically, the work focuses on conceptualizing these multi-faceted smart energy systems which optimize the use of all local distributed energy resources.

4. Conceptualizing integrated community energy system (ICES)

Currently, local communities are supplied by a centralized energy system. This top–down architecture is due to the presence of economies of scale, possibilities to ship conventional fuels such as coal and gas to a desired location etc. However, technological and economic progress has shifting the energy production and consumption towards a smart grid paradigm that is increasingly concerned with climate change mitigation. We are at the crossroads of redesigning our energy systems to integrate distributed energy resources. The energy system is transforming to a combination of top–down and bottom–up systems, being incentivized by the vulnerability and insecurities associated with centralized energy infrastructure, depletion of fossil fuels and climate change [23]. This enables communities to control generation and demand, leading to social innovation in management of energy systems.

As a result of the monotonous focus on big power plants for scale economies in the last century and recent attention on individual households, thus far local energy systems have remained in the shadows [3]. Thanks to technological advancement and socio-political acknowledgment, the potential of communities is now at the forefront of exploration with a key role in transitioning energy systems [3]. However, if a large number of households install intermittent renewables and other local generation and storage technologies, it can have adverse effects on distribution grids. These local grid issues can be solved either via network reinforcement or by encouraging smart local energy management via ICESs. Moreover, with the advents of smart grids and rising climate change concern as well as decreasing cost of distributed generation technologies, collective energy systems are receiving renewed attention. There is widespread consensus that, if the energy system as we know it has the desire to become sustainable, different energy sectors have to be integrated and, local communities engaged.

Schweizer-Ries [15] introduce the concept of sustainable communities and energy sustainable communities. Sustainable communities are communities which promote or seek to promote sustainability. However, the term “sustainable communities” is very broad and refers to all aspects of resource use and emissions reduction. Differently, energy sustainable communities are communities that use renewable energy and energy efficiency measures. On this basis, we consider ICESs as an advanced form of energy sustainable communities. Chicco and Mancarella [31], using a comprehensive distributed multi-generation framework, argue that the adoption of composite multi-generation systems through coupling of combined heat and power units with absorptions/electric chillers, heat pumps and fuel cells, can lead to higher energy efficiency, lower CO_2 emissions and enhance profitability.

We present an integrated community energy system (ICES) as a comprehensive approach for a paradigm shift in the energy sector. This approach aims at shifting the current rigid and centralized energy systems towards ones that are more flexible and decentralized. Integrated operation of distributed energy sources from the local neighborhood can lead to a flexible and robust interconnected energy system with considerable energy security benefits. ICESs are enabled through effective technical and market integration of distributed energy resources, providing a necessary platform for community engagement. The following sections focus on identifying technologies, characteristics as well as actors bringing to fruition ICESs.

4.1. *Defining ICESs*

Several definitions of ICES exist in the literature [16,51,52,55]. The initial conceptualization of ICESs is attributed to Buck [52], where a feasibility analysis of co-generation, heat and cold storage is performed for meeting the energy needs of Georgetown University in 1980, inclusive of an institutional assessment for governing interaction. Mendes et al. [16] define ICESs as a multi-faceted approach for supplying a local community with its energy requirements from high-efficiency co-generation or tri-generation as well as from renewable energy technologies coupled with innovative energy storage solutions as well as electric vehicles and demand-side management measures. According to Harcourt et al. [55], ICESs also exemplify planning, design, implementation and governance of energy systems at the community level to maximize energy performance while cutting costs and reducing environmental impact. Therefore, ICESs involve the assessment of existing energy infrastructure and available resources in a community. This helps to find innovative solutions for local generation, load shifting, local balancing, collective purchasing and energy conservation methods. In this sense, ICESs focus on the complementary role of energy and is capable of embracing technical and social innovation in the energy system integration as they become available, see Fig. 5.

The local community is a fundamental component of ICES with varying notions [7,9,15,56,49]. For ICESs, communities can range from a block of households in a street all the way to an entire district. Furthermore, community composition differs a lot between developed and developing countries as well as between urban and rural areas. Nevertheless, a local community is the sense of place, identity, localism and shared values. Wirth [9] provides a neo-institutional definition of a community as a local geographic entity from which cultural-cognitive, normative and regulative forces originate. Walker [49] distinguishes between communities of locality and communities of interest. In this work, the focus is on the former since it provides not only economic and

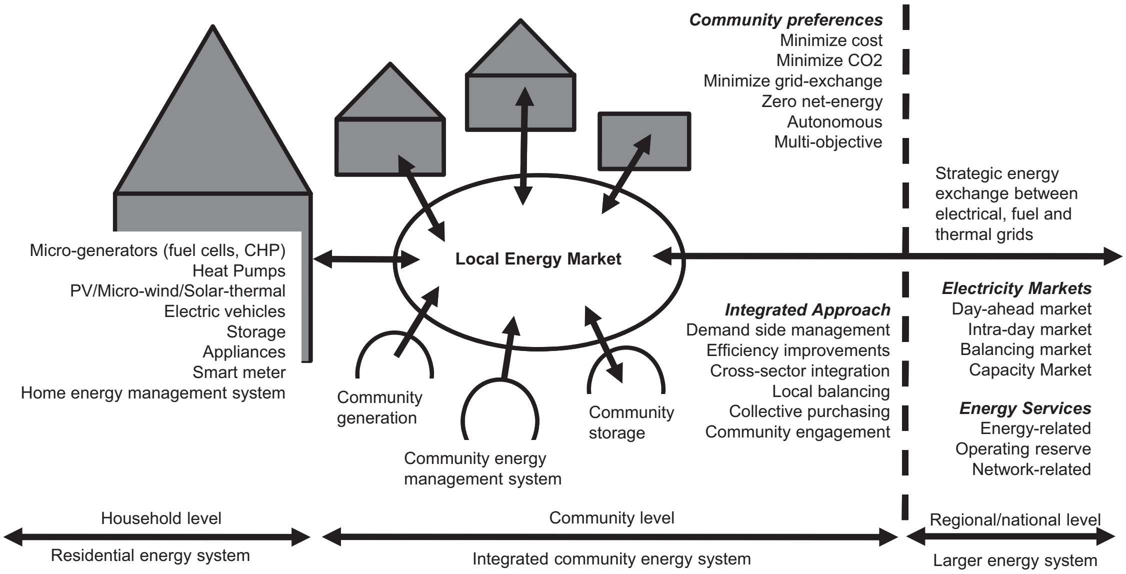

Fig. 5. Functions of an integrated community energy system in the larger system.

environmental benefits, but also a range of technical and institutional values to the local communities. Prior to delving into details of ICESs, below we discuss essential attributes to consider in such evolving systems.

4.2. Attributes of ICESs

4.2.1. Location (specificity)

ICESs on the one hand, have defined system boundaries as units of the whole energy system (see Fig. 4), integrating DERs at different scales. The advantage of extending to multiple buildings lies in the variation of demand profiles and availability of multiple generation and consumption sources, in this way increasing the flexibility of the system and overall extracted value. When consumers co-operate, more energy options become feasible at a community level due to economies of scale and local balancing. On the other hand, we do not define strict boundaries as they are up to the community wishing to integrate to make that decision according to evolving needs. Typically, a cluster of households within a distribution transformer are part of ICESs. It may even be the case that all connected users, commercial and residential alike, are part of the flexible community.

Generally, integrated energy systems can be realized at the local level by combining rooftop photovoltaics, small wind turbines, district heating, and community energy storage or biogas and hydrogen production systems. An integrated energy system can also be pursued when for example waste heat from nearby industrial plants are utilized [57–59]. ICESs promote local balancing as well as strategic exchange with electrical, fuel and thermal grid (see Fig. 5). In this way, ICESs will always have interaction and therefore coordination with the other ICESs or larger energy system no matter how remote and seemingly isolated their location may be. Although ICESs will be self-sustaining as much as possible in order to meet the energy needs of the consumers in the community, they will nonetheless need access to both power and fuel from the larger systems. When connected to the larger electricity system they may receive power at times when local generation is not enough to meet the supply. Moreover, fuel (except biogas) is difficult to produce and access at a local level, therefore interaction with the larger system is unavoidable.

There are some undeniable differences in the process when considering developed and developing countries. In developed countries, the application of ICESs have increased as a result of climate change, energy autonomy motives as well as economic reasons inclusive of subsidies for local energy sources. Differently, in developing countries the main purpose is simply the provision of energy access. Moreover, the number and type of energy carriers also differ among developed and developing countries. In developed countries, electricity, gas and heat networks have existed for decades whereas in developing countries the grids are mostly electricity-only. In this section, we elaborate ICES development in both developed and developing countries. Examples for each case are presented in Section 6.

ICESs have common practice and exchange with the larger system, but implementation, utilization and value will differ when considering urban and rural locations. Note, differences intensify depending on the implementation in urban and rural locations of developed versus developing countries. Below follows a short discussion on this differentiation between these communities and what the integrated systems entail.

4.2.1.1. Developed countries. Among developed economies, Canada, UK, Germany, and Denmark are already implementing concepts of ICESs. These developed countries especially in Europe have recently witnessed a new wave of development of local energy systems in the form of energy co-operatives [60]. Canada has developed a roadmap to benefit most of its communities from integrated community energy solutions by the year 2050 [61].

Initiatives for ICESs are emerging across Europe but with varying numbers, success rates and strategies [45]. The diversity in success of these community initiatives have been attributed to prevailing structural, strategic and biophysical conditions. Electricity market reforms together with favorable energy policy, such as feed-in tariffs in Germany have stimulated local initiatives promoting the production of clean energy by using local energy sources [45]. Over half of Germany's remarkable renewable energy portfolio is owned by citizens and farmers. There are more than 900 energy co-operatives operational in Germany. In the UK, there are already more than 5000 groups working to transform the way communities use energy [3]. According to the UK community energy strategy [3], these groups are organized in a wide variety of forms and sizes from collective switching schemes, generating local energy through community wind and solar farms to neighborhoods, joining forces to insulate their homes. Furthermore, it is estimated that such schemes involving local communities could supply enough electricity for 1 million households in the UK by 2020.

4.2.1.2. Developing countries. In developing countries, the main objective of ICESs is to provide affordable energy access to rural communities. For example, community micro-hydro plants in South and South East Asia are successful in providing energy to rural communities [62]. These community hydro systems are small decentralized energy systems based on locally available hydro resources and are established through joint effort of multiple-stakeholders with significant participation of local communities. Communities are involved from the start of the project conceptualization all the way to final operation. Higher coordination among local communities, social actors, governments, project developers, donor organizations, financial institutions and other stakeholders have yielded significant impacts in success of community energy systems development as observed in community micro-hydro solutions in countries such as Nepal and Afghanistan [81]. Community micro-hydro in Afghanistan (48 MW), Nepal (22 MW), Sri-Lanka (2 MW) and Indonesia (21 MW) are already providing an array of basic energy needs to thousands of households. Community energy systems are well integrated in local communities and contribute to the integral development of rural socio-economics. The tremendous opportunities associated with community energy systems for providing rural communities in developing countries with energy access should be further exploited; challenges can be solved with coordinated efforts.

4.2.1.3. Urban areas. Urban areas consist of towns and cities with dense population and limited space. Density entails close interactions and an emphasis on high living standards. Lund et al. [64] point out that smart energy system design in both developed and developing countries could aid in making locally produced renewables a mainstream part of cities' emissions mitigation strategies. For instance, the incorporation of local electrical storage can aid in increasing power share by 40–60% in Delhi and 25–30% in Helsinki [64]. ICESs can play important role in transforming urban energy systems.

4.2.1.4. Rural areas. Rural areas mainly consist of villages and even smaller areas with population that is dispersed and with ample space. In developed countries such as the EU rural electricity access is not a main issue because of European legislation mandating Third Party Access; an obligation for network companies (electricity and gas) to connect networks to third parties with available capacity for production and consumption. For Europe, the rural areas can connect their flexibility to the larger system or can consume it locally. Unfortunately, this is not the case for developing countries; rural access to energy brings about many challenges and even more benefits when reliable energy access is achieved. With more than one billion populations without energy access, ICESs has tremendous potential for provision of energy access.

4.2.2. Criteria for assessment

In assessing ICESs it is important to keep in mind that for community integration there needs to be an existing system in place, rarely (unless in rural areas of developing countries) will we be working with a 'green field' where an ideal system is designed bottom up. More often it is the evolution of existing energy systems that creates a path dependence which inhibits innovation. Hence, the authors propose the following assessment criteria for an energy system to qualify as an ICES; locality, modularity, flexibility, intelligence, synergy, customer engagement and efficiency.

*Locality**:** the system should have a larger proportion of local investment and ownership. It should be operated locally. Local generation should be used for self-provision through local energy exchange.*
*Modularity**:** the system should be able to cope with entry and exit of its members. Household and community level technologies could be added later to adapt with rising demand.*
*Flexibility**:** one of the important criteria for ICES is flexibility, which can be achieved through local demand response, local balancing, flexible load and supply. This flexibility can be utilized to provide energy and system services.*
*Intelligence**:** for the co-ordination of energy and information flow to match supply and demand locally, ICESs should be intelligent.*
Synergy: the system should allow synergies between different sectors such as electricity, heat and transport as well as between different technologies.
Customer engagement: the system should engage customers through different means such as investment, ownership, local energy exchange and economic incentives.
Efficiency: the system should be both technically as well as economically efficient.

According to the above criteria, the categorization of ICESs becomes a focal point which we discuss in the following section.

4.2.3. Categories of ICES

ICESs can be categorized in different groups based on their activities, scale, grid connectivity, initiatives, location and topologies as summarized in Table 2. ICESs activities can be categorized into local generation, storage and demand response, collective purchasing as well as energy exchange and trading. Ideal ICESs consist of all these activities, although the communities can also choose single activities. Further distinction can be made between supply side activities such as collective purchasing of solar panels or collective ownership of wind farms and demand side activities such as energy conservation, retrofitting of dwellings or energy awareness raising initiatives [65]. In terms of scale, macro-, meso- and micro-ICESs exist, applicable for city, neighborhood and buildings level respectively. Further distinction can be made based on grid connectivity [7]. ICESs can be initiated either by leadership of citizens or by government and private enterprises [65]. ICESs also differ based on locations such as developed and developing countries or urban and rural areas. Various topologies of ICESs are

Table 2
Categorization of ICESs.

Perspective	Categorization	References
Activities	Local generation, storage and demand response Collective purchasing Energy exchange and trading	[3,65]
Scale	Large/macro: city, region Medium/meso: neighborhood Small/micro: household/buildings	[55,60,66]
Grid Connection	Grid connected Off-grid	[7]
Initiatives	Led by citizens Led by private enterprises Led by government	[65]
Location	Developed countries – urban Developed countries – rural Developing countries – urban Developing countries – rural	Own assessment
Topologies	State of the art integration of DERs Integration through common point of coupling Autonomous	Own assessment

possible such as state of the art integration of DERs, integration through common point of coupling and autonomous systems. The authors emphasize that such systems have to be categorized and analyzed from different lenses and perspectives in order to derive their added value.

4.2.4. Local energy exchange

Local energy exchange is one of the most important attributes of ICES. Fig. 6 illustrates the architecture for such local energy exchange. Households can exchange energy locally through local buying and selling prices. Mechanism should be developed to determine these local energy prices. Local energy exchange allows local money to remain within the local economy; an attribute that becomes increasingly important in developing countries. The grid connection to the larger energy system(s) can also have strategic exchange with different energy markets. For example, the excess energy can be sold to the wholesale market at wholesale prices. The supply to cover residual demand can be purchased at retail prices. In case of autonomous ICES, total demand should be met locally. Suitable institutional arrangements should be designed in such a way that well-defining the commodities and suppliers. Note, local energy exchange with the larger system should always ensure efficiency, fair allocation of costs, right prices for participation and prevent opportunistic behavior. It should also design mechanisms to pay back local investment and share benefits. One such mechanism for local energy exchange is PowerMatcher® concept developed in the Netherlands [110,111]. It utilizes available electricity consuming and producing devices from households to derive system operation that optimally matches supply and demand maximizing individual household benefit [110,111]. For such systems to prevail, appropriate technology integration is crucial.

4.3. Technologies

Smart grid advances provide the basis for ICESs. The technologies to operate decentralized energy networks and markets have improved tremendously as a result of advancements in information and communication technologies [23]. Such technologies are required to manage ICESs, see Table 3. These systems can be characterized by active management of both information and energy flows within the context of distributed generation, storage, consumption and flexible demand [21]. Furthermore, energy management systems such as home energy management systems, building energy management systems, battery management systems and community energy management systems ensure effective control and operation of energy communities.

The architecture of ICESs depends on available technologies and the corresponding political, market and regulatory frameworks as well as technical standards adopted [69]. CHP, heat pumps, community energy storage and electric vehicles are some of the technologies which can already provide a basis for energy system integration at a community level. Recently, more decentralized technologies at affordable prices (e.g. PV, battery storage) have become available, further driving community level engagement [39]. Note, technologies will continuously be used in the future to develop energy independence through integration such as installation of heat pumps for district heating systems in combination with renewable energy systems. At given circumstances, local communities can utilize waste heat from nearby industries in local heating networks. This has been successfully implemented in places such as Sweden, Denmark, Germany and Finland with for decades, bringing about both environmental and monetary benefits [57–59].

Table 3
Technologies in ICESs.

Categories	Technologies	
	Household level	**Community level**
Local generation	Micro-CHP Reciprocating engines Internal combustion engines Fuel cells Heat pumps Pico-hydro Solar PV (rooftop) Solar thermal Micro-wind	Community CHP Reciprocating engines Internal combustion engines Fuel cells Heat pumps Biomass Geothermal Micro-hydro Community PV Solar thermal Community wind
Demand side flexibility	Flexible appliances (e.g. dishwasher, washing machine) Electric vehicles Electric and heat storage Battery energy management system (BEMS) Home/building energy management system (HEMS)	Community electric and heat storage Community BEMS Community energy management system (CEMS)

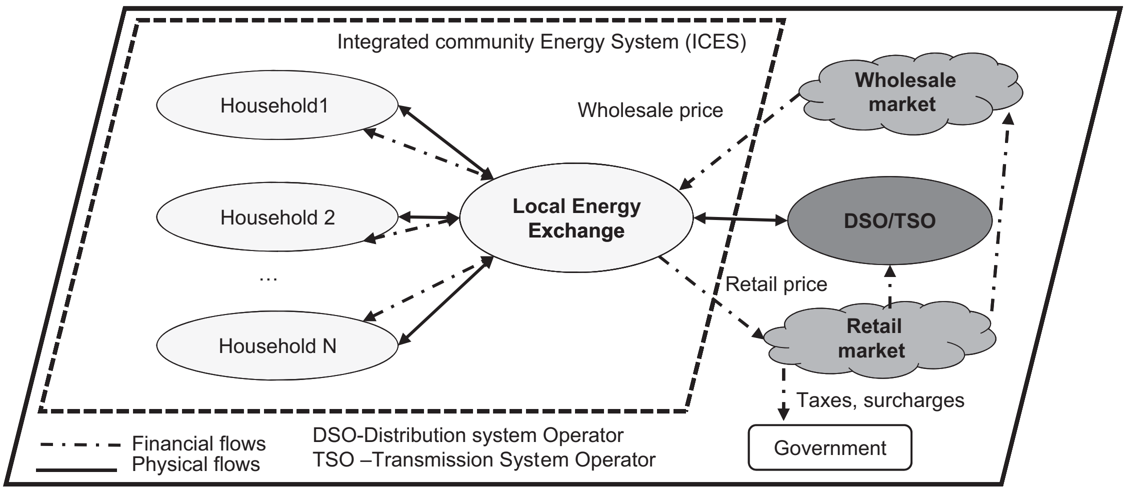

Fig. 6. Local energy exchange in ICES.

4.3.1. Local generation

The local generation can be further categorized into intermittent and flexible generation. Renewable generation such as solar and wind are intermittent [70]. Spatial and temporal variation of solar irradiance and wind speed makes the forecasting of such generation a challenge. Although in recent years there has been a significant improvement in prediction and forecasting [71], nevertheless output still remains stochastic at times. As a result it is difficult to have a system that solely depends on such production sources. Hence, ICESs consider multi-source and multi-fuel options for 'keeping the lights on'.

Fluctuations in supply as well as demand can be absorbed through flexible generation, providing the ideal basis for local balancing. Most flexible generation technologies to date use conventional fuels. Flexible renewable technologies such as hydropower and geothermal are also becoming increasingly common. ICESs help these technologies to minimize emissions and maintain the system integrity. Balancing heating or cooling demand requires an integrated approach for cost and performance. For example, ground source heat pump systems are renewable and highly efficient technologies with high energy and environmental performance. They are being widely used for covering cooling and heating demand of well-insulated buildings with low supply temperatures. Research and application of ground source heat pump integration with different cooling and heating technologies pose several challenges inclusive of climate conditions, building functionality, ground thermal balance and thermodynamics [72–74].

Thanks to high efficiency, zero or low emissions, and modular structure, fuel cells have proven merits as a flexible generation technology [75,76]. Fuel cell performance is continuously improving in terms of reliability and cost. For instance, Sulfur-oxide fuel cells can already provide very high efficiencies (close to 70% for electricity generation with possibility for heat recovery) in the context of combined heat and power applications [76,77].

4.3.2. Demand side flexibility

Effective integration of end users can be achieved through the adoption of home energy management systems and community energy management systems. Demand and supply side management system allow for effective integration of supply and demand at the local level. Electric vehicles, storage and flexible appliances can be programmed to match the local generation profiles. The availability of flexible demand varies significantly on a diurnal and seasonal basis [78]. The importance of flexible demand increases with higher fraction of non-dispatchable generation in future energy mix.

A wide range of state of the art studies have focused on demand side management [25,79,67]. On the one hand ageing assets, increasing penetration of renewables and other low-carbon generation technologies as well as advancing information and communication technologies are major drivers for wider applications of demand side management. On the other hand, several factors inhibit the widespread adoption: lack of metering as well as information and communication infrastructures; lacking insight into the potential benefits; inapt market incentives, increased complexity in system operations; and distorted competition. Furthermore, application of demand side load modification might disturb natural diversity of loads and create some undesirable and maybe even perverse effects.

4.4. Actors and their interests in integrated systems at the local level

Delivering energy to end users requires multiple processes both competitive and regulated for the procurement, production, conversion, and transformation of energy [68]. Actors in the energy sector are inter-dependent in the realization of their goals. Different actors of ICESs have varied interests from ICESs. For instance, households want low cost hassle free energy at their disposal while aggregators seek to maximize the value of flexibility in the various markets and policymakers want to ensure sustainable energy supply in the transition to low-carbon energy systems. Table 4 provides a detailed summary of the actors' interests, categorizing them into private and system interests. Note, interests can also change and evolve over time; as new developments take place, new technologies become available or new market mechanisms get established. Below follows a discussion of the critical facets that make up ICESs as discussed in this work.

5. Key issues with implementation and adaptation

ICESs are confronted with technological, socio-economic, environmental and institutional issues during implementation and adaptation [22]. Most of these issues act as driving forces to

Table 4
Interest of different actors in ICES.

	Actors	Interests Private interests	System interests
Competitive parties	*Households*	Use of local, affordable and clean energy at a low cost	Sale surplus and purchase deficit energy
	Communities	Reduction in energy related costs, provision of local energy	Emission reductions, energy independence, energy supply security, resiliency
	Energy producers	Investment in local energy system (profit maximization)	Sale local generation
	Energy suppliers	Profit from deficit energy supply, portfolio optimization	Increase renewables in their portfolios, new roles and business models
	Energy service companies (ESCOs)	Profit from energy efficiency, operation and management of local generation	Role in energy efficiency improvement activities as well as operation and management of local generation
	Technology providers	Sell technologies to transform the existing energy landscape both production and consumption (e.g. circular economy)	Promotion of local generation as well as demand side management technologies
	Aggregators	Business model for generating profit, Maximize the value of flexibility in the markets (both with capacity and energy)	Role in making system more efficient
	Balance responsible parties	Portfolio optimization, balance energy procurement at lowest cost,	Provision of accurate scheduling to the system operator
Regulated parties	*Transmission system operators (TSOs)*	Maintain larger system balance of supply and demand at lowest cost to the consumers	Maintain larger system balance of supply and demand
	Distribution systems operators (DSOs)	Distribute energy to the neighborhood with safe, reliable and affordable grid,	Avoid grid congestion, defer network investments, self-balancing energy islands in smart grids
	Government, policy makers and regulators	ensure competition for affordable energy for end-users	Sustainable energy supply, transition to low-carbon energy system, energy security

encourage such systems emerge on the premise of sustainability. Moreover, ICESs aim at maintaining energy security or striving for energy independence, tackling climate change and keeping the prices affordable.

Although ICESs are often portrayed as neutral and inherently positive solutions, there are different barriers in the process of transition. The biggest barriers of ICESs are institutions favoring centralized energy systems [23]. Government agencies, private companies and utilities are often at the top of this list. According to Swider et al. [63], the main factors affecting the deployment of DERs are site conditions, grid connection issues, generation costs, feed-in tariffs and support schemes as well as the allocation of the costs. Furthermore, scarcity of public and/or private space needed to install the power generating units as well as the temporal availability of the resources present challenges for ICESs [79].

ICESs, on the one hand can even face resistance from local communities if they do not align with local interests. For example, the issues of coordination and split-incentives can arise when costs and benefit of ICESs do not boil down to the same actor. Coordination requires transparency in the interactions between market parties in order to ensure mitigation of unfair cost-benefit allocation [80]. On the other hand, the local communities should also be very pro-active to take control of their energy system. The drivers and barriers of ICESs will however continuously change on account of technological and institutional changes, fuel costs, economics of technologies, and incentives. In this section, we elaborate on technological, socio-economic, environmental and institutional issues in detail, see Table 5.

Table 5
Key issues related to integrated community energy systems (ICESs).

Technological issues	Socio-economic issues	Environmental issues	Institutional issues
1. Intermittency of local RES generation and demand response 2. Energy efficiency 3. Storage 4. Local balancing of supply and demand 5. Localflexibility and impact on larger energy system 6. Load and grid defection	1. Paradigm shift through community engagement 2. Economic incentives 3. Willingness to pay 4. Split-incentive problem 5. Energy poverty 6. Energy autonomy and security of supply 7. Initial costs and financing	1. Environment and climate change 2. Emission 3. Waste 4. Spatial	1. Trust, motivation, and continuity 2. Energy democracy 3. Ownership 4. Locality 5. Support schemes and targets 6. (self-) governance 7. Regulatory 8. Institutional design 9. Roles and responsibilities

5.1. Technological issues

Technology progress is essential to linking local energy services and making them accessible and affordable. At the same time, technologies should ensure environmental compatibility by continuously shaping and adapting ICESs to the local circumstances. Technology choices are often linked to laws and regulations that reflect community capabilities, social preferences and cultural backgrounds [68]. Accordingly, ICES implementation differs among communities. At the same time, technological innovations help reduce initial costs of the energy system and increase reliability, enabling citizens and communities to adopt ICESs. Walker [49] argues that ICESs may, however, be inhibited by technical obstacles such as lack of equipment, technical knowledge and expertize. Table 6 provide an overview of the different technological issues and what role ICESs can play in their mitigation.

5.1.1. Intermittency of local RES generation and demand response

Some DERs such as local RES generation and demand response are stochastic by nature. The latter is dependent on energy demand which varies with time, weather and consumer behavior which is at times habitual and predictable but most often not. Renewable local generation varies with wind and solar irradiation but also with the choice of use by the owners. For instance, a rooftop solar PV owner may want to transfer excess production to his neighbor and not sell generation back to the grid, which in turn causes further stochasticity. The generation variability is partly due to naturally occurring weather conditions but also the mechanisms in place for exchange, e.g. net metering. Despite the intermittency, the adoption of local generation and demand response mechanisms is continuously increasing. As fluctuations in generation and demand challenge balancing on a local community level, it is up to the transparent mechanisms in place to foster the right environment which will mitigate uncertainty.

5.1.2. Energy efficiency

Although large improvements have been made at the household level with appliances (e.g., energy star in the US [81] and Eco Label in the EU [82]), energy efficiency projects are not yet common practice in local communities. ICESs facilitate communities to take part in energy efficiency improvements programs such as buildings' insulation. Sometimes, community energy efficiency improvements also include co-generation and utilization of waste heat from nearby industries driven by ICESs [60]. They can improve efficiency of local energy systems by combining different sectors such as heat, electricity and transport. Moreover, ICES help to reduce line losses compared to a purely centralized system. Through smart local production and hence consumption, energy efficiency can be increased as well. ICESs are expected to optimize

Table 6
Overview of technological issues.

Issues	Examples	Role of ICESs
Intermittency of local RES generation and demand response	Intermittent generation Fluctuation in demand	Local balancing, storage, activation of flexible generation and demand, aggregation, promote load uniformity throughout the day in order to avoid peaks
Energy efficiency	Poor implementation	Collective purchasing of insulation materials and energy-efficient appliances, provide feedback within community, community economies of scale can bring down costs
Storage	High initial cost Storage duration	Collective purchasing of household storage devices, community energy storage system, peak curtailments, efficient utilization of local generation
Local balancing of supply and demand	Matching supply and demand locally	Demand side management, storage, diversity in demand and supply
Local flexibility and impact on larger energy system	Flexibility within communities Flexibility for regional/ national grid	Provide flexibility for larger energy system (s), local balancing, trade energy with other local communities/ICESs, increase penetration of renewables
Load and grid defection	Decrease of load in general and increase in peak demand at times	Complementary role to larger energy system through local energy system services, local balancing

the energy as well as the exergy (i.e. energy that is available for use) of local energy systems.

5.1.3. Storage

Fluctuating renewables make the case for storage an important part of the future energy mix. Storage of electricity, heat or gas is vital for ICESs as it helps to deal with local demand and supply intermittency in the form of thermal, chemical, mechanical or in intermediate products [79]. Storage type and size differs based on daily, weekly and seasonal demand to store energy. Although short-term electricity storage technologies are available, long-term electric storage technologies are still missing.

Hadjipaschalis [76] presents an overview of current and future energy storage technologies for electric power applications inclusive of flywheel, battery, super-capacitor, hydrogen, pneumatic and pumped-hydro technologies. Among them lead-acid, lithium-ion, nickel–cadmium batteries as well as flywheels are considered most promising. Due to high discharge rate, flywheels are suitable for the provision of only short-term (yet reliable) standby power. Flywheels can be used to smooth out the generation profiles of solar and wind energy within an ICES. Lead-acid batteries are common due to high-energy efficiency, low self-discharge rate, easy installation, low maintenance and low investment cost. The limiting factor for lead-acid batteries is relatively low battery operational lifetime. Although nickel-based batteries perform better in this regard, their costs are very high compared to lead-acid batteries. Lithium-ion batteries are also becoming increasingly important and have several advantages over lead-acid batteries. Although pumped-hydro and compressed air energy storage technologies can store very high power, these technologies are less likely to be incorporated into ICES unless suitable locations are available in local communities. In addition, heat storage technologies facilitate the efficient utilization of renewable energy sources as well as energy conservation [73].

Based on where the storage systems are installed (i.e. household level and community level or a combination of both), it might help ICESs to withstand peaks in demand as well as to achieve power balance. Additionally, storage allows flexible generation to run at rated power, thereby with higher efficiency. Moreover, distribution networks could be operated at full capacity when needed, reducing the need for reinforcement and expansion. Furthermore, Hapaschalis [76] recommends to study the network environment as well as available storage devices specifications before making decisions on storage technology. Accordingly, storage solutions are very tailored and much system specific.

Local energy systems are likely to change with the introduction of plug-in electric, hybrid and vehicle to grid technologies [21]. Rising penetration of electric vehicles will yield higher load as well as storage capacity for ICESs. Electric vehicle flexibility is expected to bring added benefits such as stability and reliability to the local grid as well as flexible back-up for intermittent renewable energy.

5.1.4. Local balancing of supply and demand

Balancing supply and demand at the household level is inefficient mainly due to the diversity in appliance usage. Most demand is largely uncontrollable and varies during the day and year. One of the strengths of ICESs is local balancing of supply and demand. ICESs, which combine different households at the community level, can have significant value if the demand has to be met locally [79]. The ratio between maximum coincident total demand of the system and the sum of maximum demand of individual consumers in the system is defined as coincidence factor [79]. Electric load profiles together with the coincidence factor are used for accurate load forecasting, network planning and scheduling generation capacity.

Local generation technologies such as renewables and combined heat and power continue to expand in our energy systems and facilitate local balancing. However, with new and heavier loads such as heat pumps and electric vehicles as well as distributed generation and home energy management systems, the future electricity consumption patterns of residential consumers will change [83]. Citizens engaged in ICESs are expected to take an active role in demand response activities as well. The role of local energy systems in demand-side management has been investigated in Ward and Phillips [67]. Demand flexibility can enable more renewable integration through localized policies such as load preference [84]. ICESs are expected to positively contribute to demand response and ultimately to local balancing through an integrated approach.

5.1.5. Local flexibility and impact on the larger system

Significant benefits are associated with an increase in the flexibility of local energy systems [38,39]. Technologies and methods employed for increasing ICES flexibility include: co-generation, fuel cell batteries, heat pumps, electric vehicles and community energy storage as well as demand response. Increasing flexibility allows higher penetration of intermittent renewables within local energy systems and opens new possibilities to trade energy with neighboring communities and the national grid. Wide-spread emergence of ICESs creates a new role for communities as flexibility providers. The value of flexibility from ICESs, however, can be different for different actors such as communities, energy suppliers, grid operators and aggregators. Moreover, ICESs can contribute to system services such as capacity and ancillary services needed to operate the grid [40].

Lund and Muenster [38] analyze the benefits of increasing flexibility of Danish energy system using the integrated energy systems. The advantages of combining small and large combined heat and power plants with heat pumps have been highlighted. One such advantage is the possibility to increase the share of wind energy in the Danish energy mix from 20% to 40% without causing significant imbalance issues [38].

The energy mix of a country is expected to impact the emergence of ICESs as well. Although renewables penetration is constantly rising, it still represents a very small share of the total production worldwide. The deeper the renewable energy penetration in a system, the higher the expected value of ICES flexibility. For example, in Denmark 40% of total electricity consumption comes from wind, in turn the system is heavily dependent on balancing power from the combined heat and power of local communities as well as its strong interconnection capacity with neighboring countries [38].

5.1.6. Load and grid defection

Energy systems at their current state will have to overcome several problems in the future. Namely, a higher share of demand for intermittent renewables, higher investment in new power lines and storage. Moreover, the majority of grids today are reaching the end of their lifetime and need replacing in the coming years, consequently demanding investment for network expansion and reinforcement. In Europe alone there is a need for €600 billion in grid investments by 2020, of which more than two third in the distribution grids [85].

Investment costs are ultimately passed on to the customers. This means the fixed part of the electricity tariffs will rise in spite of a decrease in wholesale electricity prices from increasing penetration of renewables. Soon, it might be profitable to generate energy locally, all while using local resources. If this happens on a larger scale, it might lead to grid defection, which means on-site generation may become cheaper than the increase in grid tariffs resulting from investments needed for staying heavily

Table 7
Overview of socio-economic issues facing ICESs.

Issues	Examples	Role of ICESs
Paradigm shift through community engagement	Passive consumers	Deliberative and inclusive participation of consumers in the energy system
Economic incentives	Rising energy costs Free-riding behavior	Collective distribution of benefits, higher bargaining power, saving on energy bills, less risk to invest
Willingness to pay	Higher willingness to pay for local energy	Absorb higher willingness to pay in local energy system
Split-incentives problem	Cost and benefits do not boil down to same actor	Design mechanism to allocate benefits
Energy poverty	Lack of energy access	Bring welfare to low-income households
Energy autonomy and security of supply	Degree and scale of energy autonomy Security of supply at local level	Manage local resources, local balancing, reduce dependencies on imported fuels
Initial cost and financing	High initial cost Risk aversion of banks	Collective purchasing and financing, innovative business models

interconnect with the larger system. Furthermore, policy cost of renewable energy support schemes and a nuclear phase out drive this phenomenon with amplified speed. Since 2011, feed-in tariffs have been kept lower than retail electricity prices in Germany to encourage self-consumption. Currently, feed in tariffs for such systems are comparable to wholesale electricity prices. With the technology learning, the cost of storage systems is also expected to decrease. Photovoltaic storage systems are expected to reach grid parity in the near future as well, which will make the case of grid defection even stronger.

The Rocky Mountain Institute in the U.S. recently published a detailed analysis of defection from the large electricity grid using storage together with solar photovoltaics [86]. This study suggests that solar photovoltaics together with storage can make the electric grid optional without compromising reliability and at lower prices.

Along these lines, CSIRO [87] foresees a future Australian energy system that will look very different than the one today; 2050 distribution systems will become even more customer-centric where customers consume, trade, generate and store electricity. Furthermore, if suitable policies for integrating local generation are not in place, then leaving the grid (i.e., grid defection) will become economically viable in 2030–40. This will give a way for a third of Australian consumers to go off-grid by 2050, a likely outcome as a result of the rich solar resources and soaring electricity prices.

5.2. Socio-economic issues

As mentioned above, technology will drive the end-user activation in energy systems, yet this also remains the trickiest part of the ICES engagement process. In the following section we present an overview of the socio-economic issues facing communities, see Table 7 for a summary.

5.2.1. Paradigm shift through community engagement

In essence, local communities encourage bottom–up solutions. A growing number of state of the art literature is increasingly concerned with the importance of more deliberative and inclusive participation of consumers in the energy production process [60,88]. In the developed world, ICESs are being motivated by increased climate awareness and willingness to become autonomous among pro-active communities. In recent years, our energy system is shifting towards more distributed generation driven mainly by techno-economic improvements and ambitious carbon and energy policy targets [7]. Communities having self-imposed and targeted local energy strategies are expected to benefit from such implementation strategies. In addition, the push from local government entities as well as local business and residents will have a larger impact and a greater probability of success [66]. Furthermore, community mobilization has a very important role in initiating and sustaining ICESs [88]. Collective community identity and the quest for autonomy play a critical role community engagement in the larger context of energy systems.

Citizen engagement is considered to be the best way to obtain public acceptance for energy systems [60]. Energy generation from ICESs is reported to have higher public acceptance compared to private or utility-based generation. The word acceptance however is misleading in the context of ICESs as it implies to something external. Hence, local support or citizen engagement is preferred [60]. Citizen engagement or local support is composed of an attitude towards technologies, inducing changes in energy consumption patterns and investment in ICESs. Community engagement is deemed essential in the transformation from existing centralized energy supply to a more distributed supply system that exploits the full potential of local generation including renewables [9]. It is expected that some of the best opportunities for reducing energy demand and carbon emissions as well as for realizing flexible and integrated energy infrastructures are through stronger engagement of local communities.

A strong sense of community is a prerequisite for ICESs [65]; such systems result from a high degree of involvement at the local level in the planning, development and administration of energy projects as well as collective distribution of benefits [50]. Local energy systems such as ICESs are open and participatory as well as local and collective [50]. An emergent and self-organized community approach is expected to change the experience and outcomes of energy technology implementation as communities become both producers and suppliers of energy [6,22,66].

5.2.2. Economic incentives

Community action on energy has significantly increased during the past decade due to rising energy costs [88]. Citizens in developed countries are eager to invest in local energy systems over the alternatives. For example, a large number of communities in Germany have been self-organized as energy co-operatives. The members in these co-operatives are getting average dividend of 4% which is much higher than the interest rate given by the banks [89]. Moreover, communities willing to install solar panels on their roofs or implement energy efficiency programs together will have higher bargaining power. According to recent survey by DECC[2] [3] in the UK, 42% of people surveyed show interest in community energy participation, if it results in energy bill savings. Still, the incentive for citizens to participate in ICESs are low because the benefits do not accrue just to those who make the investment, but rather tempt free-riding behavior among citizens [88].

In recent years, small energy projects are grabbing investors' attentions in contrast to their bigger counterparts. It may be the

[2] Department of Energy and Climate Change (DECC), from the United Kingdom.

case that investment in local energy systems such as ICESs is less risky. Economic benefits of ICESs can be remunerated as the interplay between increasing electricity tariffs and decreasing up-front investment costs of local energy systems. Local citizens should be enticed to invest in local and collective electricity production and storage whenever possible. However, there are case specificities especially when considering energy poverty.

5.2.3. *Willingness to pay*

In the developed world, research has shown that for a local energy system consumers are willing to pay a higher price for sustainable energy. To illustrate, 92% of Germans support further growth of renewables and are willing to pay higher prices for locally produced energy [42]. Differently, in the UK, despite renewable energy being highly valued by the households, the willingness to pay is not large enough for a majority of the households to adopt micro-generation [90]. Through household and community level investments, an ICES enables local generation in such a way that the responsibility and cost are shared and in this way creating a local scale economy. Hence, with locally induced economies of scale, a community level becomes more interesting and households may be better inclined to accept the surplus. This surplus can be used to further expand ICESs or in other innovative activities which the community members agree upon.

Given these observations, for ICESs a different demand curve seems to exist, with a willingness to pay that is higher than that of conventional generation. We have coined the term '*ICES surplus*' to represent the consumer willingness to pay. It refers to additional willingness to pay by the consumers in the developed world for energy which is locally produced (see Fig. 7(b)). The shaded area above the equilibrium price and demand (P_e and Q_e) and below the ICES equilibrium price (higher willingness to pay) and demand (P_{ices} and Q_e+Q_{ices}) represent the ICES surplus. This surplus can be used to improve further the welfare of the community involved. Further, research could aim at quantification of this ICES-surplus. In developing countries, the surplus for practical reasons is zero (see Fig. 7(a)).

5.2.4. *Coordination and split-incentives*

The value of community flexibility depends on how it is utilized, therefore the actors with access to it must communicate transparently in order to ensure the highest benefit for the community members. Co-ordination is necessary to ensure that the flexibility is not sold to more than one parties as well to ensure complementary but not opposing signals for flexibility.

Split-incentives problems are prevalent in energy efficiency projects where owners need to make investment and tenants reap the resulting benefits [91,92]. This does not provide the right incentives for investments in energy efficiency projects. Similarly, it is important that in ICESs, costs and benefits are shared fairly amongst the stakeholders involved, making sure that those who are not involved in the costs do not rip the resulting benefits. Hence, it is critical that all interests are mapped accordingly in order to avoid issues with split and perverse incentives (see Table 4).

5.2.5. *Energy poverty*

Energy poverty is of growing public interest in both developed and developing countries. The global definition of energy poverty considers end-users lacking access to modern energy services. Specifically, energy access is a development indicator; in the developing world over 1.6 billion people remain without access to electricity. The traditional top–down approach providing energy is clearly not working for rural areas, where access is plagued by remoteness and the resulting heavy investment needed [93]. Even in the cases where a village has access to an electricity grid, there may be a lot of problems on both the supply and demand side. On the supply side, common issues include low voltages and frequent power cuts. For the demand side problems like affordability and large difference between off-peak and peak demand are often visible. Note, utilities have always kept the rural areas in the least priority for the electricity supply [60,93].

In the context of advanced economies energy poverty often encapsulates low-income households which cannot afford enough energy to cover their basic needs [94]. ICESs are expected to be in a better position over profit-seeking traditional utilities to tackle the issues of energy poverty.

5.2.6. *Energy autonomy and security of supply*

Energy autonomy is one of the key drivers for local energy systems such as ICESs. Bradley and Rae [7] find that the shift towards a more distributed energy generation system presents numerous social and technical challenges. At the same time, energy autonomy at community level can deliver a host of social, financial and environmental benefits. The main issues include [7]: the degree and scale of energy autonomy; matching of demand with supply; importance of socio-economic and political factors and energy autonomy in island and remote communities.

ICESs can enhance security of supply at the local level; communities are in best positions to manage heat, cooling and electricity demand locally. This can be done through co-generation and local distribution network for heat and electricity. ICESs

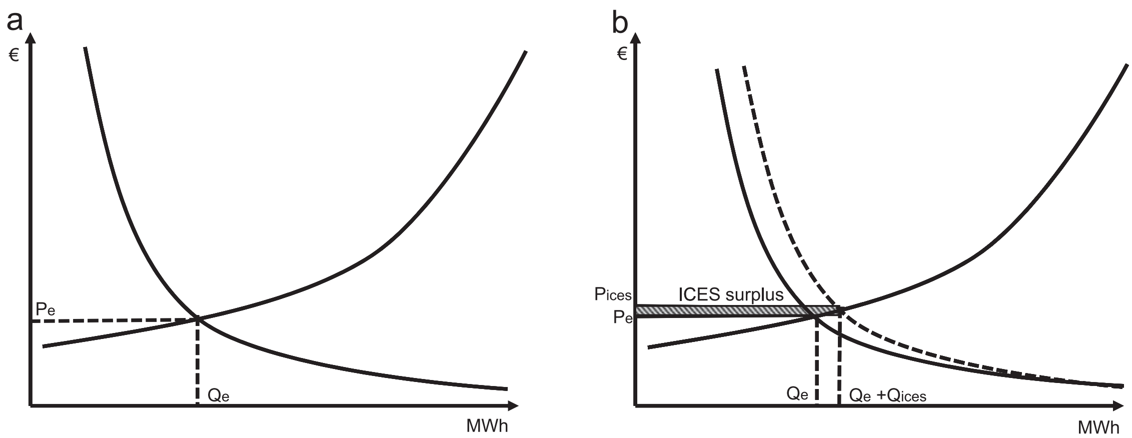

Fig. 7. Willingness to pay for ICESs in developing (a) and developed countries (b).

exploit locally available resources in a sustainable way and are expected to reduce dependencies on imported fuel which has several geo-political issues.

ICESs fit very well into the neo-liberal ideas of self-reliance and independence [65]. Many communities around the globe are concerned with security of supply and are planning to achieve energy self-sufficiency through dedicated energy efficiency and emissions reduction targets. The expansion of energy systems from residential to community level helps to achieve higher energy and power balance. With larger areas, more primary energy is locally available and generation profiles from intermittent renewables can be absorbed within the local system. However, as more communities attempt to achieve energy balance at the local level, the national energy systems might have negative rebound effects if peak demand of many ICESs coincides, in turn leading to higher electricity prices during peak hours. Moreover, it is very difficult to achieve the power balance in real time when individual technologies are considered. ICESs enable a power balance through smart local consumption, community energy storage, and flexible micro-generation units such as CHPs, fuel cells and heat-pumps as well as hydrogen or ammonia production. As heating, cooling, and transport sectors are being increasingly electrified, it remains an open question if ICESs can cover future demand. If all of this demand has to be met from the national grid, distribution grids will need substantial reinforcement to avoid local congestion. Alternatively, a significant portion of this demand could be met locally with the help of ICESs.

5.2.7. Initial costs and financing

One of the main barriers for ICESs is high up-front costs compared to existing national-grid alternatives. ICESs mobilize private capital of households, enabling investment in local generation technologies. Policy incentives to persuade local households to enable such self-financing model is necessary. Braun and Hazelroth [95] has stressed for then national, state and local policy to mobilize local money for local energy, capturing and optimizing local economic benefits.

Moreover, the cost of DER technologies are going down constantly. For instance, storage and fuel cells technologies are continuously improving in term of investment cost [76]. Furthermore, several studies attempt to understand the costs and benefits associated with the renewable energy technologies in the context of modern electricity system [96]. However, such studies do not exist for ICES. Although, there are funds available and favorable conditions in loan packages in many countries, risk aversion of banks concerning loans for communities is a major barrier to financing [22].

5.3. Environmental issues

Similar to distributed generation, environmental policies and awareness are probably the major driving force behind the surge in implementation of ICESs [97]. Together with improvement in efficiency and reliability, ICESs are considered to be an environmental friendly alternative to the centralized power supply system [21]. Being local, these systems have higher social acceptance than their giant counterparts. Consequently, community action on energy have increased significantly during the last decade as a result of rising concerns about climate change [88]. In this section, we further elaborate environmental related issues with ICESs such as emissions, waste and space constraints.

5.3.1. Emissions

Harcourt et al. [55] estimate that ICESs in Canada have the potential to reduce CO_2 emissions by 5 to 12% annually by 2050. Furthermore, the role of local community engagement in reaching CO_2 emissions reductions goals is becoming increasingly evident. Moreover, using optimization based design of a district energy system for an eco-town in the UK, optimal mix of technologies to decrease the emissions and increase the resilience of supply has been identified [98]. According to Weber [98], it is not encouraged or desired to avoid electricity from the grid completely, however, CO_2 reductions up 20% at no extra costs are achievable.

5.3.2. Waste

Waste management is becoming an increasingly important issue in local energy systems. Schemes of energy from waste and biomass residues are becoming increasingly common, despite the public acceptance issues. Moreover, management of decayed electric batteries are also an issue with the rising need for storage. In several countries, recycling facilities for batteries have been established in parallel to the diffusion of these technologies. ICESs contribute to reduce waste through wider use of reusable product and comprehensive recycling programs [61].

5.3.3. Spatial issues

A fundamental change of local energy system through ICESs also requires re-organizing spatial structures. Critical aspects concerning the local energy systems and their spatial issues are elaborated in Wächter [99]. Limited availability of private and public space for the installation of energy systems at local areas challenges the emergence of ICESs. Most of the communities do not own public space. Therefore, acquisition of land or renting of land for development of community energy projects are often the first hurdle to overcome. Moreover, most renewables such as solar and wind have lower energy density, requiring more space. This affects the goal of some communities to become energy independent and to reduce CO_2 emissions.

5.4. Institutional issues

Jacobsson and Johnson [100] identified hard and soft institutions, which are equally applicable to ICESs. Hard institutions refer to legislations, capital markets, or the educational system whereas soft institutions consider cultural and social norms. These institutions are comprised of regulative, normative and cultural-cognitive elements which together with associated activities and resources can provide stability and meaning to ICESs. There are five categories of institutions for the provision of low-carbon energy such as ICESs: (i) government policies; (ii) dominant technologies; (iii) organizational routines and relations; (iv) industry routines and relations; (v) societal expectations and preferences [21]. These characteristics and links connect ICESs with the larger energy systems. ICESs experiment with current institutional arrangements, take risks and grab opportunities, and create new institutions or, even self-organize energy systems if needed [22]. Changing local energy landscape requires reconsidering roles and responsibilities of different actors. Financial and regulatory risks can be dealt with by leaving some aspects such as economic incentives to market and regulating other aspects such as co-ordination of shared infrastructure and facilities. Opportunities such as self-regulation and self-governance emerge in local energy systems. Institutional transformations must be a critical aspect for ICESs because it is the only way to effect significant and lasting social change to ensure the sustainability of the smart grid systems. In the following section, we present an overview of the institutional issues facing communities, see Table 8.

5.4.1. Trust, motivation and continuity

The main themes that are essential for initiating and sustaining ICESs are trust, motivation and continuity [65]. On the one hand, increasing number of communities are not satisfied with the fact

Table 8
Overview of institutional issues.

Issues	Example	Role of ICESs
Trust, motivation and continuity	Lack of trust and motivation	Win trust and motivate individual households and local communities, gain trust of local government, sustainable business models
Energy democracy	Enforced energy system Missing local participation	Create decentralized structures to democratize energy systems
Ownership	Ownership model	Local ownership
Co-operatives	Co-operative tradition Lack of business model	Energy co-operatives with sustainable business models
Locality and responsibility	Lack of Local and responsible energy system	Direct accountability, self-regulation
Support schemes and targets	Lack of suitable support schemes and incentives	Lobby for suitable support schemes, incentives, collective formulation of targets
(Self-) governance	Governance of local energy systems	Local governance, (self-) governance
Regulatory Issues	Design of prices for service, grid access	Local control of distribution grid, re-bundling, self-regulation
Institutional (re)design	Transforming institutions of centralized energy system	Dynamic and flexible institutions
Roles and responsibilities	Refer Table 9	Refer Table 9

that the energy system is not yet on a sustainable track. These communities trust more on ICESs than in government or incumbent energy companies as these systems deliver on their mission and objectives and provide suitable alternatives for their energy concerns. On the other hand, governments are also expected to trust these community initiatives and provide necessary support. Motivation of citizens as well as a sustainable business models, are crucial for collective investment of time and other resources in local energy systems.

5.4.2. *Energy democracy*

ICESs are often linked to creating decentralized structures and democratization of energy production and supply through new organizational forms [9]. Locally and collectively owned energy systems open up new opportunities, create wider basis of support as well as mobilize participation and contributions.

5.4.3. *Ownership*

ICESs promote commons-based energy supply. In a liberalized market, it is possible to establish local producer/prosumer – consumer energy commons. Different actors can be enabled to co-create a smart local energy system. ICES could be 100% community owned or may be developed together with private or public sector under co-ownership arrangement [49]. Although many communities are already involved in the ownership and financing of local energy production which is directly fed into the grid, the ICESs advocate a combination of locally owned production and consumption of energy. Following a legal and financial model of ownership, four arrangements for ICESs ownerships are observed namely co-operatives, community charities, development trusts and co-ownerships (shares owned by communities) have been observed in the literature [49]. As most common ownership arrangement, we further elaborate co-operatives below.

5.4.3.1. Co-operatives. A co-operative is an organization owned and run jointly by the members who shares the profits or benefits. Energy co-operatives have been flourishing in European countries due to the environmental concerns after the oil crisis in 1973. Some examples of collective organizations of renewable energy are wind and biogas co-operatives in Denmark and photovoltaics co-operatives in Germany [9]. The numbers of energy co-operatives increased significantly in Germany between 2007 and 2013 (from 100 to 900). Similarly, in the Netherlands, there are close to 500 active energy co-operatives [60].

Differently, the electricity sector in the United States (US) presents a traditional and well-established example of co-operatives mainly driven by the objectives of rural electrification. There are 905 electric co-operatives among of which 840 are distribution and 65 are generation and transmission co-operatives serving 42 million people in 47 states [60]. Most of these energy co-operatives are also involved in renewable energy supply. Other relatively successful co-operative experiences in the context of rural electrification have been observed in Bangladesh, Costa Rica, Nepal, Bolivia, Tanzania and the Philippines [60,62].

Energy co-operatives that enable citizens to investment in generation units and energy efficiency measures are a specific way of involving citizens in the diffusion of ICESs. Whether co-operative tradition is really a driver for ICESs is a matter of further investigation. It appears that the US model of co-operative ownership helps in market mechanisms for renewable energy supply, however, the European model where these co-operatives are well embedded in the society and part of their culture is more suited for the development of ICESs. Renewable energies and other forms of local generation are suitable for co-operative in light of high initial costs and local availability. Currently, energy co-operatives in Germany are facing difficulties to develop new business models, leading to stagnation in their growth [101]. Innovative business models such as self-consumption and energy services can be enabled through the development of ICESs.

5.4.4. *Locality and responsibility*

ICESs as non-profit entities are more effective and efficient in providing services to local energy consumers. Direct accountability to the customer base makes ICESs responsive to the concerns and needs of local communities. This can encourages a system of self-regulation [60].

5.4.5. *Support schemes and targets*

Limited political support for market based policies to price externalities such as taxes on emission or a tradable permit system leading to the creation of policies to promote renewable and local energy directly [96]. Suitable support schemes can drive the development of ICESs. These support schemes could be through subsidy on the initial cost or priority access to the grid. Collective subsidies schemes for solar PV as implemented in some of the Dutch cities help in establishing community energy systems in the neighborhood. Moreover, these support schemes and incentive programs should be updated continuously as the market dynamics change. For example, German feed-in tariffs are already encouraging self-consumption over direct feed-in of solar electricity to the grid. Furthermore, skills development training or tours to some exemplary ICESs sites helps in empowerment of local communities to manage these systems. Furthermore, incentives could be incorporated in ICESs to increase competition for improving energy performance among neighbors in local communities.

Targets set by central or local governments in collaboration with local communities could help in the emergence of ICESs. For example, the Scottish government has set a target of 500 MW community or locally owned renewable sources by 2020, which has encouraged community mobilization through grant and loan schemes [88]. The UK government has also sought to develop community renewable energy since 2000 through support schemes and funding programs [49].

5.4.6. (Self-) governance

The main barrier for incorporating local and community actors in the emerging energy governance structures and policy delivery mechanisms is the lack of understanding of how they work in the field and how best to support and develop effective local energy governance [102]. Development of ICESs challenges existing energy-structures and creates opportunities for self-governance [65]. There are good examples of common pool resources managed by communities. However, the ICESs ask for more specific skills such as technical expertize.

Avelino et al. [65] identify four categories of challenges for self-governance of community energy: economic and financial challenges, legal issues, socio-cultural conditions, and micro-political struggles as well as conflicts. Moreover, a community energy system is largely affected by inter-personal dynamics, intellectual capacity of community members and their long-term commitment. Often, the community energy initiatives are due to enthusiastic leaders. Yet, there are often free rider problems in such initiatives.

A multi-actor perspective has been used to identify roles of different actors namely, the state, market, and the community involved in the self-governance of community energy systems [65]. Parag et al. [102] highlight the important role of intermediary organizations in local governance structures. Likewise, Frantzeskaki et al. [22] introduce the concept of 'beyond controlling and beyond governing' or 'invisible governance' or 'meta –governance'. These concepts can be utilized for the governance of ICESs. This type of reflexive governance diagnoses paradoxes and facilitates space for self-correction and action without neglecting the roles and responsibilities of the government. This provides higher control for local communities in shaping their energy systems.

5.4.7. Regulatory issues

With the competition between centralized and decentralized resources, the design of prices for services based on markets such as energy markets, capacity markets, balancing markets as well as ancillary services as well as charges for regulated services such as network and other energy policy costs as subsidies to renewable energy are of crucial importance to achieve a sustainable and efficient future energy system.

5.4.7.1. Grid issues. Access to a distribution grid for the local transfer of locally generated energy is of crucial importance for the emergence of ICESs. Existing and persisting problems include tax issues associated with the use of distribution grid for local consumption. Community energy labeling and different tariff design for the energy produced from ICESs might help in local consumption of the energy. Moreover, some communities have taken control of the distribution grid (e.g. Schönau EWS, Germany [65] and Feldheim, Germany (see Section 6.2.1) and many other communities are considering to take control of the distribution grid. In Germany, there is emerging trends for re-municipalization of the distribution grids [103].

5.4.7.2. Re-bundling. ICESs might cause conflicts with unbundling requirements of the European Union third energy package [104]. According to Harcourt et al. [55], ICESs are more likely to be feasible if the regulatory system accept some re-bundling, specifically of the local energy generation and distribution, allowing experimentation to facilitate innovation.

5.4.8. Institutional (re-) design

Delivering energy by traditional means to end users requires multiple processes such as production, conversion, transformation and distribution as well as many actors from both the public and private sector [68]. Similarly, ICESs involve a diverse set of institutions and stakeholders and operate at the interface of community, policy and institutions.

Most state of the art research related to institutional design of ICESs revolves around examining existing arrangements in energy systems to see if they are satisfactory and altering them when necessary through rethinking and reshaping of formal structures as well as interventions in any of the arrangements which coordinates the behaviors of the individuals in the society [9]. In other words, it is not necessarily about designing new institutions but more about adapting existing institutions so that ICESs could emerge. Furthermore, Frantzeskaki et al. [22] argues that the institutional design focus has to shift from designing diffusion instruments to designing suitable institutions that fit the operation of ICESs. Distributed strategy in both technological developments and governance is desired. Such design should also be able to link markets and grassroots initiatives such as ICESs. For this, design should be dynamic and flexible (see criteria 4.2.2). The design should also incorporate lessons from experience and evaluation obtained through feedback and monitoring [105].

Wirth [9] presents a framework for analyzing emergence of community energy projects from institutional perspective based on biogas cooperatives in South Tyrol. In this framework, a community is treated as an individual institutional order which shapes decisions. Community spirit, a co-operative tradition and the norms of locality and responsibility are presented as central drivers behind the emergence and constitution of biogas co-operatives. These institutional features influence the decision not only concerning involvements of citizens but also plant location and scale. These outcomes from the research of biogas co-operatives could also be applied to ICESs.

Institutional space available for ICESs differs among countries. Oteman et al. [45] analyzes the available institutional space for local energy systems in the Netherlands, Germany and Denmark. This study was performed by putting the local energy systems within the institutional context of the policies, power structures and energy discourses in each country. By giving the example of traditionally civil society friendly energy sector of Denmark, market-oriented energy sector of Netherlands and state-dominant energy transitions strategy of Germany (*Energiewende* in German), it was demonstrated that evolving institutional configuration of the energy sector strongly influences the available institutional space for local energy systems development.

5.4.9. Roles and responsibilities

As the citizens and communities start to become prosumers, new actors and roles will emerge in energy systems, see Table 9. ICESs imply new roles for communities as they might have to be actively involved in energy production, supply and other energy conservation measures. Roles of communities in production, further depends on institutional arrangements of ownership and control of the production units and distribution grids [60]. Industries will contribute by local generation and demand response as well as via the provision of waste heat to the local communities. Commercial as well as residential end-users will also play a role in local generation and demand response. In addition, residential end-users can collectively purchase energy systems or energy efficient technologies. The community will have collective responsibilities in formalizing business models as well as local balancing arrangements. Distribution system operators have to adapt the system operation as per system needs. These developments challenge the governance and traditional business structures [65].

However, as energy infrastructures are extremely complex, it would be impossible for communities to manage the entire energy systems. Therefore, the traditional companies need to be adapted accordingly with the emergence of ICESs. In this respect, a growing numbers of literature has advocated the adaptation of roles and responsibilities of different actors in the context of ICESs [60,65,22]. The existing energy companies could assume the role of aggregators or could even establish partnership with the local communities for the management and operation of integrated community energy systems. Furthermore, accountability and beneficiary issues of community owned projects also need to be specified. Moreover, for the success of ICESs, national and local government should play the role of facilitator.

The establishment of a mediating organizations will make a significant difference enabling communities to undertake initiatives and succeed as indicated by the example of such endeavor, Community Energy Scotland initiative [22]. Similarly, establishing knowledge exchange platform could also be beneficial for these initiatives as they can learn from each other. One such example is Hydro Empowerment Network which is knowledge exchange platform for community micro-hydro in South and South East Asia [62].

6. Application of ICESs

6.1. ICESs business model canvas

The success of local energy systems such as ICESs largely depends on the business model adopted. Business models differ significantly between developed and developing countries. In developed countries these system could provide different energy services for the members as well as to the neighboring ICESs or larger energy systems. The same is not possible for ICES implemented in the rural areas of developing countries. Therefore, ICESs in developing countries have to solely depend on revenue from self-provision. Therefore, the business case for ICESs is not always straightforward. In this section, we fill this gap using the framework of the business model canvas [106]. This framework is extensively used to develop new business models for smart energy systems [107].

Table 9
Changing roles and responsibilities in ICESs.

	Actors	Roles and responsibilities	
Competitive parties		*Current system*	*ICES*
	Households	Consumption, payments	Consumption, payment investment, generation, energy management
	Communities	Passive and inactive individual consumption	Local energy exchange platform, accounting and billing, flexibility
	Energy suppliers	Electricity, gas and heat supply, billing, energy procurement	Supply the deficit, management of local energy systems, flexibility and energy procurement
	ESCOs	Financing, supply and installation of energy efficient equipment, building refurbishment	Management of local generation fleets; financing, supply and installation of energy efficient equipment, building refurbishment
	Technology providers	Provide energy efficient and Distributed generation technologies	Technologies for local generation, energy efficiency, energy management system
	Aggregators	–	Aggregate the flexibility from the local community
Regulated parties	*DSOs*	Grid operation, reinforcement	Grid operation, local congestion management
	TSOs	System balance	Use flexibility for system balance
	Government, policy makers and regulators	Ensure sustainable energy supply, subsidies	Investment and subsidies for ICES, policies, Reduce barriers, shape local markets
	Balance responsible parties	Balance responsibility	Incorporate flexibility in portfolio

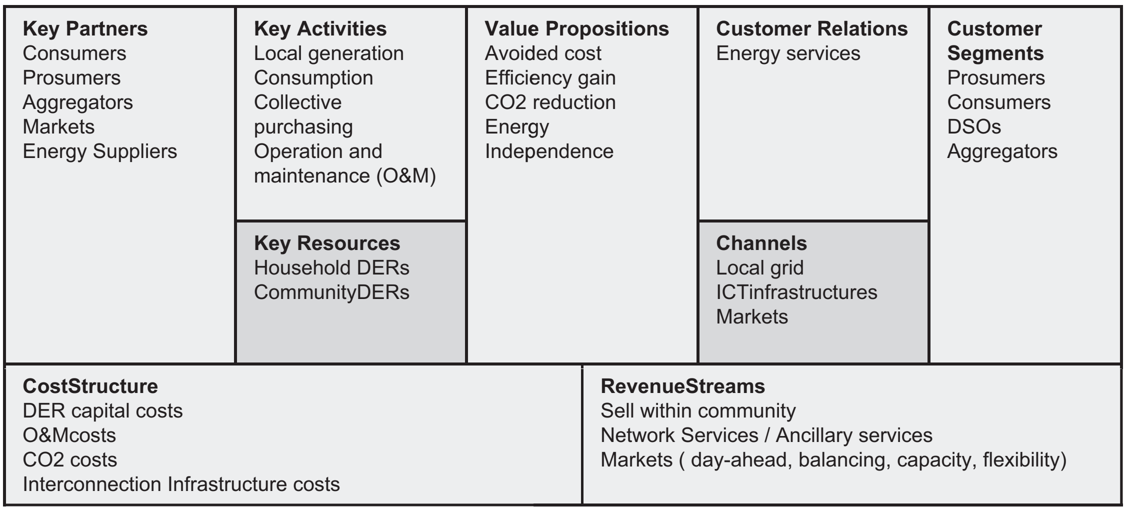

Fig. 8. Business model canvas for ICESs.

Taking developed countries case as reference, examples for each building-block is provided in Fig. 8. Below we define the 9 building-blocks used in the ICES business model canvas.

Key partners: anyone who help ICES to leverage the business.
Key activities: main activities in ICES to create values.
Value propositions: product and services of ICES that create value for customer segments.
Customer relations: the type of relationships established by ICES with customer segments.
Customer segments: households and organization ICES aim to serve and create value.
Key resources: infrastructures to create, deliver and capture value.
Channels: ICES platform for delivering value and interacting with customers
Cost structure: cost to realize the business model
Revenue structure: the pricing mechanism with which the business model is capturing values

6.2. ICES examples in developed and developing countries

6.2.1. Feldheim, Germany

Feldheim, a small village 60 km from Berlin with 37 household; this case is used to present ICES in the developed world. This village is a successful example of decentralized self-sufficiency in Germany. Feldheim is organized as a local energy co-operative and is run by the local renewable energy company *Energiequelle* [108]. The installation of a first wind-turbine by a local entrepreneur and co-founder of Energiequelle in Feldheim dates back to 1995. The energy system was gradually increased in size to a final expansion of 81.1 MW wind farm, a 2.25 MW_p solar farm and a 500 kW_e/500 kW_t biomass-plant for district heating and storage. Feldheim meets all its local energy demand and sells 99% of the generated electricity to the central grid [109]. The unsuccessful attempt of Feldheim community to buy or lease the distribution grid owned by E-ON led Feldheim to build its own electricity and heating network, funded by Energiequelle, EU subsidies, capital loans and individual contributions. This alternative form of energy arrangement in the form of ICES, has resulted in lower energy prices which is set independently by the co-operative irrespective of the wholesale market. Feldheim is self-sufficient in terms of energy and is dependent on the national grid only for exporting electricity and providing system services. Recently, Feldheim also started to provide primary frequency control services to a transmission system operator through its 10 MW h battery. Although these results need to be translated carefully due to the subsidies involved, Feldheim nevertheless represent an interesting example of ICES.

6.2.2. Urja Upatayaka, Nepal

The Urja Upatayka Mini-grid Co-operative in Baglung state/region of Nepal is a representative example of how ICES could look like in developing countries. Six nearby micro-hydro units were integrated in 2011. The co-operative functions as grid operator and electricity distributor, while the micro-hydro units work as Individual Power Producers (IPPs). The co-operatives buy electricity from micro-hydro units at 5 € cents/kW h and sell it to the consumers at 8 € cents/kW h, using the difference for operating and maintaining the system. This price is still lower than the price in the Nepalese national grid. With an 8 km long distribution grid, the system provides electricity to more than 1200 households. Due to the integration, the quality, reliability and availability of electricity has been enhanced. The voltage and frequency of the system is stable (390–415 V/49–50.5 Hz). Thanks to the integrated approach, income generating end-use such as a communication tower (15 kW) and a stone crusher (40 hp) has also been made possible. Micro-hydro units were installed through 50% subsidies from the alternative energy promotion center, 30% loans and 20% contribution from the individual members. The integration of six-units of micro-hydro plants was realized through external funding. This project helped to improve inter-community co-ordination, increasing their confidence level to construct, own and manage bigger projects. Demand side management as well as retrofitting of compact florescent lamps with light emitting diodes lamps has also been successfully implemented in the community. The mini-grid has become a social entity for the generation, transmission and distribution of local energy. As a result communities are now convinced that integrated micro-hydro systems can be a permanent source of electricity, while the national grid of Nepal suffers from load shedding of up to 16 h a day.

7. Conclusion and discussion

This work has reviewed developments in Integrated Community Energy Systems (ICESs), presenting them as an option of comprehensive energy system integration for the transitioning local energy landscape. ICESs are multi-source and multi-product complex socio-technical systems emerging through changes in the local energy landscape. With the motto of 'think global and act local', ICESs provide the necessary platform for local energy exchange, through effective integration of different sectors and engagement of local communities. ICESs also provide system-wide services to both neighboring communities as well as larger interconnected energy systems. The above analysis points to ICESs performing exceptionally in terms of self-provision and system support services over other energy system integration options.

As summarized in 4.4, this modern way of organizing local energy systems will impact different actors both directly and indirectly as local and system-wide exchanges and interactions take place. Hence, it is critical that all interests are mapped accordingly in order to avoid issues with coordination in addition to split and perverse incentives (5.2.4). It is important that in ICESs, costs and benefits are shared fairly amongst the stakeholders involved, making sure that those who are not involved in the costs do not rip the resulting benefits. ICESs have the potential to reduce community dependence on national energy systems and provide needed flexibility as well as security of supply, in addition to keeping (smart) grid investment costs at bay (see 5.1.6). Accordingly, ICESs improve the performance of local energy systems while contributing to renewable penetration and energy efficiency targets as well as climate change goals such as EU 2020 objectives and beyond. In Section 5.1.5, we discuss the Danish case as a prime example of what ICES can achieve; a stable system and deep RES penetration in addition to emissions abatement.

The attractiveness of ICESs have been internationally demonstrated; as they promote an array of benefits inclusive of sustainability as well as security of supply, self-reliance and energy independence. ICESs result in effective engagement of the local communities by means of collective purchasing, community ownership, co-operative operation and maintenance arrangements as well as from the integration of different sectors such as electricity, heating, cooling, gas and transportation. These arrangements also make citizens more energy conscious, contributing to energy efficiency improvements as well as reduction in CO_2 emissions. In essence, what this work has brought to light is the fact that the engagement of local energy systems can help to defer new investments in power lines, reducing the system peaks and distributing load more evenly throughout the day. With increasing electricity tariffs and grid defection, ICESs will have a progressively important role in the future as they keep the grid intact or enable off-grid options when desired. Widespread availability of flexible generation and energy storage facilities will enable these communities to provide flexibility to the national energy system as needed. In this way, supply and demand will co-operatively optimize system operation while keeping overall costs low, security of supply high and ultimately reaching climate policy objectives.

Overall, this review has found the main challenges which ICESs need to overcome are a bi-product of dominant culture, structure and practices from the centralized energy system. Institutional design and business models (Section 6.1) as well as the regulatory framework still need to be adapted to the emergence of ICESs. Similar to the development of renewable energy, the deployment of ICESs still focus on technical aspects. As indicated above, focusing evenly on technical, socio-economic, environmental and institutional aspects will bring further support in the emergence of ICESs in the smart grid paradigm.

On the basis of the above, ICESs will be shaped by technological, socio-economic, environmental and institutional issues as well as current trends in the energy landscape (Section 5). We have identified and further elaborated six technological issues, seven socio-economic issues, three environmental issues and nine institutional issues. ICESs will involve a diverse set of institutions and actors; the operation of such system will lie at the interface of community, policy and institutions. Although ICESs do face tensions, controversies and institutional problems, new technical and socio-economic developments are expected as different actors attempt to align their incentives with those of ICES. These new developments will reshape operational roles and responsibilities, energy markets, behavior of different actors, business models for energy services as well as corresponding institutional arrangements. Moreover, at a local level, various new energy technologies will change the existing energy mix and enhance energy independence. In ICESs, local communities will play a significant role in energy production, consumption as well as distribution. As a result, the power of change is actively given back to consumers.

From this analysis, the authors recommend a quantitative assessment with the empirical data from several demonstration projects to help institute the value of ICESs. Such an assessment is expected to increase the understanding and impact of ICES to different actors as well as to the larger energy system. If these valuations are available in time, the political economy within could be understood more clearly. Accordingly, appropriate governing institutions could be established to overcome barriers and challenges in the design, planning, implementation and operation of ICESs. On this basis, the authors conclude that such an assessment and quantitative outcomes will contribute positively to understanding how ICESs can contribute to the vision of a low-carbon energy future and achieve the trifecta of availability, affordability and acceptability for all.

Overall, increasing environmental concerns and renewed attention on universal energy access are the main drivers for the surge in the progress of local energy communities in both developed and developing countries. Irrespective of where implemented, these systems will be a significant component in future energy systems of developed and developing countries alike. ICESs can transform local energy systems, becoming an inspiring example for sustainable development worldwide.

Acknowledgments

Binod Prasad Koirala and Elta Koliou have been awarded an Erasmus Mundus PhD Fellowship. The authors would like to express their gratitude towards all partner institutions within the program as well as the European Commission for their support. The authors are grateful to Mr. Soren Johnson of Institute of Languages at Faculty of Technology, Policy and Management, Delft University of Technology for proof-reading the English of this manuscript. The authors would also like to sincerely thank Dr. Jose Pablo Chaves Avila and Prof. Tomas Gomez for their valuable suggestions throughout the preparation of this manuscript.

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Local Alternative for Energy Supply: Performance Assessment of Integrated Community Energy Systems

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Academic Editor: Paras Mandal
Received: 17 August 2016; Accepted: 14 November 2016; Published: 25 November 2016

Abstract: Integrated community energy systems (ICESs) are emerging as a modern development to re-organize local energy systems allowing simultaneous integration of distributed energy resources (DERs) and engagement of local communities. Although local energy initiatives, such as ICESs are rapidly emerging due to community objectives, such as cost and emission reductions as well as resiliency, assessment and evaluation are still lacking on the value that these systems can provide both to the local communities as well as to the whole energy system. In this paper, we present a model-based framework to assess the value of ICESs for the local communities. The distributed energy resources-consumer adoption model (DER-CAM) based ICES model is used to assess the value of an ICES in the Netherlands. For the considered community size and local conditions, grid-connected ICESs are already beneficial to the alternative of solely being supplied from the grid both in terms of total energy costs and CO_2 emissions, whereas grid-defected systems, although performing very well in terms of CO_2 emission reduction, are still rather expensive.

Keywords: distributed energy resources (DERs); energy communities; smart grids; multi-carrier energy systems; optimization

1. Introduction

Traditionally, the energy system has been developed to meet the needs of local communities [1,2]. The energy demand of the cities and communities increased rapidly with the increasing number of activities. Due to economies of scale, increasing demand as well as resource complementarity, the energy systems quickly took present, centralized and networked form. The large centralized power plants produce electricity which is transferred unidirectional to the households, industry and commercial buildings through transmission and distribution networks [3]. At present, built environment accounts for two-thirds of primary energy demand and 70% of global CO_2 emissions [1]. Despite performing well in terms of techno-economics, social and environmental values could not be adequately considered in the centralized energy system. Moreover, the role of local communities and cities so far has been largely limited to the passive consumers. These issues demand the energy system transformation efforts to focus on cities and local communities.

The recent energy system transformation, together with technological changes, are opening several ways for a large number of distributed energy resources (DERs) to be part of the energy system. Several recent researches focus on system integration of these DERs in the energy system [4–7]. Moreover, the traditional energy supply systems consisting of separate networks for electricity, gas and district heating designed to operate independently are changing with increasing interaction and complementarities between the different energy carriers, see Figure 1 [8–10]. In this context, different energy carriers can work in synergies leading to a more sustainable and integrated energy system [8,9,11–13]. For example, currently available DERs, such as combined heat and power (CHP), heat and electricity storage as well as advancement in information and communication (ICTs) and smart grid technologies enable integrated operation of a smart energy system [8,13,14]. At the same time, the decarbonization efforts on traditionally centralized energy systems will have a significant impact on current energy networks and will lead to new forms of energy systems where DERs will play more important roles in energy supply. One such impact is increasing electrification of different sectors as depicted in Figure 1. Almost all types of local energy demand can now be met with electricity.

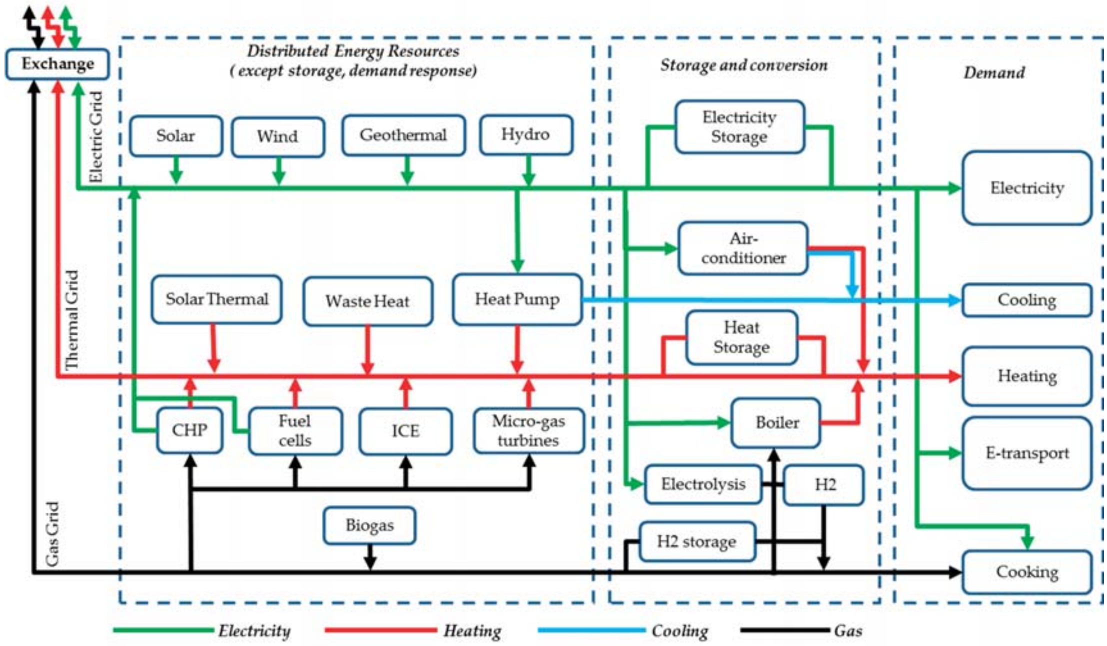


Figure 1. Multi-carrier energy flows in an integrated energy system. CHP: combined heat and power; and ICE: internal combustion engine.

Household and community level energy generation, storage and energy management systems are expected to gain more importance in the integrated energy system [15]. Moreover, consumers will not only consume but also actively invest in DERs as well as respond to price signals and provide services to the system [16–18]. The rapid fall in prices of DERs indicates the possibility of locally-owned, independent power systems [19]. As a result, the technological and institutional arrangements of the current energy systems at crossroads also need to change and new business models need to emerge [20,21].

In this context, integrated community energy systems (ICESs) are multifaceted smart energy systems to optimize the use of all local DERs, dealing effectively with a changing local energy landscape and local communities. ICESs are significantly different from individual households installing DERs due to the possibility of co-operation and local exchange. ICESs represent a comprehensive and integrated approach for community energy systems where local communities can manage their energy system capturing benefits of energy system integration options. The concept of ICESs is further elaborated in detail in [22–24].

The grid so far has always been an enabler for the system integration of DERs [20]. This has positively impacted the penetration of DERs all around the world. For example, the excess energy from DERs can be sold through the electricity grid and the local bio-gas can be mixed to the natural gas grid. However, current high retail prices and charges for energy as well as improving economics of DERs, are encouraging alternative organizations, such as ICESs where local consumers can take back the control of their energy system. With increasing penetration of DERs, ICESs can either be integrated to the grid or defected from the grid [25,26]. In the grid-integrated operation, the deficit can be purchased and the surplus can be sold to the grid. In other words, the grid acts as storage for the ICES. On the other hand, the grid-defected system has to meet all the demand locally. The rising regulated cost in the energy bills and decreasing DERs cost, are creating an enabling environment for customers to get disconnected from the grid and manage their own local grid [19,27–30].

The alternative organization of ICESs as grid connected or grid-defected system has both benefits and challenges. While it is technically possible to have both grid-integrated and grid-defected ICESs, the economic and environmental assessment and evaluation of such ICESs operation is still lacking. Specifically, the value of a group of households being organized as a single entity, such as an ICES, to the local community as well as to the whole energy system is yet to be determined. The main aim of this paper is to develop the assessment framework for the grid-integrated and grid-defected ICESs and present a model-based analysis on the value of both systems.

This paper begins with the conceptualizing of ICESs as a local alternative for energy supply, followed by a problem statement in Section 3. In Section 4, the research design in terms of modelling framework and the model-structure as well as formulation are presented. Section 5 introduces the case study from the Netherlands. In Section 6, different results on investment and operation as well as economic and environmental performance of both grid-integrated and grid-defected Dutch case studies are presented. Finally, Section 7 concludes and provides policy recommendations.

2. Integrated Community Energy Systems as Local Alternative for Energy Supply

Local communities are well-placed to identify local energy needs, and bring people together to achieve common goals such as self-sufficiency, resiliency and autonomy [31–35]. Commons-based energy systems such as ICESs are implemented with the aim of reducing energy cost, CO_2 emissions and dependency on traditional incumbent utilities.

Although local energy initiatives are rapidly emerging, the motivations have been mainly economic incentives. For example, the lucrative feed-in-tariffs in Germany attracted local investment in DERs through energy co-operatives and individual households. As a result, more than half of renewables installed in Germany are owned by local citizens and communities [36]. However, the market conditions and support incentives in terms of feed-in tariffs have changed resulting in stagnation of the growth of energy co-operatives in Germany [37]. These co-operatives are now in a dilemma on how to make the most out of the locally generated energy. This means household and community generation have to compete with centralized generation with economies of scale, highlighting further the need of higher local balancing within ICESs. Alternative business models such as local balancing and ancillary services for the whole energy system, as characterized also in the ICESs, are expected to continue their growth. The association of German energy co-operatives already recognizes such needs [37]. Other challenges include split-incentives problems, collective financing, fair cost-benefits allocation, operation and complexity in decision-making [22]. Moreover, ICESs might encourage opportunistic behavior by avoiding contribution towards network and policy costs, widely known as spill-over effects.

ICESs consist of variety of options for local generation of heat and electricity, flexible demand, e-mobility as well as energy storage. Such an integrated approach at the local level helps the efficient matching of local supply and demand. At the same time, advancement in smart-grid technologies not only increase reliability and efficiency of such local energy systems but may also affect the existing system architecture and influence the way ICESs will evolve.

Increasing numbers of local communities around the world have resources and willingness to implement the ICES. For example, there are more than 2800 energy co-operatives in Europe, of which 900 in Germany and 500 in the Netherlands alone, showing a huge potential for the emergence of ICESs [38,39]. Several houses in the local communities cooperate for collective purchasing or community level investment further reducing the initial cost. ICESs also lead to local job creation and local economic growth, foster the transition to a low-carbon energy system, build consumer engagement and trust as well as providing valuable flexibility to the market [22].

As illustrated in Figure 2, the households are the basic units of the ICES. In the changing local energy landscape, these households can invest in local generation technologies such as solar photovoltaics (PV), solar thermal, CHP, fuel cells, electric and thermal storage, electric cars and heat pumps (HPs) as well as home energy management systems to ensure effective energy balance and smart operation at household level.

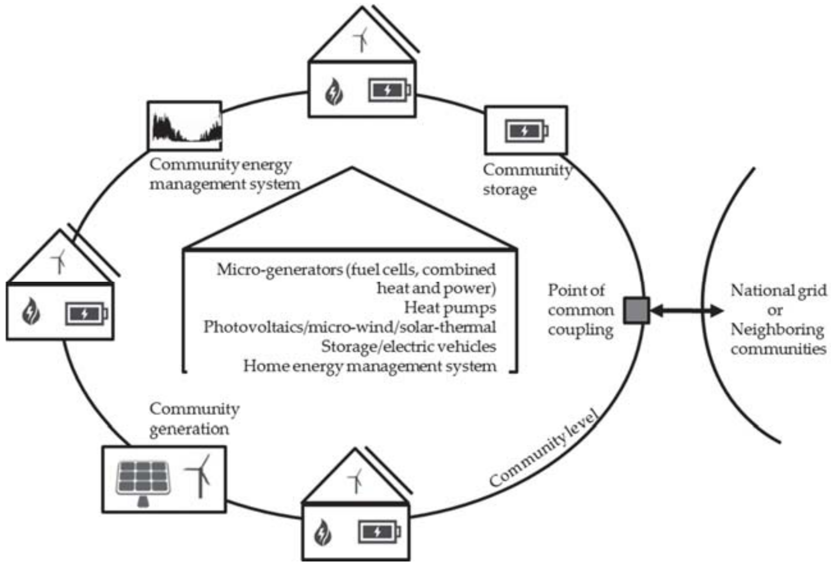


Figure 2. Conceptual design of an integrated community energy system (ICES).

A group of consumers may join and cooperate together in the form of ICESs, implying some advantages and challenges. The advantages include larger economies of scale due to common installations; multi-carrier efficiency gains from bundling different energy sources (e.g., electricity, heating, cooling); increasing reliability at lower costs; community engagement and fulfillment of community visions, such as autarky or energy independence where consumers are willing to pay higher costs for self-provided electricity within a community. Further investments are possible in community level technologies, if the local community supply is not enough or it is cheaper compared to the household investment or grid-supply in the case of grid-connected systems. On the other hand, the challenges include collective decision making on investment and operation of the local network and energy management systems; mismatch between life cycles of DERs and the local network; a complex decision making process as well as split-incentive issues. Based on these advantages and challenges, the local communities can decide to operate their energy system integrated to the grid or defect completely.

Surplus of local generation from the households is pooled in the community energy exchange platform. The household can also purchase deficit energy from the platform. Different options exist for operating the local energy exchange platform such as peer to peer exchange, marginal or average cost-based local energy markets [40]. Due to the system perspective in this study, the transactions between the members are considered but not priced, and the energy exchanges among households are free of charge. As cost allocation of the local exchange is very important for the success of the ICES, the design of the system of prices and charges within the ICES definitely should be a future research agenda. For grid-integrated ICESs, energy deficits or surpluses at the community level can be purchased or sold to other communities or market agents through the national grid. The grid-integrated ICES can also provide different energy services for the system operators, such as balancing and flexibility, however this is beyond the scope of this research. The grid-defected ICES, on the other hand, has to maintain the energy balance locally.

3. Problem Statement

It is technically possible to have both grid-integrated and grid-defected operation at household level and the economic and environmental assessment and evaluation of the former system is promising [19,27–29]. Despite falling prices of DERs, the grid-defected system for individual households, on the other hand, is not yet economically attractive. Assuming the technical possibility, the aggregation of group of local consumers in the form of ICESs might further improve these results. For this, economic and environmental assessment and evaluation of such local aggregation is needed.

ICESs are expected to have technical, economic and environmental potential for improving local energy systems. Yet, the modelling of complex socio-technical systems under the changing energy landscape is a tedious task. Several technological, socio-economic, environmental and institutional issues as well as emerging trends at the energy landscape shape the emergence of ICESs [22]. As the benefits and costs are understood, the added value of ICESs could also can be assessed. The local aggregation in the form of ICESs may improve the economics of DERs. The interaction and complementarities among multiple-energy carriers might also have significant value in the energy system. Critical empirical assessment of the economic and environmental value of alternative energy system organization, such as an ICES, is needed [41].

4. Materials and Methods

4.1. Modelling Framework

The general modelling framework for ICESs is presented in Figure 3. Households are the basic units of ICESs with different energy demand profiles. For the base case, it is assumed that households are passive consumers and do not invest in DERs. A number of households cooperate to form ICESs which can operate either in grid-integrated or in grid-defected mode. The investment and operation of DERs, as well as associated cost and benefits are different for each case which in turn impact its economic and environmental performance.

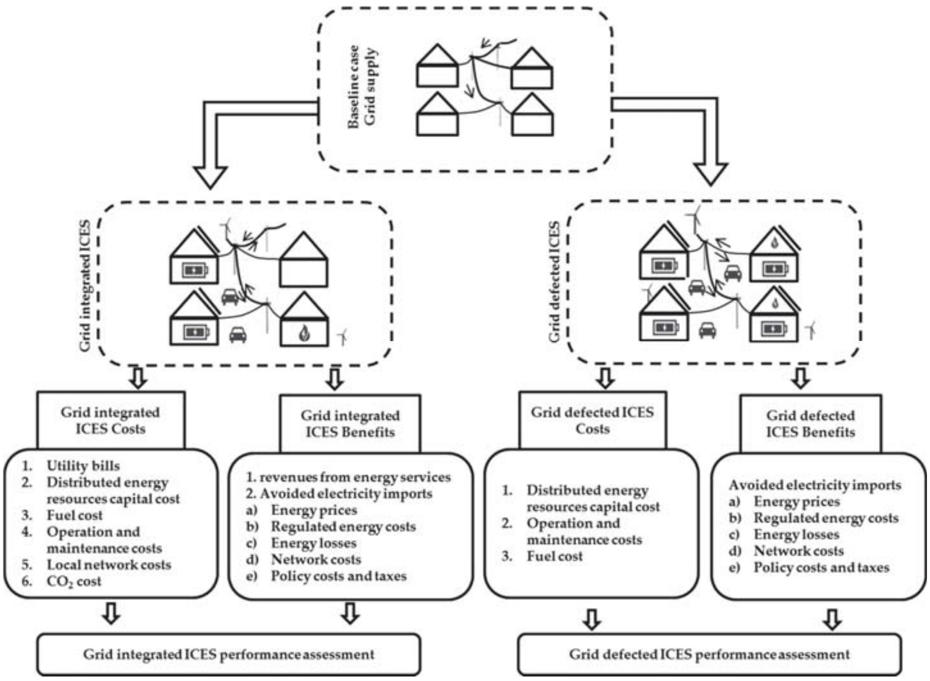


Figure 3. Assessment framework for grid-integrated and grid-defected ICESs.

Grid-integrated ICES costs involve utility energy bills, capital costs for DERs and the energy management system, fuel costs, operation and maintenance costs as well as network costs to interconnect households. There are many benefits of the ICES as result of the several services provided to their members and to the system. Some of these benefits create efficiency in the whole energy system, such as energy sales, avoided energy imports at lower costs than the one provided by the external system and corresponding energy losses, whereas other benefits such as saving in network charges, or policy costs and taxes might be opportunistic; for further details on efficient and opportunistic benefits of aggregation strategies in the power system please refer to [26]. In addition, the ICES may present system benefits, such as reduced network usage due to local balancing which can defer the need for network reinforcement. When assessing the grid-integrated and grid-defected ICES profitability, these avoided costs should be accounted properly. Grid-defected ICES's cost mainly comprises of DER capital cost, operation and maintenance expenditure as well as fuel costs for the back-up system.

4.2. Integrated Community Energy System Model

Problems in energy systems related to efficient planning and operation are nowadays very complex and very often a large data set is associated. Optimization techniques such as linear and non-linear programming has played important roles in economic, secure and reliable operation of present energy system. The rise of DERs and bottom-up local energy initiatives further complicates the planning and operation of the present energy system as well as the associated economic and environmental implications [42]. In this context, DERs investment and scheduling problems have been addressed by several studies [43–47]. Many of these studies present sophisticated optimization techniques to solve DER investment and scheduling problems. In this process, several tools such as hybrid optimization model for electric renewables (HOMER) and distributed energy resources-consumer adoption model (DER-CAM) have been developed [43,47]. In HOMER, investment and operation costs as well as techno-economic and emission constraints are considered for the optimal sizing of hybrid renewable energy systems [47]. A recent study on grid-integrated and grid-defected operation of DERs at household level using HOMER is presented in [19]. DER-CAM is a mixed-integer linear programming model developed at the Lawrence Berkeley Laboratory [43,48]. DER-CAM is being widely used to solve DER investment and scheduling problems as well as for economic and environmental analysis of DERs [43,48]. Recently, a web-based version of DER-CAM, called DERs Web Optimization Service (WebOpt), as well as DER-CAM+, is also available [48].

Despite these developments, little has been done regarding DER investment and scheduling considering a collective and co-operative action of a group of households in local communities. The aggregation of DERs is proven to be beneficial even for relatively small groups of prosumers in comparison with individual configurations [6]. This work advances the study on the ICESs where a group of customers cooperates to efficiently manage their local energy systems, including DERs at individual premises as well as in common spaces. DER investment and scheduling problems as presented in [43], are taken to one level higher from a one-node building level to the multi-node community level. DER-CAM is used as the modelling basis due to its validated use as well as inbuilt capability to conduct economic and environmental analysis of DERs.

In this study, we adapted the previously one-node DER-CAM model to the multi-node DER-CAM based ICES model incorporating aggregated investment and operations of DERs at several household and community levels. The main highlights of the model over DER-CAM are:

(1) A new set for households (H) has been added to each equation;
(2) Different electricity, hot-water, space-heating and cooling demand profiles for each household are considered;
(3) The simulation and optimization of DER investment and scheduling in several households simultaneously are possible;
(4) In addition to individual investment in DERs, the community can also decide to invest in community-level technologies provided there are economies of scale;
(5) The local exchange between the households is enabled;

(6) The DER installed capacity and exchanges are constrained by the maximum line capacities;
(7) Grid connected and grid-defected operation options are available.

Figure 4 presents the input and output block diagram for the ICES model. In demand profiles, different energy carriers and end-uses are considered: electricity, hot-water, and space-heating and cooling demands for each individual household. Provided there is demand profile available, the community size can be chosen accordingly. The techno-economic data of the available household and community level DERs is also the input for the ICES model. The system of prices and charges varies according to the region or country and should be provided as an input. The resource data, such as temperature and solar irradiation, is also the key input to the model. Consumers have the possibility to invest in DERs and perform local exchanges in order to reduce their energy bills as well as carbon footprint. Optimal investment options are considered for both households and communities as more DERs become technologically and economically available.

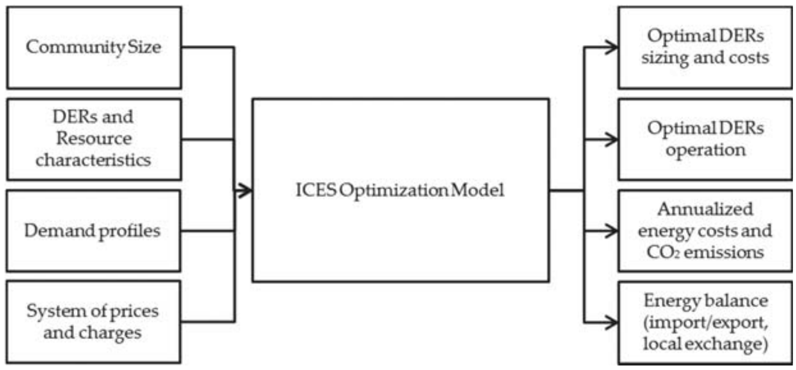


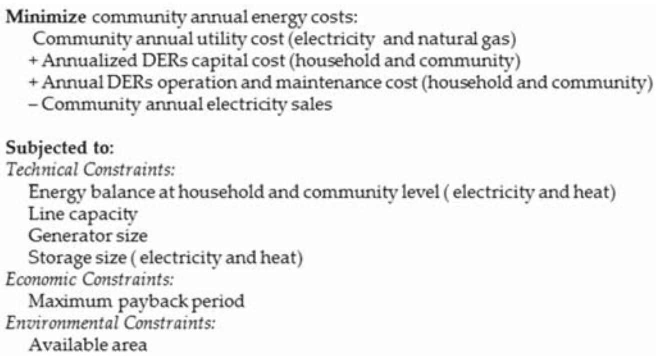
Figure 4. Block diagram of the ICES model. DER: distributed energy resource.

The outputs of the model are optimal for DER sizing and operational for both household and community level. The annualized energy costs and CO_2 emissions are used as performance metrics for economic and environmental analysis. In addition, detailed data on energy balance at household and community level such local exchange, unused or curtailed energy, import and export is also available as output.

4.3. Integrated Community Energy System Model Formulation

Similar to DER-CAM, the ICES optimization model is a mixed integer linear programming. It has been solved in the general algebraic modelling system (GAMS) environment [49]. Figure 5 presents the structure of the DER-CAM based ICES model, including the main objective function as well as the key constraints. The main objective of the model is to minimize annualized total energy costs for the community. The community annual energy costs consist of annual utility costs for electricity and gas of each household; annualized DER capital; operation and maintenance costs, as well as revenues from the annual electricity sales outside of the community.

The operation of ICESs is subjected to several techno-economic, and environmental constraints. Technical constraints mainly include the operational constraints. The energy balance of both heat and electricity at household and community level should be ensured such that local generation and imports always exceed the demand. Energy imports and exports capacity are constrained by the thermal limit of the conductor. The maximum generation is limited by the installed capacity. The operation of storage is constrained by several storage parameters, such as size, charging and discharging efficiency. Economic constraints include a maximum payback period allowed to get a return on investment in ICESs. The size of DERs, such as solar PV, is also constrained by the available area for installation whereas generation from solar PV is also constrained by resource availability in terms of solar insolation. The detailed model formulation is presented in Appendix A.



Minimize community annual energy costs:
Community annual utility cost (electricity and natural gas)
+ Annualized DERs capital cost (household and community)
+ Annual DERs operation and maintenance cost (household and community)
− Community annual electricity sales

Subjected to:
Technical Constraints:
Energy balance at household and community level (electricity and heat)
Line capacity
Generator size
Storage size (electricity and heat)
Economic Constraints:
Maximum payback period
Environmental Constraints:
Available area

Figure 5. Structure of the ICES model.

5. Case Study: Integrated Community Energy System in The Netherlands

The described ICES model has been tested in a 77 household virtual energy community in the Netherlands. This community size has been chosen as per the availability of the open access smart meter data set Zonnedael from Liander on household electricity and natural gas consumption in the Netherlands [50]. The annual electricity, space heating, hot-water, and cooling community demands are 327 MWh, 781 MWh, 310 MWh and 0 MWh, respectively. The annual gas consumption is 133,618 m^3. The total annual energy cost is 152,372 € and total annual CO_2 emissions are 390 tons.

5.1. Energy Demand Profiles and Weather Data

The individual hourly metered data for both electricity and gas are obtained from the Liander open data platform [50]. The aggregated hourly demand profiles of the 77 households for electricity and gas are presented in Figure 6. The demand profile varies depending on household types, occupants and their behavior. Furthermore, the seasonal variation on the natural gas demand is significant whereas electricity demand has a slight seasonal variation. The annual electricity demand among households ranges from 1000 to 11,173 kWh whereas the natural gas demand varies between 69 and 790 m^3. These profiles are further processed to represent the three typical demand profiles namely week, peak and weekend, for each month and for each household, in order to make them suitable for the ICES model input. The hourly solar irradiance, wind speed and temperature data are obtained from [51].

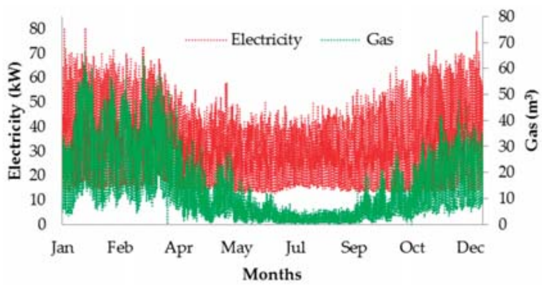


Figure 6. Aggregated hourly data for electricity and natural gas consumption.

5.2. System of Prices and Charges

The Dutch electricity and gas prices and charges for 2015 are presented in Table 1. The Netherlands uses a mix of volumetric and fixed charges for the electricity and gas supply services. The network tariffs and suppliers' margins are a fixed cost per month per household; wholesale energy prices are passed-through and sustainable energy surcharges (SDE) as well as regulated energy taxes are volumetric (€/MWh). Although, the Netherlands has a net metering policy (*saldering*) in place for annual energy balance, we do not consider it in this study. According to the Postcoderoos regulation to promote DER penetration and local balancing, renewable electricity could be generated and sold to consumers in the same postcode area. Participants get discount in energy tax which is financed by increasing the energy prices to the rest of the consumers. This regulation allows implementation of ICESs. Furthermore, for household electricity, consumers' annual tax reduction is applied. ICESs as entities with higher consumption are subjected to lower tax regimes as presented in Table 1. Therefore, it is assumed that ICESs consumers do not benefit from annual tax reduction.

Table 1. Dutch system of prices and charges for electricity and gas in 2015. SDE: sustainable energy surcharges.

Components	Electricity	Gas
Electricity procurement and supply costs		
Wholesale energy price	Amsterdam power exchange (APX)	Title transfer facility (TTF)
Suppliers margin	3.25 €/month	3.25 €/month
Network tariffs	19.22 €/month	12.34 €/month
State-introduced price components		
SDE		
0–10,000 kWh	0.0036 €/kWh	0.0074 €/m^3
10,000–50,000 kWh	0.0046 €/kWh	(up to 170,000 m^3)
50,000–10 million kWh	0.0012 €/kWh	-
Regulated energy tax		
0–10,000 kWh	0.1196 €/kWh	0.1911 €/m^3
10,000–50,000 kWh	0.0469 €/kWh	(up to 170,000 m^3)
50,000–10 million kWh	0.0125 €/kWh	-
Tax reduction	312 €/year/house	-
Value added tax	21%	21%

5.3. Distributed Energy Resources Techno-Economic Data

Table 2 presents the techno-economic data of the household and community level DERs used in this study. In addition, fixed costs of 2000 € and 10,000 € per storage unit is assumed for household and community storage units respectively, for the cost associated to the battery management systems and bi-directional inverters. The fixed costs for charging infrastructure for electric vehicles is assumed to be 1071 € per vehicle [52]. Similarly, the fixed costs for absolute chillers, ground source HP and heat storage is assumed to be 1000 €, 2286 € and 1000 € respectively. The economies of scale effect is evident in case of community investment. The cost of capital is 5% and the maximum payback period for the investment is limited to 10 years. The CO_2 emissions from natural gas is 0.18 kg CO_2/kWh. The emissions per kWh of electricity consumed through the Dutch grid is 0.44 kg CO_2/kWh [53]. The CO_2 tax is assumed to be 8 €/ton.

Table 2. Techno-economic data for household and community level DERs. ASHP: air source heat pumps.

Level	DERs	Capital Cost (€/kW(h))	Operation and Maintenance Costs (€/kW(h)/Year)	Life-Time (Year)	Reference
Household	Solar PV	1280	6	30	[54]
	Electric Storage	300	1.3	10	[55,56]
	Heat Storage	100	0	17	[57]
	Absolute chillers	525	22.6	20	[57]
	ASHP	558	6	30	[58]
	Ground-source HP	1076	27.6	30	[58]
	Solar thermal	500	5	20	[57]
	Electric vehicles	130	1.3	10	[52,59]
	Micro-CHP	8000 (1 kW)–4000 (3 kW)	0.021/kWh	20	[60]
Community	Community PV	1000	5	30	[54]
	Community Storage	250	1.2	10	[55,56]

6. Results

6.1. Baseline Case

The current energy system in which consumers purchase all their energy demand from the grid is considered as the baseline for the assessment of the ICES. To reduce computational time, for most of the study, a group of the first 20 households out of the available data of 77 households is considered. These households cooperate to have a more efficient local energy system in the form of an ICES. However, all 77 households are considered to simulate the effect of the community size. The reference year is 2015 and input data are from the Netherlands. For 20 households' ICES, the annual electricity, hot-water, space heating and cooling demand are 71.2 MWh, 167.4 MWh, 67.7 MWh and 0 MWh, respectively. The total annualized energy cost is 33,459 € and total annual CO_2 emissions is 84.5 tons.

6.2. Individual Distributed Energy Resources Investment

The households are assumed to be economically rational profit-maximizers. In the current liberalized market, households can invest in DERs and trade the surplus to the energy market through the aggregators. Most of these households can optimize their energy systems based on onsite conditions, energy prices, and available DER technologies. The economic benefits include, among other, avoided energy purchase costs and revenues from selling energy surplus. However, these households operate as independent individual units and do not contribute towards local energy exchange.

In this case, the investment takes place mainly in roof-top solar PV and heat-pumps, see Table 3. As presented in Table 4, significant cost savings are achieved due to installation of DERs at households. Savings in total energy costs and total CO_2 emissions are 15% and 48% lower than the solely grid supplied option (baseline), respectively.

Table 3. Optimal DER investment for grid-integrated ICES. HP: heat pump.

Level	Individual DER Investment		Individual DER Investment (ICES)		Individual Plus Community DER Investment (ICES)	
	PV (kW_e)	HP (kW_{th})	PV (kW_e)	HP (kW_{th})	PV (kW_e)	HP (kW_{th})
H1	12	8	8	8	-	8
H2	6	9	8	9	-	9
H3	5	2	7	2	-	2
H4	5	2	8	3	-	3
H5	6	3	9	3	-	3
H6	9	5	9	5	-	5
H7	11	6	9	6	-	6
H8	7	5	9	5	-	5
H9	8	6	8	6	-	6
H10	7	5	9	5	-	5
H11	4	3	8	3	-	3
H12	11	6	11	6	-	6
H13	5	3	8	3	-	3
H14	4	4	8	4	-	4
H15	4	0	8	0	-	0
H16	4	4	6	4	-	4
H17	8	4	11	4	-	4
H18	3	0	8	0	-	0
H19	7	5	9	5	-	5
H20	12	5	9	5	-	5
Community	-	-	-	-	168	-
Aggregated	139	87	172	88	168	88

Table 4. Grid integrated ICESs.

Cases	Annualized Total Energy Costs (€)	Annual CO_2 Emissions (tons)
Grid supply (baseline)	33,459	84.5
Individual DER investment	28,615	43.9
Individual DER investment (ICES)	26,872	32.9
Individual plus Community DER investment (ICES)	23,951	32.9

6.3. Grid-Integrated Integrated Community Energy System

An increasing number of energy communities are willing to take control of the energy system and prefer to optimize the local energy system based on total energy costs or CO_2 emissions. The model assumes that households within an ICES are energy cautious, co-operative and economically rational utility-maximizers. The households within ICESs perform similarly to the case of individual DER investment but also contribute towards local energy exchange. Hence, the prosumer households can optimize their self-consumption and feed electricity into the community pool based on techno-economic and environmental criteria. The economic benefits include, among others, avoided energy purchase costs and revenues from selling energy surplus at community level. The community can also collectively decide to invest in community DERs, such as community PV and storage. In the latter case, further cost savings are foreseen in capital costs as well as in operation and maintenance costs of DERs as presented in Table 2. Based on this distinction, we identify two cases of ICES, namely an ICES with individual investment and ICESs with individual and community investment.

6.3.1. Investment and Operation

We assume that in the base case, there is no investment in DERs. The investment results based on objectives to reduce total energy costs are presented in Table 1 for the individual DER investment, the ICES with individual investment and the ICES with individual plus community investment cases. For the given system of prices and charges, resource availability, techno-economics of DERs and demand, the investment takes places in solar PV and air source heat pumps (ASHP). As the heat demand is balanced within the households, the installation size of the HPs does not differ between cases whereas due to the possibility for local exchange and community investment, the amount of PV investment varies in all three cases. The possibility of local energy exchange enables further investment of 33 kW of solar PV from the individual DER investment case to the ICES with the individual investment case.

Figure 7 illustrates the energy balance at the ICES with the individual investment case. PV generation refers to aggregated profiles of 20 households whereas PV self-consumption represents aggregated self-consumption of PV generation at each household. The surplus from each household is first pooled to manage the local deficit. As PV is the only generation and each household has Solar PV installed, the local exchange on this day has a small share (37 kWh) but it is expected to increase with the diversification of DERs. Ultimately, the remaining surplus is traded to the energy market directly or through intermediaries.

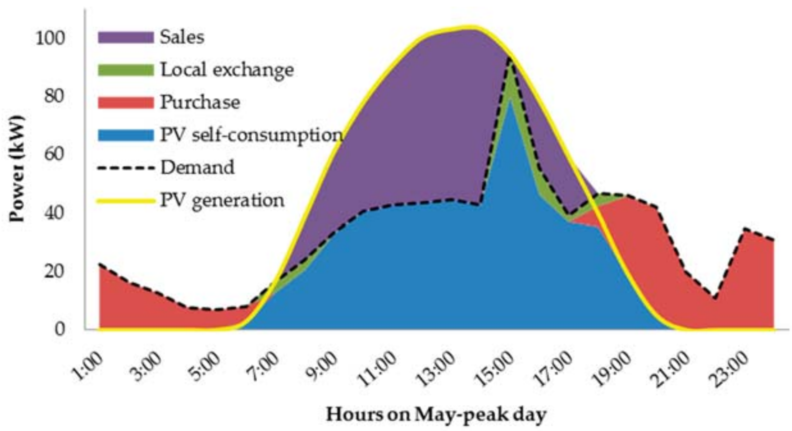


Figure 7. Energy balance for may-peak day for the grid-integrated ICES.

6.3.2. The Economics of Grid-Integrated Integrated Community Energy Systems

The results based on objectives to reduce total energy costs are presented in Table 4 for the baseline, the individual DER investment, the ICES with individual investment and the ICES with individual plus community investment case studies. ICES implementation leads to further savings in terms of total energy costs as well as CO_2 emissions due to local energy exchange, community engagement through load shifting, and lower tax regimes for larger consumers and economies of scale. We assume that ICES member households are more conscious and are capable of load shifting by 15%. For the ICES with the individual plus community investment case, further cost reductions of 16% are achieved compared to individual DER investment, thanks to economies of scale of community PV. In terms of CO_2 emissions, a further 11 (25%) tons of CO_2 is avoided in the respective ICES cases compared to the individual DER investment case.

Figure 8 represents detailed results of all four grid-integrated case studies. Although the major energy cost saving comes from technological change from natural gas-based heating systems to HPs and self-consumption, savings in policy costs and taxes are also significant. As the Dutch system of prices and charges uses fixed costs for network costs and suppliers' margins as presented in Table 1, no savings are possible in these categories through implementation of a grid-integrated ICES. The DER costs are a major component in a grid-integrated ICES.

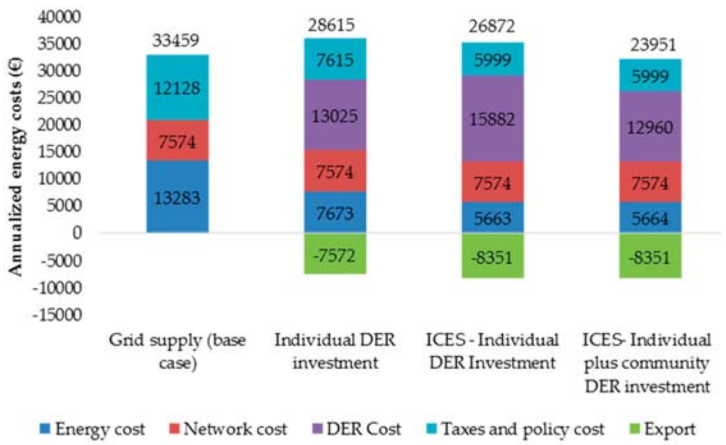


Figure 8. Detailed breakdown of annualized energy costs for different grid-integrated cases.

6.3.3. Effect of Community Size

The household DER investment depends on household demand as well as the possibility of local exchange within ICESs. For the grid supply baseline and the grid-integrated ICES with individual DER investment, the annualized total energy costs and CO_2 emissions evolutions with increasing community size are presented in Figures 9 and 10, respectively. The derivative of total energy costs and CO_2 emissions decreases more rapidly with increasing community size. The CO_2 emission reduction is much more significant compared to the reduction in the total energy costs. However, this is highly subjected to the invested technology-mix of solar PV and HPs. As various DERs such as energy storage, fuel cells and micro-wind with diverse generation hours are invested, higher local exchange is expected. This can significantly impact the trend on total energy costs and CO_2 emissions.

In Figure 11, the reduced annual energy costs and avoided annual CO_2 emissions are the difference between the base case and the grid-integrated ICES with the individual DER investment case divided by the number of households. Unlike Figures 9 and 10, the non-linearities in reduction in total energy costs and CO_2 emissions per households with increasing community size is observed. In general, the total benefit per household increases with increasing community size whereas the avoided CO_2 emission per household also increases slightly. These non-linear trends can be explained as follows. The household demand profiles considered in this study are measured data and therefore are not homogeneous. In addition, the investment in roof-top PV constrained by space availability introduces further non-linearity. As only individual household investments are considered in this particular case, the economies of scale are limited. Due to the small area, the stochasticity in generation and demand profiles are also limited. To conclude, the economic and environmental benefits of the increasing community size is not evenly distributed and cost and benefit allocation should be designed based on local conditions.

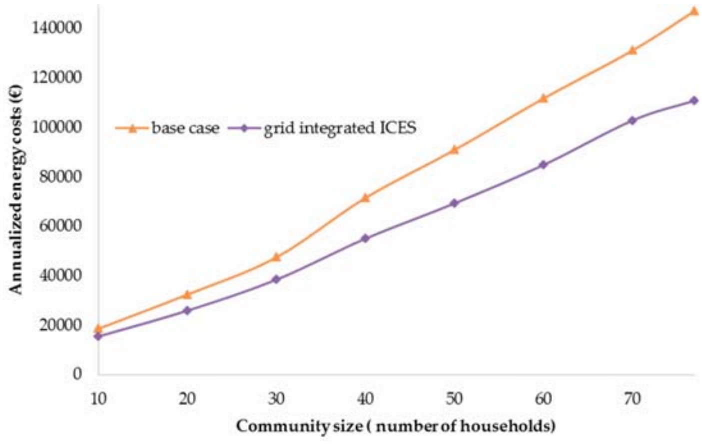


Figure 9. The effect of community size on total energy costs of the ICES.

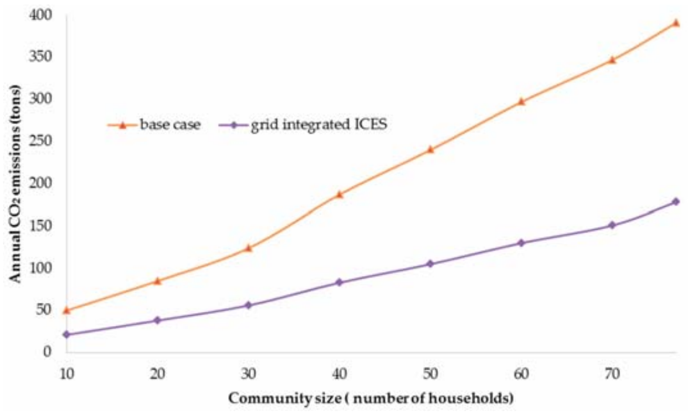


Figure 10. The effect of community size on CO_2 emissions of the ICES.

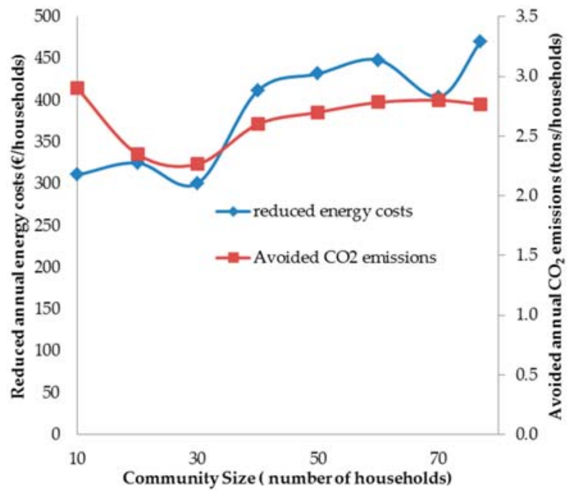


Figure 11. The effect of community size on CO_2 emissions of the ICES.

6.3.4. Sensitivity Analysis

The present energy landscape is changing [19,22,61]. The customers are expected to be more flexible in the future [62–64]. The capital costs of DERs, especially solar PV and electric storage are falling more rapidly [19,65]. The CO_2 prices are expected to increase [66]. Moreover, in urban areas, limited space is available for the DERs installation. To address the changing energy landscape, a sensitivity analysis for some of the parameters assumed in this research is performed.

For illustration, a grid-integrated ICES with individual DER investments case with annualized total energy cost of 26,872 € and total annual CO_2 emissions of 32.9 tons is further analyzed. Figure 12 shows the result of a sensitivity analysis in terms of percentage deviations in annualized energy costs and CO_2 emissions. For example, increasing the cost of capital by 5% will increase the total energy costs and the total CO_2 emissions by 10% and 29%, respectively. The higher cost of capital leads to higher investment costs and the lower investment in DERs. Accordingly, the import from the grid will be higher and the export to the grid will be lower, leading to the higher total energy costs and CO_2 emissions. If exporting the excess energy to the market or neighboring energy communities via the grid is not an option, the ICES loses the revenues from the export. This leads again to the lower investment in DERs, increasing the total energy costs and CO_2 emissions by 9% and 23%, respectively. There is widespread consensus that in order to have a significant contribution to the climate policy, the CO_2 price or tax should be very high. Increasing CO_2 tax from 8 €/ton to 50 €/ton will increase total energy costs by 6% and reduce CO_2 emissions by 4%. This can be explained by higher investment in low-carbon DERs leading to the higher energy costs and the lower CO_2 emissions. The decrease in capital cost makes investment in DERs more attractive. For example, 20% decrease in capital costs of DERs will reduce total energy costs and CO_2 emissions by 19% and 13%, respectively. This can be attributed to the avoided energy costs for import from the grid and the higher revenues through export of the excess energy. At the same time, the ICESs members are considered to be more energy conscious due to their engagement in the development and operation of the local energy system. The possibility of further 15% load shifting within the ICES will reduce the total energy costs and CO_2 emissions by 5% and 12%, respectively. This can be explained by flexibility within ICESs leading to the higher local exchange and lower import during peak hours.

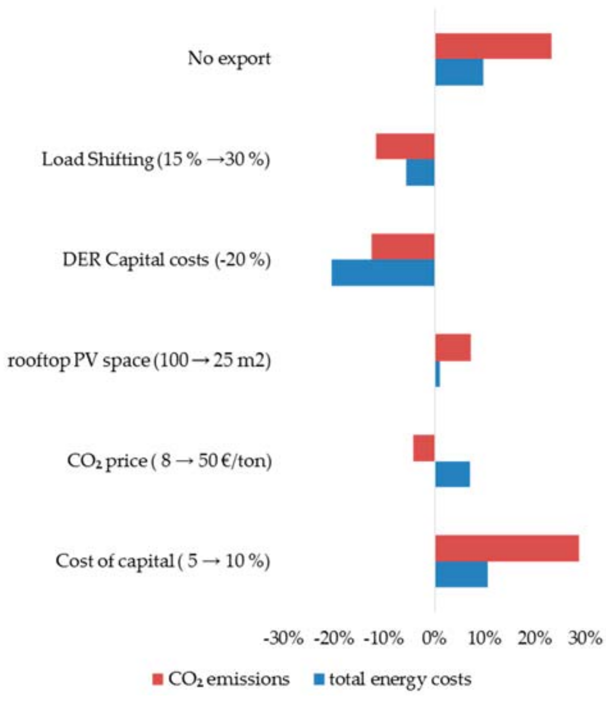


Figure 12. Sensitivity analysis of input parameters affecting total energy costs and CO_2 emissions.

The decrease in capital costs has more impact than performing the load shifting, as the former reduces both the import and increases the export of energy whereas the latter only reduces the energy cost by less import during peak hours and more local energy exchange. Moreover, among the considered parameters in this analysis, the performance metrics are more sensitive to input parameters such as DER capital costs, cost of capital and export options as these parameters can directly impact the amount of DERs invested in the ICES.

6.4. Grid-Defected Integrated Community Energy System

More communities are willing to take complete control of their energy systems. Some of these energy communities might decide to defect from the grid for non-economic reasons such as energy independence, higher CO_2 emissions reductions than the centralized system, self-governance and other local preferences. For further analysis, we use a grid-defected ICES with an individual plus community DER investment case.

6.4.1. Investment and Operation

In the case of grid defection, all the community energy demand has to be met locally. Therefore, more and diverse technologies are invested in the grid-defected ICES compared to the grid-integrated ICES case. In the grid-integrated case the DERs invested are community PV (168 kW) and air-source HPs (0.24–1.1 kWe) whereas in the case of the grid defection, the DERs invested are community PV (1274 kW), household and community storage (1660 kWh), air-source HPs (0.4–1.5 kWe) as well as electric vehicles (16–38 kWh), for details see Tables 3 and 5 respectively. The electric vehicles are used in this case as an alternative form of energy storage and the driving behavior is not considered. For environmental reasons, we do not consider the option of a back-up diesel generator either.

Table 5. Optimal DER investment for the grid-defected ICES.

Level	PV (kW_e)	HP (kW_{th})	Electric Storage (kWh)	Electric Vehicles (kWh)
H1	-	9	-	16
H2	-	9	-	8
H3	-	2	28	33
H4	-	3	-	15
H5	-	4	-	13
H6	-	6	-	18
H7	-	6	-	
H8	-	5	30	38
H9	-	6	-	12
H10	-	6	-	12
H11	-	3	-	11
H12	-	7	-	17
H13	-	3	-	11
H14	-	4	-	7
H15	-	0	16	20
H16	-	5	-	8
H17	-	4	-	18
H18	-	0	-	12
H19	-	6	-	14
H20	-	6	-	18
Community	1274	-	1586	-
Aggregated	1274	87	1660	303

The reliability is defined as the ratio of supplied energy to the total demand. Lower energy costs are expected for the grid-defected system with lower reliability but consumers have to compromise with the comfort of having electricity around the clock. Non-served energy refers to the amount of energy demand not met by the ICESs whereas unused energy refers to surplus energy not absorbed within ICESs and which has to be curtailed, as exporting to neighboring communities or the national grid is not an option due to the absence of a physical connection. In the case of grid defection, the amount of unused energy is significant. For example, in this particular case, 400,298 kWh of unused electricity has to be curtailed annually which is 6.6 times higher than the annual electricity demand for the whole community. This can be attributed to the oversized DERs in comparison to the grid-integrated case. The grid-defected ICES implies an oversized and rather expensive local energy system with long periods of unused energy from renewable sources to be curtailed, as emphasized in Figure 13. However, this situation can change with a more diverse technology-mix.

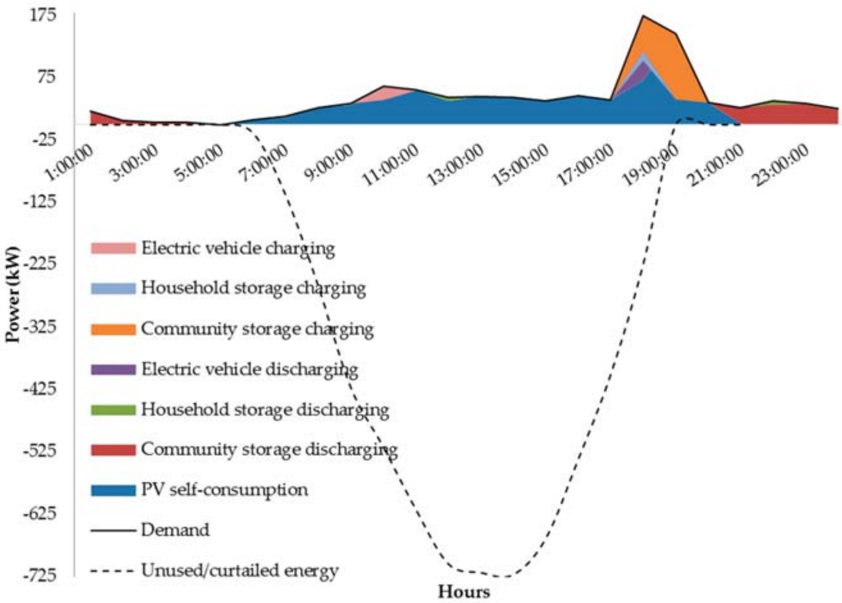


Figure 13. Energy balance on peak-day of May for the grid-defected ICES.

6.4.2. The Economics of Grid-Defected Integrated Community Energy Systems

Table 6 presents total energy costs and CO_2 emissions for the grid-integrated and the grid-defected ICES case with individual plus community DER investment. Under current DER economics, the grid-defected case is 8.3 times more expensive than the grid-integrated case. However, further CO_2 emission reduction of 58% is achieved in the grid-defected case compared to the grid connected case. Figure 14 presents a detailed cost breakdown for both the grid-integrated and the grid-defected cases for the ICES with individual plus community DER investments.

As seen in Figure 14, grid-defected ICESs are not yet economically rationale. The grid defection might still make economic sense if there is a huge network connection or reinforcement costs and lower investment costs for energy storage. For grid-defected ICESs to be economically feasible, they might have to be connected back to the grid so that the unused or curtailed energy can be marketed to the neighboring communities and the energy markets or used to provide system services for the whole energy system [19]. In this case, the system will be self-sufficient on the demand side but will still depend on the network to transfer the surplus energy. The energy community in Feldheim, Germany is the prime example for this case. The Feldheim energy community is self-sufficient in terms of demand and only consumes 1% of total generated energy, selling 99% of the energy to other market parties [67].

Table 6. Total energy costs and CO_2 emissions for grid-integrated and grid-defected ICES cases.

Case	Annualized Total Energy Costs (€)	Annual CO_2 Emissions (tons)
Grid integrated	23,951	32.9
Grid defected	198,762	14

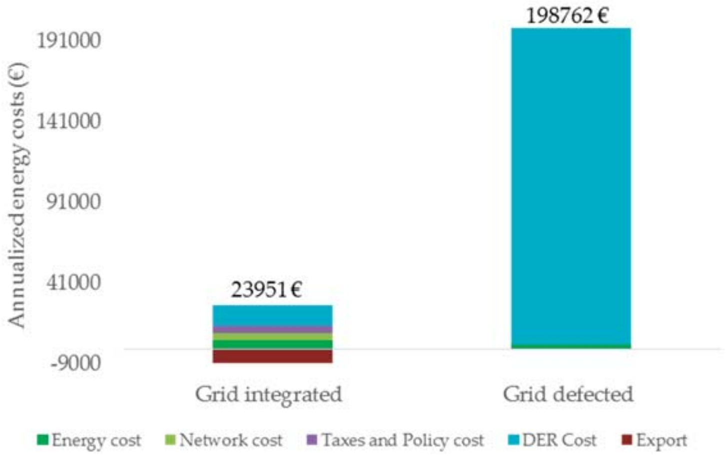


Figure 14. Annualized energy costs for the grid-integrated and grid-defected cases.

7. Conclusions

In this research, ICESs are conceptualized and assessed as an alternative for local energy supply. ICESs can operate in a grid-connected and grid-defected mode based on community objectives. Local communities can optimize their energy system based on onsite conditions, energy prices, and available DER technologies. A model-based framework considering benefits and costs to assess the value of grid-integrated and grid-defected ICESs is presented. The proposed modelling framework can establish the value of ICESs in the changing local energy landscape. The study focuses on economic and environmental benefits from the community perspective and proposes the community annualized energy cost and the annual CO_2 emission metrics as main performance indicators.

Under current Dutch energy prices and charges, grid-integrated ICESs are already an attractive option over solely grid-supplied alternatives, both in terms of reducing energy costs and CO_2 emissions. The total energy costs and CO_2 emissions are found to be more sensitive to input parameters which directly impact the optimal size of the DERs installed in the ICES, such as DERs capital costs, cost of capital and possibility to sell excess energy. Diversity of demand, as well as generation profiles among the households within the ICES, leads to the increased local exchanges reducing energy losses in comparison to importing energy from the system. An analysis on effect of community size reveals that the benefits of ICESs in terms of costs and emissions are highly dependent on demand profiles of the households in the community size considered.

Moreover, there could be a spill-over effect of the ICES savings on the remaining customers of the whole energy system, such as paying less taxes and policy surcharges. At the same time, these communities already contribute toward energy policy goals through local investment. The growth of DERs in general and the ICES in particular might affect all actors of the energy system alike. It is important to prevent opportunistic aggregation and free rider behaviours that avoid paying system costs which otherwise should be recovered through other market agents. Moreover, the benefits of the grid-integrated ICES are highly subjected to the system of prices and charges as well as institutional settings available for their operation.

With respect to grid defection, it is far from being economically rationale over grid-integrated options. Reliability and permanent local energy balance need leads to more diverse but over-sized grid-defected renewable systems with a very high unused energy to be curtailed. At the same time, if the unused energy in the grid-defected case can be marketed to the neighboring communities and the energy markets or used to provide system services for the whole energy system, the economics of the ICES might improve as well. In this case, the system could be self-sufficient on the demand side but will still depend on the network to transfer the surplus energy. The energy community in Feldheim, Germany is a very good example for this particular case.

Under current energy prices and charges, it is more likely to have grid-integrated communities than grid-defected communities. Future research should establish a system of prices and charges for the efficient local exchange in ICESs. An assessment on a grid defection alternative should be performed for cases requiring significant network connection or re-enforcement costs. To prevent inefficient grid defection, network and sunk system costs recovery should be carefully addressed.

In future, with an increasing need for flexibility in the whole energy system, surplus energy from both grid-integrated or grid-defected ICESs might be traded in different energy markets or used in providing different energy services. This is expected to positively affect the economics of both grid-integrated and grid-defected ICESs. This emphasizes the important role of the grid in enabling future energy systems, such as ICESs. Further improvement in the economics of the ICES can be expected, as the energy storage costs decrease, more storage technologies become available, and their different energy services is utilized.

Integrating multiple local generation, storage, energy efficiency and demand management systems not only provides higher economic benefits for ICESs but also would enable them to play a more active role in achieving low-carbon growth. An ICES offers more than the low-carbon transition; it improves efficiency, strengthens security of supply and empowers local customers. Moreover, due to challenges in ICESs operation such as joint investment, joint decision making, and fair allocation of costs and benefits among members, it might be challenging to capture all the benefits of ICESs demanding an appropriate institutional design of such systems. This research will certainly help in understanding the role of ICESs in the future energy systems which can be useful in decision support as it can help to ensure necessary precautions as well as arranging suitable institutions for low-carbon transformation of the local energy systems.

Acknowledgments: European Commission awarded Binod Prasad Koirala an Erasmus Mundus fellowship for the Joint Doctorate in Sustainable Energy Technologies and Strategies. The authors would also like to acknowledge the collaboration with the DER-CAM team at Berkeley Lab.

Author Contributions: Binod Prasad Koirala and José Pablo Chaves Ávila developed the model formulation and analyzed the data. Tomás Gómez, Rudi A. Hakvoort and Paulien M. Herder assisted in developing the research design and assessment framework; Binod Prasad Koirala wrote the paper and improved it further with the feedback from José Pablo Chaves Ávila, Tomás Gómez, Rudi A. Hakvoort and Paulien M. Herder.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Model Formulation

In addition to the model equations presented in [43], we have added further equations to the ICES model to simulate the local exchange and community level operation, see Table A1. The indices y, H, m, d, h refer to year, household, months, day types (week, peak, weekend) and hours, respectively.

Appendix A.1. Decision Variables

Table A1. Additional decision variables in ICES model.

S.N.	Decision Variables	Description
1	$ElectricityCommunityPhotovoltaics_{y,m,d,h}$	Hourly Electricity generated by community PV
2	$ElectricityCommunityPhotovoltaicsOnsite_{y,m,d,h}$	Hourly Electricity generated by community PV for onsite use
3	$ElectricityCommunityPhotovoltaicsExport_{y,m,d,h}$	Hourly Electricity generated by community PV for export
4	$ElectricityforCommunityStorage_{y,m,d,h}$	Hourly electricity needed for charging community electric storage
5	$ElectricityfromCommunityStorage_{y,m,d,h}$	Hourly Electricity discharge from community electricity storage to meet community demand
6	$CommunityElectricSales_{y,m,d,h}$	Hourly electric sales from the community
7	$CommunityElectricityPurchase_{y,m,d,h}$	Hourly electric purchase from the community
8	$CommunityElectricityConsumed_{y,m,d,h}$	Hourly electricity demand at the community
9	$CommunityContractCapacity_{y,m}$	Monthly Peak import or export from community
10	$TotalCapacityCommunityInYearY_{CommunityContinuousTechnology,y}$	Installed capacity of community generation technologies such as community PV and community electric storage

Appendix A.2. Objective Function

The objective function is to minimize annualized community energy costs, see Equation (A1).

$$\begin{aligned} &AnnualizedCommunityEnergyCosts \\ &\quad = CommunityElectricCosts + CommunityNGCost \\ &\quad + CommunityDERCost - CommunityAnnualElectricitySales \end{aligned} \tag{A1}$$

where, community electric costs (see Equation (A2)) and community natural gas (NG) costs (see Equation (A3)) represent total utility costs for electricity and natural gas for the whole community.

$$\begin{aligned} &Communityelectriccosts \\ &\quad = \sum CommunityElectricFixedCost_{y,m} \\ &\quad + \sum CommunityElectricTOUCost_{y,m} \\ &\quad + \sum CommunityElectricCO2Cost_{y,m} \end{aligned} \tag{A2}$$

$$CommunityNGTotalCost_{y,m} = \sum_{m}\sum_{H} HouseholdNGTotalCost_{y,H,m} \tag{A3}$$

The community DER Cost (see Equation (A4)) is the aggregated cost of household and community level DERs and considers both capital as well as operation and maintenance costs.

$$\begin{aligned} &CommunityDERCost_{y} \\ &\quad = \sum_{H} HouseholdDERCost_{y,H} + AnnualizedCapitalCostCommunity_{y} \\ &\quad + \sum_{m} (FixedMaintenanceCostCommunity_{y,m} \\ &\quad + VariableMaintenanceCostCommunity_{y,m}) \end{aligned} \tag{A4}$$

The community annual energy sales (see Equation (A5)) refers to the revenue generated from the export outside of the ICES. Where, PX is the day ahead market price input to the model and community electric sales is the hourly amount of energy export from the ICES and calculated in the energy balance equation. The import happens at retail prices whereas the export is remunerated at wholesale prices.

$$\begin{aligned} &CommunityAnnualElectricitySales_{y} \\ &\quad = \sum_{m,d,h} CommunityElectricSales_{y,m,dh} \times PX_{y,m,d,h} * NumberofDays_{m,d} \end{aligned} \tag{A5}$$

Appendix A.3. Constraints

The objective function (see Equation (A1)) presented above is subjected to several technical, economic, and environmental constraints. Technical constraints include community and household energy balance, line capacity, generator as well as storage size. For household energy balance equations, refer [43].

Appendix A.3.1. Community Energy Balance

The community energy pool consists of the surplus from each household (electric sales), the deficit from each household (electric purchase), and the generation from community DER technologies (community electricity generation, electricity community PV and electricity from community storage). For the grid-integrated ICES option, the surplus (community electric sales) can be exported and the deficit (community electricity purchase) can be imported through the external grid. However, for the grid-defected case, there is no exchange with the external grid and all the energy demand has to be met locally. The local exchange is the net surplus from the household which is consumed within the ICESs.

$$\begin{aligned} & CommunityNetExchange_{y,m,d,h} \\ & = \sum_{H} ElectricSales_{y,H,m,d,h} + ElectricityCommunityPhotovoltaics_{y,m,d,h} \\ & + CommunityElectricityGeneration_{y,H,m,d,h} \\ & + ElectrictyFromCommunityStorage_{y,m,d,h} - ElectrictyForCommunityStorage_{y,m,d,h} \\ & - \sum_{H} ElectricPurchase_{y,H,m,d,h} \end{aligned} \tag{A6}$$

$$\begin{aligned} CommunityNetExchange_{y,m,d,h} & \\ & = CommunityElectricSales_{y,m,d,h} \\ & - CommunityElectricityPurchase_{y,m,d,h} \end{aligned} \tag{A7}$$

Appendix A.3.2. Line Capacity

The household and community DER investment are constrained by the available connection line capacity which depends on conductor types.

$$\begin{aligned} CommunityContractCapacity_{y,m} & \\ & \geq CommunityElectricityPurchase_{y,m,d,h} \\ & - CommunityElectricSales_{y,m,d,h} \end{aligned} \tag{A8}$$

$$HouseholdElectricSales_{y,H,m,d,h} \leq HouseholdMaxExportCapacity \tag{A9}$$

$$CommunityElectricSales_{y,m,d,h} \leq CommunityMaxExportCapacity \tag{A10}$$

Appendix A.3.3. Storage Constraints

Equations (A11)–(A18) represent operation of community storage. The operation of storage is constrained by several storage parameters such as size, charging and discharging efficiency.

$$\begin{aligned} CommunityStorageElectricityStored_{y,m,d,h} & \\ & = CommunityStorageElectricityStored_{y,m,d,h-1} \\ & + CommunityElectricityStorageInput_{y,m,d,h} \\ & - CommunityElectricityStorageOutput_{y,m,d,h} \\ & - CommunityElectricityStorageLosses_{y,m,d,h} \end{aligned} \tag{A11}$$

$$\begin{aligned} CommunityElectricityStorageInput_{y,m,d,h} & \\ & = ElectricityforCommunityStorage_{y,m,d,h} \\ & \times CommunityElectricityStorageChargingEfficiency \end{aligned} \tag{A12}$$

$$\begin{aligned} ElectrictyFromCommunityStorage_{y,m,d,h} & \\ & = CommunityElectricityStorageOutput_{y,m,d,h} \\ & \times CommunityElectricityStorageDischargingEfficiency \end{aligned} \tag{A13}$$

$$\begin{aligned} CommunityElectricityStorageLosses_{y,m,d,h} & \\ & = CommunityStorageElectricityStored_{y,m,d,h-1} \\ & \times CommunityElectricityStorageSelfDischarge \end{aligned} \tag{A14}$$

$$\begin{aligned} CommunityElectricityStorageInput_{y,m,d,h} & \\ & \leq CommunityElectricityStorageCapacity_{y,m} \\ & \times CommunityElectricityStorageMaxChargeRate \end{aligned} \tag{A15}$$

$$CommunityElectricityStorageOutput_{y,m,d,h} \leq CommunityElectricityStorageCapacity_{y,m} \times CommunityElectricityStorageMaxDischargeRate \tag{A16}$$

$$CommunityStorageElectricityStored_{y,m,d,h} \leq CommunityElectricityStorageCapacity_{y,m} \tag{A17}$$

$$CommunityStorageElectricityStored_{y,m,d,h} \geq CommunityElectricityStorageCapacity_{y,m} \times CommunityElectricityStorageMaxDepthofDischarge \tag{A18}$$

Appendix A.3.4. Generator Constraints

Equation (A19) represent PV generator constraints due to the size and available solar insolation.

$$ElectricityCommunityPhotovoltaics_{y,m,d,h} = TotalCapacityCommunityInYearY_{CommunityPV,y} \times \frac{SolarInsolation_{m,h}}{PeakPVefficiency} \times PVefficiency_{m,h} \tag{A19}$$

Appendix A.3.5. Space Constraints

The household and community DER investment are constrained by the available area. The roof top area is shared by the solar PV and solar thermal Equation (A20). Similarly, the community PV size is constrained by the available common space Equation (A21).

$$\frac{TotalCapacityInYearY_{PV,y,H}}{PeakPVEfficiency} + \frac{TotalCapacityInYearY_{SolarThermal,y,H}}{PeakSolarThermalEfficiency} < MaxSpaceAvailableHouseholdPV \tag{A20}$$

$$\frac{TotalCapacityCommunityInYearY_{CommunityPV,y}}{PeakPVEfficiency} < MaxSpaceAvailableCommunityPV \tag{A21}$$

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Chapter 18

Integrated Community-Based Energy Systems: Aligning Technology, Incentives, and Regulations

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1 INTRODUCTION

As described in other chapters of this volume, technological advancement, falling costs, as well as support schemes for renewables, distributed self-generation, energy efficiency, and demand response has resulted in the rapid deployment of distributed energy resources (DERs) throughout the world, especially in Europe. DERs, by definition, not only include distributed generation but also energy storage, such as in the form of batteries, electric vehicles, and heat storage, as well as demand response. With increasing DERs penetration, the role of households and local communities is changing from passive consumers to active prosumers (van der Schoor and Scholtens, 2015). Accordingly, clusters of residential and community level DERs, in the form of local energy initiatives, such as integrated community energy systems (ICESs), capable of providing a viable alternative to the present centralized energy supply system are emerging. The future energy system is expected to be a combination of the centralized, large-scale system and the local distributed system. The interaction between central and local system will be determined by the ongoing innovation and the way energy market parties handle these developments.

In Europe, there are more than 2800 such initiatives in the form of energy cooperatives of which around 1000 are in Germany and around 350 are in the Netherlands, Fig. 18.1 (REN21, 2016; Morris and Pehnt, 2016; Hier Opgewekt, 2016). This has forced several energy utilities to develop new customer-centric business models for managing energy (Energy Post, 2013; E.ON, 2014; Burger and Weinmann, 2013, 2016). The important role of citizens

Innovation and Disruption at the Grid's Edge. http://dx.doi.org/10.1016/B978-0-12-811758-3.00018-8

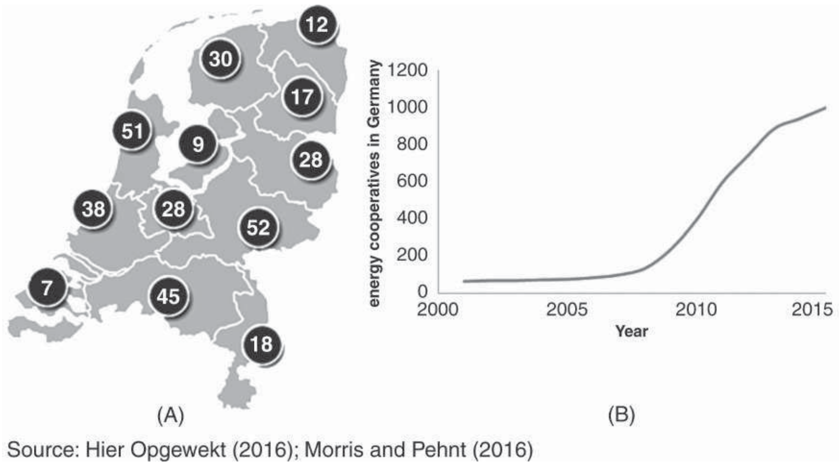

FIGURE 18.1 Energy cooperatives in the Netherlands (A) and in Germany (B).

and communities in the energy system has been highlighted also in the recent energy union package of the European union (Energy Union, 2015, 2016).

Although the local energy initiatives are rapidly emerging, the motivation so far has mainly been economic incentives. For example, the lucrative feed-in-tariffs in Germany attracted local investment in DERs through energy cooperatives. As a result, more than half of the renewables installed in Germany are now owned by local citizens and communities (Morris and Pehnt, 2016). However, the market conditions and support incentives in terms of feed-in tariffs have changed resulting in stagnation of the growth of energy cooperatives in Germany (DGRV, 2015). These cooperatives are now in dilemma on how to make most out of the locally generated energy. This means household and community generation have to compete with the centralized generation with economies of scale, highlighting further the need of higher local self-consumption of local generation. In addition, alternative business models, such as local balancing and ancillary services are needed to continue their growth.

A comprehensive and integrated approach for local energy systems where communities can take complete control of their energy system and capture all the benefits of energy system integration is still lacking. Many challenges, such as split-incentive problems, financing, operation, and complexity in decision-making remain for this new type of community energy organization (Koirala et al., 2016b). Would central community energy planning or market mechanisms better serve the objectives of ICESs? How can pricing and incentive schemes be structured to encourage DERs investments in ICESs? Which operational strategies lead to a reduction of peak demand? How can cost and revenue be fairly distributed to benefit the whole community and other stakeholders? In this chapter, we precisely address these issues for local energy systems, such as ICESs, which could also be applicable for broader solutions in the grid's edge.

Availability of numerous technologies, actors, institutions, as well as market mechanisms, further complicates the development of ICESs. Such complexity demands new mechanisms and institutional arrangements to optimally integrate generation and demand at a local level. New initiatives, such as reforming the energy vision in New York (NY REV) with goals to reduce 40% greenhouse gas emissions, to generate 50% electricity from renewables and to reduce energy consumptions of building by 23%, as well as its focus on sustainable and resilient communities can help further emergence of ICESs (NY REV, 2016), as further discussed in chapter by Baak in this volume.

This chapter consists of four sections in addition to the introduction. Section 2 provides new thinking for local energy systems and introduces the concept of ICESs. Section 3 covers the necessary institutional precursors of ICESs. Section 4 examines the institutional design of ICESs from technoeconomic perspective followed by the chapter's conclusions.

2 RETHINKING LOCAL ENERGY SYSTEMS

The technological and institutional changes in present energy system are rapid. In addition to aging infrastructures, these transformations have resulted in technical and economic changes in the power system as summarized in Table 18.1. The energy system is at the crossroad, providing a tremendous opportunity for the reorganization and transformation toward the more sustainable system. The key challenge of the future energy system is a seamless integration of increasing penetration of DERs. One of the prominent solutions lies in increasing self-consumption and matching supply and demand at the local level, such as in ICESs.

2.1 Integrated Community Energy Systems Concept and Definition

Local communities have started to respond to the challenges posed by unsustainable production and consumption practices in the energy sector. These communities are well-placed to identify local energy needs, take proper initiatives, and bring people together to achieve common goals, such as self-sufficiency, resiliency, and autonomy. Local energy projects are inclusive, democratic, and sustainable and might lead to job creation and economic growth (Lazaropoulos and Lazaropoulos, 2015). These initiatives can further the transition to a low-carbon energy system, help build consumer engagement and trust, as well as provide valuable flexibility in the market.

Bottom-up solutions are desired to capture all the benefits allotted by DERs. Recently, the interest of households and communities in generating, supplying, managing energy, as well as improving energy efficiency collectively has also increased and thereby local energy systems are being formed. Recent research also focuses on community energy system where citizens can jointly invest

TABLE 18.1 Technoeconomic Changes in the Energy Landscape

	Traditional power system	Future power system
Technical	Centralized	Centralized and decentralized
	Schedule supply to meet demand	Match both supply and demand
	Base load, off-peak, and peak power plants meet the demand	Decouple supply and demand with flexibility—grid expansion, demand-side management, storage and flexible back-up, low capacity factor for some technologies
	Passive network management	Active network management
	Flexibility from ramping-up and down, peak power plants, interruptible loads, interconnection	Flexibility market, demand response, storage, interconnection, curtailment
Economic	Centralized day-ahead, intraday, and balancing market	Centralized markets for energy and other services and decentralized market for local flexibility
	CO_2 emissions are external	CO_2 emission is internalized through carbon tax, carbon pricing
	Retail prices are in proportion to wholesale prices	Mismatch between wholesale and retail prices due to increasing fixed costs
	Volumetric network tariffs	Advanced network tariffs
	Price inelastic consumers	Price elastic consumers

and operate the local energy systems (Rogers et al., 2008; Walker et al., 2010; Bradley and Rae, 2012; Walker and Simcock, 2012; Wirth, 2014). In a liberalized market, it is possible to establish local producer/prosumer—consumer energy commons enabling them to cocreate commons-based smart energy system at the local level (Lambing, 2013).

In this context, ICESs are multifaceted smart energy system, which optimizes the use of all local DERs, dealing effectively with a changing local energy landscape. ICESs are capable of effectively integrating energy systems through a variety of local generation inclusive of heat and electricity, flexible demand, e-mobility, as well as energy storage. Such integrated approach at the local level helps in the efficient matching of local supply and demand, impacting the existing system architecture and influencing the way the energy systems evolve. The concept of ICESs, as building blocks for the smart grids, is further elaborated in detail (Koirala et al., 2016b; Mendes et al., 2011; Xu et al., 2015). ICESs also represent planning, design, implementation, and governance of energy systems at the community level to maximize energy performance while cutting costs and reducing environmental impacts (Harcourt et al., 2012).

ICESs should have defined system boundaries. Specifically, ICESs can integrate DERs at building and neighborhood scale. Typically, a cluster of households within a distribution transformer can be part of ICESs. The advantage of extending to multiple buildings lies in the variation of demand profiles and availability of multiple generation sources, increasing the flexibility of the system as well as economies of scale but is limited by the complexity of collective decision-making process.

2.2 ICESs as Sociotechnical System

ICESs are complex sociotechnical systems with a strong degree of complementarity enabled through physical and social network relationship, Fig. 18.2 (Künneke et al., 2010). The physical system consists of generation, distribution, storage, and energy management technologies to manage the commodities flow. The social system with different actors, such as consumers, prosumers, aggregators, energy suppliers, and system operators ensures efficient economic operation at minimum environmental effects at the same time providing consumers with different choice options. These systems are complex in the sense that they consist of different decision-making entities and technological artifacts that are governed by energy policy in a multilevel institutional space.

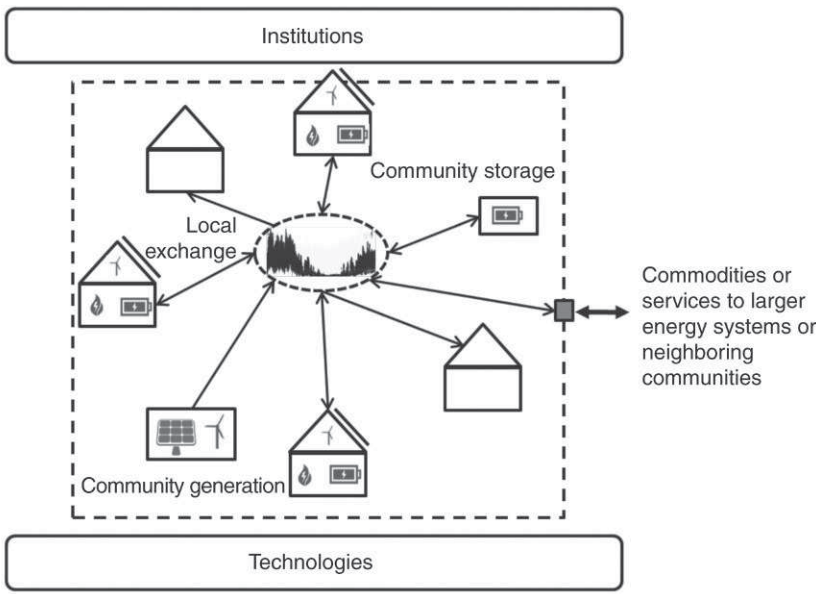

FIGURE 18.2 ICESs as complex adaptive sociotechnical systems.

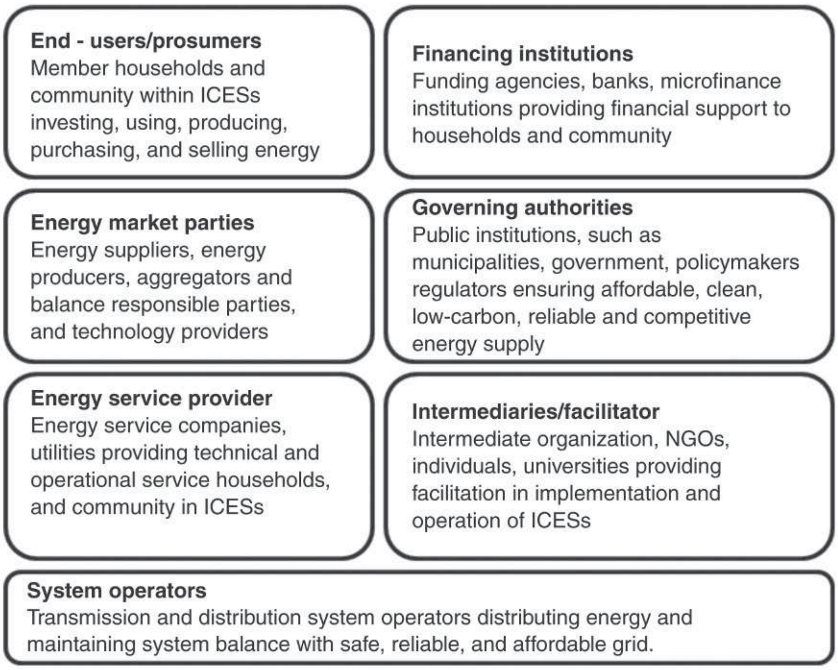

FIGURE 18.3 Various actors in ICESs.

2.2.1 Actors

The energy system comprises a great variety of public and private actors with different interest and functionalities within a specific institutional environment. The roles and responsibilities of these actors change in the context of ICESs as presented in Fig. 18.3. ICESs are community-based, providing more roles to them in investing, using, producing, selling, and purchasing energy. The complex technical operation in ICESs often needs the engagement of third-party actors, such as system operator or service provider.

2.2.2 Technologies

ICESs consist of households and community level DERs as shown in Fig. 18.4. Several DERs with flexible and intermittent generation, as well as demand- and supply-side management technologies are increasingly becoming available. The technology invested and topologies chosen by local communities is expected to substantially influence future energy system pathways. New services can be driven by information and communication technologies (ICTs) through advancement in the smart grids, for example, to align local demand and supply in time and location or to provide flexibility, as further discussed in the chapter by Knieps in this volume (Clastres, 2011; Järventausta et al., 2010). ICES can

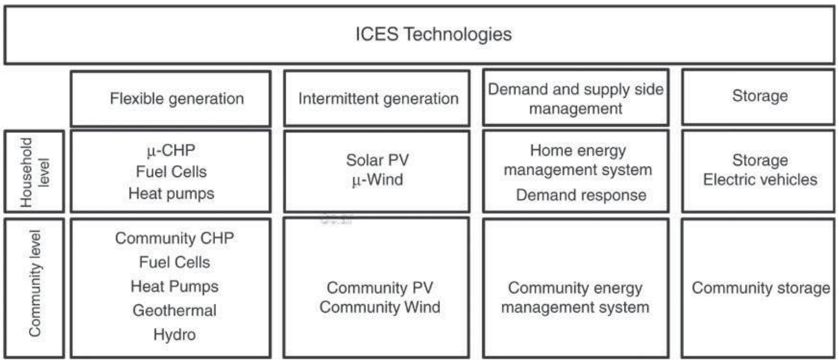

FIGURE 18.4 Few examples of available technologies for ICESs.

provide necessary local infrastructures for an efficient match between demand and supply complementing further development of smart grids. Development of smart-grid technologies and demand-side management technologies facilitate an increase in reliability and efficiency of such local energy systems.

2.3 Added Value of Integrated Approach

ICESs combine energy system integration and community engagement, Fig. 18.5. In this way, ICESs are capable of embracing technical and social innovation, cocreating sustainable and affordable local energy system.

The interactions and complementarities between the different energy carriers are increasing (Lund and Muenster, 2003, 2006; Lund and Kempton, 2014). Different energy carriers can work in synergies leading to a more sustainable and integrated energy system (Lund and Muenster, 2003, 2006; Lund et al., 2010, 2015; Orehounig et al., 2015). The advancement in ICTs as well as smart-grid technologies will further facilitate such integrated operation (Lobaccaro et al., 2016; Lund and Muenster, 2006; Orehounig et al., 2015). ICESs might provide cost-effective solutions to local congestions and help avoid or defer grid reinforcement foreseen with increasing penetration of local renewables.

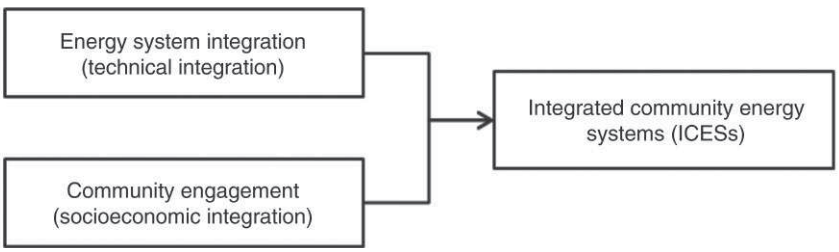

FIGURE 18.5 Technical and socioeconomic integration in ICESs.

ICES stand out from other energy system integration options due to engagement of the local communities. The engagement of citizens and communities increases the acceptance of new energy systems. ICESs also help to keep the local money for the local economy and help fight energy poverty. It not only creates more jobs at the local level but also increases values, such as trust, identity, and sense of community, helping to build stronger communities.

2.4 Benefits and Challenges of ICESs

2.4.1 Benefits of ICESs

The benefits of ICESs include reducing energy cost, CO_2 emissions, and dependence on the national grid, as well as (self-) governance. ICESs help to increase penetration of intermittent renewables and bring new roles for local communities, such as flexibility and ancillary services (Howard, 2014). ICESs provide opportunities for citizens and communities to decide about their energy future, thereby ensuring strong local support and social acceptance. Other benefits of ICESs include increased awareness, reduced energy poverty, affordable energy for all, as well as increased sense of community, pride, and achievement. The benefits of ICESs for communities, system operators, and policymakers are summarized in Table 18.2.

2.4.2 Challenges of ICESs

The main challenge for implementation of ICESs comes from the centralized design and regulation of present energy systems, which do not always provide level playing field for ICESs. In a centralized system, the energy and information flow are unidirectional. However, successful implementation of ICESs needs interaction among several actors of the energy system. For example,

TABLE 18.2 Benefits of ICESs

Community	System operators	Policymakers
Hedging against price fluctuations Modular in development Reliability Resiliency Economic benefits—savings and revenue generations Grid support within ICESs Higher efficiency Integrated Improved power quality Sense of community	Improved reliability of the energy system Grid support—ancillary services and flexibility Occasional roles as service provider Investment deferrals	Higher energy efficiency Higher renewables penetration Local economic growth Increased energy security Environmental benefits Sustainability

TABLE 18.3 Challenges of ICESs

Challenges	Description
Operation	Need a service provider or expert companies for complex technical operation beyond its technical capabilities
Financing	Access to private finance, microfinance, and loans for ICESs
Cost–benefit sharing	Fair allocation of costs incurred and revenue generated among actors
Business case	New business model for flexibility and ancillary services
Monetization of services	Monetization of essential community as well as other ICESs services
Managing utility relations or grid issues	Network access and cost recovery of network investment especially when energy networks are a natural monopoly

selling electricity to neighbors is not allowed and affordable grid access for community generation can be long, complex, and costly.

Although the technologies for ICESs are ubiquitous, there are major challenges in its institutional organization, which must be satisfactorily resolved before they can be successfully deployed and integrated. As highlighted in Table 18.3, these challenges include financing, operation, revenue adequacy, community participation, as well as the fair allocation of costs and benefits.

3 INSTITUTIONAL PRECURSORS FOR ICESS

3.1 Regulation

Energy laws and policies around the world have been built to support centralized energy systems. Accordingly, there are legal barriers to the implementation of ICESs. One of the most prominent ones is EU energy market legislation, the third energy package (EU, 2009). According to this package, generation, distribution, and retail should be unbundled. With the engagement of citizens and community, ICESs are likely to control the local energy system and take over all these roles as a single entity, demanding rebundling.

In the Netherlands, there are similar obligations to both small and large producers in terms of the license of supply (Avelino et al., 2014). As also discussed in the chapter by Löbbe and Hackbarth in this volume, in Germany, after 2014 amendment to the renewable energy law (EEG), small- and medium-sized producers have to compete with large producers (BMWI, 2014).

As also discussed in chapters by Pelegry and by Haro et al. in this volume, recent self-consumption regulation in Spain discourages self-generation as well as ICESs (MIET, 2015). Moreover, administrative hurdles for renewable energy installation, legislative uncertainty, disincentive for self-consumption and production, as well as ineffective unbundling of integrated energy companies inhibit ICESs implementation in Spain. Similarly, in Portugal, the *Decreto Lei n. 153/2014,* a net-metering law despite allowing self-consumption and trading with 10% contribution going to network maintenance, still does not encourage local energy exchange. Similar issues in the United States and Australia are covered in chapters by Baak, Jones et al., and Mountain & Harris, respectively, in this volume.

For the emergence of ICESs, space for innovation, often introduced by new actors is a necessary precondition. As ICESs might take different forms based on local conditions, the legislation should keep open space for as much as possible options for the development of local models. Experiments should be encouraged so that the effects of different models can be assessed. Legal frameworks should promote a wide range of models for community ownership, participation, and investment in ICESs. Several countries in the world, such as Germany, Denmark, the Netherlands, the United Kingdom, and the USA already have policy incentives to promote community-based energy systems.

3.2 Support Incentives

As the focus is shifting to auction/tendering process to support future renewable energy development, the community participation should nevertheless be safeguarded. To speed up low-carbon transition, ICESs should also be given access to national support policies for renewable energy mainly designed for households and large investors, such as feed-in tariffs, tax incentives, grants, low-interest loans, grid access, guaranteed power purchase, and virtual net metering.

The implementation and success of these support incentives differ among countries, which again is affected by several institutional factors. Rather than a one-size-fits-all approach, support schemes designed and tailored to local conditions might prove beneficial in long-run. At the same time, support and mentoring of these local energy initiatives through dedicated intermediary organizations has been proven successful in the United Kingdom and Scotland (Seyfang and Smith, 2007; CES, 2016). At European level, European Federation for Renewable Energy Cooperatives (RESCOOP) is playing this role through networking and knowledge exchange among European renewable energy cooperatives (RESCOOP, 2016).

Few examples of the support incentives addressing community-based energy systems are postcode regulation for local energy exchange in the Netherlands; community net-metering in New York; priority access to the grid in Germany; government grants in Germany, the United Kingdom, and Scotland; as well as low-interest loans in Germany. In the United States, several states, such as New York through reforming the energy vision (REV), California through its community-based renewable energy self-generation program (SB 843), as well as several other states are pushing all sorts of opportunities for community energy (NY REV, 2016; Community Solar, 2012). Similarly, Australia is also expecting high shares of community solar (C4CE, 2016).

3.2.1 Postcode Regulation in The Netherlands

Since 2013, the Dutch postcode (*postcoderoosregeling*) regulation supports local generation and promotes DER penetration. Local entities, such as Energy cooperatives and housing corporation can jointly invest in community energy. Participants get a heavy discount in energy tax up to 10,000 kWh per members. For example, in 2016, the locally exchanged energy is exempted from energy tax. For details on Dutch postcode regulation, see Visbeek (2016).

3.2.2 Community Net Metering in New York

In July 2015, the New York Public Service Commission established a community net-metering in New York state (DOE, 2015). To qualify, the energy community should have a minimum of 10 members and maximum installed capacity of 2 MW. The energy community can have an individual member having a demand of more than 25 kW (with the generation from this member limited to 40% of the energy community output) whereas all other members should have less than 25 kW demand. Moreover, 60% of the generation from the energy community should be self-consumed. This policy enables renters, low-income citizens, and homeowners to engage in energy community. The sponsor of such energy community could be facility developers, energy services companies, municipal entities, and civic association who will be also responsible for building and operating such energy community.

3.3 Grid Access and Local Balancing

There can be resistance from the incumbent grid operator to transfer the ownership or lease the network to the community as seen in Feldheim and Schönau in Germany (EWS, 2015; NEFF, 2016). Feldheim had to build a parallel grid and Schönau had to buy back the local grid to realize the local energy system. As private utilities are often biased toward incumbent energy suppliers, increasing number of formally privatized distribution grids, including Hamburg, are remunicipalized and further 20% are planning such a step in Germany (Wagner and Berlo, 2015; Nikogosian and Veith, 2012).

Moreover, local energy exchange among ICESs members should be enabled and incentivized. The community can be connected directly to the national grid through a point of common coupling. As shown in Fig. 18.6, the local energy exchange might not always be straightforward. It might involve changing the point of delivery of energy, building a physical interconnection between households across the street or utilizing higher level network infrastructure. In each case, the rules for access to technologies and networks should be well-defined to prevent the opportunistic behavior.

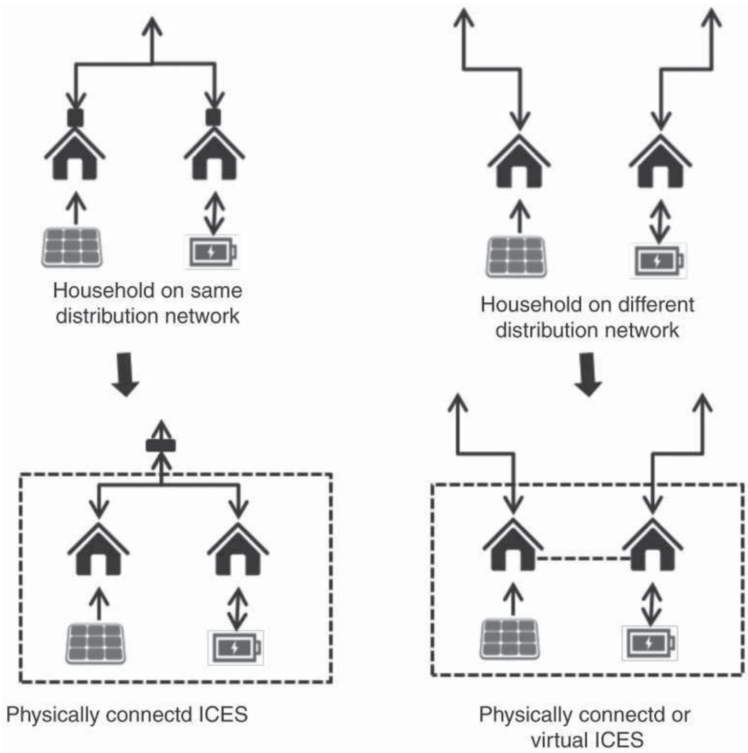

FIGURE 18.6 Grid access issues in ICESs.

Increased incentive to follow load or to integrate renewables might improve local balancing and reduce stress on the grid during hours of peak generation. Moreover, although *time netting* of solar PV generation through net metering has proven beneficial for Dutch households, it might be counterproductive for the operation of energy storage. *Location-based netting* promotes cooperation among households through local exchange and might be beneficial for the emergence of ICESs. Moreover, ICESs should be provided with right incentives to collaborate with system operator on storage, energy management, and grid issues.

3.4 Aligning Institutions and Technology

Following the sociotechnical system perspective, ICESs should be seen as a combination of technical elements, characteristics, and links (Wolsink, 2012). Although technologies to realize such local energy system are widespread, the institutions to govern these energy systems are still lagging behind. "Institutions" are the systems of established and prevalent social rules that structure the social interaction (Hodgson, 2006). They are often considered to be the result of enduring interaction processes by which actors have developed ways to reconcile their conflicting interests (Klijn and Koppenjan, 2006).

The current centralized institutional arrangement does not always provide enough incentives for ICESs as the latter were not foreseen during the development of these institutions. New Institutional arrangements are needed to coordinate and shape collective action, thereby leading to further innovation through value-sensitive design and cocreation (Klijn and Koppenjan, 2006).

The institutions and technologies surrounding ICESs also need to be adapted and aligned to each other for optimal performance. The institutions should be established, (re-)designed or adapted, to enforce the necessary roles, responsibilities, control, and intervention. New models of partnerships between the energy distribution networks, utilities, private developers, and communities need to be allowed and examined. In addition, performance expectations, such as sustainability, flexibility, and cost minimization also play an important role in shaping technology and institutions in ICESs.

4 INSTITUTIONAL DESIGN OF ICES THROUGH TECHNOECONOMIC PERSPECTIVE

New energy systems, such as ICESs are not without technical and operational challenges. The technical design ensures commodity flow through reliable and robust system whereas market design ensures monetary flow through the efficient allocation of goods and services according to the community needs (Scholten et al., 2015). These two essential design approach although complementary may sometimes be in odds. A comprehensive design, called institutional design, is necessary which combines the technoeconomic perspectives in the design of institutions for ICESs. Moreover, Due to the involvement of multiple stakeholders and technologies, the institutional design of ICES is complex. For example, collective decisions have to be made to meet the individual needs. Different institutional arrangements for physical and financial administration are necessary for well functioning of these systems.

4.1 Technical Perspective

4.1.1 Flexibility

In recent years, technological change has enabled households and business to fine tune their energy consumption, as well as higher penetration of renewables and disruptive technologies, such as electric vehicles. The variations in electricity demand and supply can be forecasted but an unexpected mismatch might still occur and the system must ensure that supply and demand are always equal (Strbac et al., 2012). This feature of an energy system is called *flexibility* (Denholm and Hand, 2011).

ICESs are capable of decreasing or aligning the production and consumption depending on the requirement of the larger energy system. The technical

TABLE 18.4 Different Functionalities of Storage in ICESs

Functionalities	Community-level storage	Household-level storage
Balancing demand and supply	Seasonal/weekly/daily and hourly variations, peak shaving, integrated electricity and heat storage	Managing daily variations, peak shaving, integrated operation of electricity and heat storage
Grid management	Voltage and frequency regulation, ancillary services, participation in balancing markets	Aggregation of household storage for grid services
Energy efficiency	Demand-side management, better efficiency of ICESs minimize energy losses	Local production and consumption, behavior change, increase value of local generation, integrated operation

and socioeconomic integration make ICESs more flexible. For example, excess PV generation could be stored as heat through heat pumps or in the electricity storage. Similarly, when electricity demand is higher, combined heat and power units can continue to produce electricity storing the excess heat in thermal storage. At the same time, members of ICESs are more energy cautious allowing higher demand-side flexibility.

The flexibility provision, however, should be carefully designed to incorporate multiple households and communities as well as to avoid possible rebound effects. A clear, transparent, and reliable pricing mechanism, such as the one proposed by Universal Smart Energy Framework (USEF), for the trading of flexible energy might be beneficial (USEF, 2016). The energy markets itself should also be more flexible allowing trade close to the real time.

4.1.2 Storage

Energy storage is not only the great source of flexibility but also an enabler of integrated operation as illustrated in Table 18.4. Energy storage is vital to balance supply and demand at household and community level. Storage type and size differ based on seasonal, weekly, daily, or hourly demand to store energy. Long-term energy storage is still technologically challenging. Moreover, integrated operation of heat and electricity storage is desirable. The energy storage can enable location-based netting, ensuring local energy balance and overall higher energy system performance.

4.1.3 Energy Services

The increasing penetration of intermittent renewables and DERs in the energy systems is forcing a debate on new energy services as well as their pricing and provision (Perez-Arriaga et al., 2015). As presented in Table 18.5, these energy

TABLE 18.5 Energy Services Within ICESs and to the Larger Energy System

	Services	Description
Energy-related services	Electrical energy	Electricity sold or purchased at given location and time within the ICESs and to the system
	Flexibility	Upward and downward flexibility to the system
	Operating reserve	Primary: immediate, automatic, decentralized response to system imbalances stabilizing system frequency. For example, Feldheim energy community in Germany provides primary reserves for TSOs through its 10 MWh storage (NEFF, 2016) Secondary: up- or downregulation service to accommodate normal, random variations in system frequency, and normal variability and uncertainty of load and generation balance
	Firm capacity	A guaranteed amount of installed capacity that is committed to producing when called upon under system-stress conditions
	Black-start capability	The availability of resources to restore ICESs to normal conditions after black out
Network-related services	Network connection	Physical connection between the households, to the electricity distribution network and access to the associated services
	Voltage control	Maintenance of voltage within regulated limits throughout ICESs
	Power quality	Minimum voltage disturbance in delivered power
	Congestion management	Overcoming local congestion through network reconfiguration, redispatch/utilization of generators, modifications to load or generation, utilization of flexibility from ICES members
	Energy loss reduction	Local consumption reduces energy losses

services will also be relevant for ICESs; some of these services are internal to ICESs whereas others are system services. For more details on energy- and network-related services of the energy systems, see Perez-Arriaga et al. (2015).

4.1.4 Autarkic Design

The decreasing costs of DERs and the rising retail prices are creating an enabling environment for customers to optimize the planning and operation of the local energy system with the national grid or to get out of the national grid to manage their own local grid (Chaves-Ávila et al., 2016). ICESs might redefine the

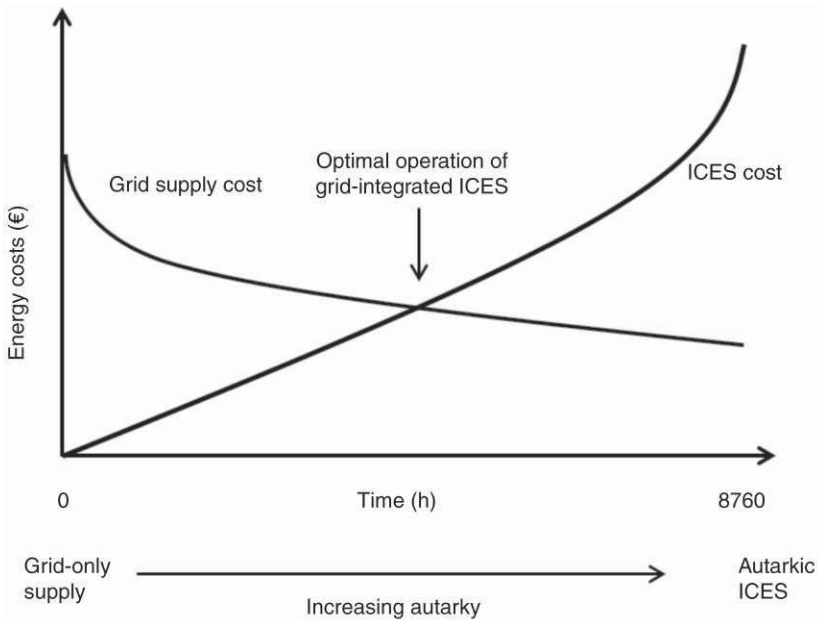

FIGURE 18.7 Trade-offs in autarkic design of an ICES.

relation between production and consumption as they enable resiliency through coproduction. This helps to reduce or substitute the industrial production of energy at centralized power plants by decentralized local production. The excess energy can be sold directly to the grid. The residual demand should be met by the industrial production until large-scale storage becomes financially viable.

Accordingly, ICESs can take different architecture: grid-integrated and grid-defected or autarkic ICES as demonstrated in Fig. 18.7. The most optimal solution is the hybrid system with a combination of the grid and the ICES. Such system can also be islanded during emergency situations to provide critical community functions. The driving forces for the grid defection are independence from the national grid, CO_2 emissions reduction at higher levels than the centralized system, self-governance, and other local preferences.

Under the current system of prices and charges and DER economics, grid-defected ICESs are not economically rationale (Koirala et al., 2016a). As also discussed in the chapters by Steiniger and Sioshansi in this volume, aggregation of the diversity of demand as well as generation profiles among the households within ICES might make community grid defection less expensive than individual grid defection. However, higher reliability needs lead to an oversized system with a very high unused energy to be curtailed and dumped. Nevertheless, it is important to identify the conditions under which such autarkic system can already be a policy option. The cost of an autarkic ICES should be estimated after considering the price of emergency service and the cost of avoided grid reinforcement.

4.2 Economic Perspective

4.2.1 Collective Financing

ICESs may require funding from a variety of sources, such as individuals, municipalities, local cooperatives, and banks. Each ICESs projects will require a customized approach for financing considering both costs and revenue streams. The willingness to invest in local energy initiatives again depends on several institutional factors and local conditions. For example, with long traditions of local energy and opposition to the nuclear energy, German citizens exhibit higher willingness to invest in local energy projects (Kalkbrenner and Roosen, 2016). ICESs can bring much-needed investment and financing to the local energy system through citizens' engagement.

4.2.2 Mismatch Between Wholesale and Retail Price

The current retail electricity price includes wholesale price, regulated costs, such as network costs and other surcharges, as well as taxes. Although the wholesale price might decrease with the high penetration of renewable, the retail price is expected to increase in future due to increasing fixed costs for network reenforcement, grid expansion, balancing costs, as well as other surcharges. ICESs enable local communities to hedge against fluctuating energy prices.

4.2.3 Business Case for ICESs

As the main technologies for ICESs, such as DERs, storage, and energy management systems are gaining maturity, the next step is to create the enabling environment for business model innovation through flexibility in regulation as well as energy policy. The success of ICESs depends on the business model adopted and its flexibility. These business model should reflect self-provision of energy, local exchange, as well as different energy services to the system.

4.3 Institutional Design of ICESs

In this section, institutional design recommendations are provided considering the technoeconomic perspective. ICESs should be managed in a flexible manner adapting to capabilities and interests of the community involved. This translates to efficient (self-) governance, lower transaction costs, fair cost–benefit allocation, and simplified legal requirements.

4.3.1 Roles and Responsibilities

In ICESs, the role and responsibilities of the actors will change. For example, the domestic consumers can have a more active role as prosumers. Local communities can have new roles as *flexibility providers*. The function of "aggregators" which is so far only exercised by the suppliers can also be performed by ICESs through aggregation of small consumers, similar to the virtual power plants concept elaborated in the chapters by Steiniger and Sioshansi in this volume.

Installers can finance as well as operate the installations themselves ensuring consumers "comfort" rather than just supplying equipment. The emergence of new roles and new interpretation of existing functions can ensure efficient development of ICESs.

4.3.2 Design and Coordination of Local Exchange

The local exchange can take several forms, such as peer–peer exchange and prosumer community groups (Giotitsas et al., 2015; Rathnayaka et al., 2015; Brooklyn Microgrid, 2016). Using a well-known blockchain technology, a new community microgrid project in Brooklyn, New York is providing a platform of peer–peer, transactive energy trading among neighbors in a local neighborhood (Brooklyn Microgrid, 2016).

Suitable institutional arrangements should be designed to prevent local energy exchange from being a monopolist. The commodities and suppliers should be well defined, ensuring efficiency, fair allocation of costs and benefits, right prices for participation, and preventing the opportunistic behavior. The local energy price should reflect all the capital costs, operation costs, as well as local network costs.

There is no single best organizational model applicable for ICESs but it should be based on the available sources, types of participants, as well as their needs and expertise. The technical and operational complexity of ICESs might require the involvement of the service provider. The service provider could be energy service companies (ESCOs), distribution system operators (DSOs), or private company with expertise in ICESs. The service providers not only provide assistance in ICESs planning and operation but also provide access to the financing resources.

Nevertheless, two models are outlined here to show how the ICESs could be operated namely service and cooperative model, Table 18.6. In the cooperative model, the actors jointly find the local planning and coordination site, operate the facility together, lifting the separation between production and use. The complex technical operation can be handled by the service provider, however, the ICESs remains in control of the local cooperative. In the service model, the social desire for local utility with a wide range of services is reflected with a great emphasis on the development of ESCOs.

There should be freedom to organize the energy to the local requirements. Laws and regulations should, as far as possible, create space for actors to actually try these or other models. In practice, it may turn out which models are viable and which are not. By analyzing the implications of these operation models in the short and long term, it will become clearer how the ICES can emerge and in what areas further legislation is possible or desirable.

4.3.3 Ownership and (Self-) Governance

Ownership refers to a source of control rights over a resource or property and power to exercise control when the contract is incomplete, such as excluding the

TABLE 18.6 Overview of Functions and Actors in the Service and the Cooperative Model

	Functions	Service model	Cooperative model
Final function	Energy use	Customers	Cooperative
System function	Production	Producers (decentralized)	Local production by the cooperative
	Storage	Customers, producers, or system operators	Cooperative
	Transport	Operators (capacity contracted by ESCO)	Within the community, the cooperative
	Balance responsibility	System administrator	System administrator
	Coordinator	None	On community scale, the cooperative
Marketing functions	Trade	ESCO	Within the cooperatives, local exchange and outside the cooperative through the national market parties
	Delivery	ESCO	
	Aggregation	ESCO	
	Program responsibility	ESCO	
Service functions	Installation	ESCO, installers	Installers in cooperation with cooperative
	Advising	ESCO	Cooperative
	Market coordination	ESCO (limited)	Cooperative
	Financing and insurance	ESCO (in terms of the project in the community)	Cooperative
	Metering	Metering responsible or ESCO	Metering responsible or cooperative
	Communication	Through public networks or desired by ESCO	Through public networks or desired by cooperative
	Switching	ESCO	Cooperative
	Billing	ESCO	Cooperative

ESCO, Energy service company.

TABLE 18.7 Ownership and Governance Model for ICESs

Ownership	(Self-) governance
Community	All costs and benefits are covered by ICESs. Cooperative structure for the management and operation can be outsourced to the service provider.
Utility (DSO)	Utilities remain relevant in ICESs as owner, service provider or grid connection enabler, or combination of these roles. ICESs can benefit from its technical and financial capability. The utility can decide independently and level of community engagement is subjected to the utility.
Private	Private expert companies own and operate ICESs. Incorporating social and economic objectives of the local communities requires negotiation and bargaining.
Public–private (hybrid)	Joint decision-making and planning through the engagement of local communities and private expert companies. Private expert companies can hedge against future uncertainty.

DSO, Distribution system operator.

nonowners from access, selling and transferring resources, as well as appropriately streaming the economic flows from use and investments (Grossman and Hart, 1986; Gui et al., 2016). The ownership in energy systems, such as ICESs is affected by the financing requirements, social welfare issues, as well as risk preferences (Haney and Pollitt, 2013; Walker, 2008). ICESs can have locally owned and controlled community ownership, utility ownership, private ownership, and public–private ownership, Table 18.7. Governance refers to a structure to practice economic and administrative authority, such as rules of collective decision-making among actors (Goldthau, 2014; Avelino et al., 2014).

In the context of ICESs, (Self-) governance refers a group of people that exercise the control over themselves by self-ruling or autonomy. Ostrom (2005) has demonstrated the robustness of self-governance in socioecological systems where government and markets could not do better. Cayford and Scholten (2014) has analyzed the viability of self-governance in community energy system and reported that it depends on communities' abilities to be adaptive to coordinate with different governance circles and may even take different forms according to the social and technical complexity.

4.3.4 Costs and Benefit Allocation

Local balancing reduces peak demand and volume of imported energy in ICESs. The energy losses of the centralized system are also reduced through local generation and exchange. The different energy and network services provided by ICESs avoid energy costs and generate revenues. Grid-defected ICESs provide ancillary services locally, saving on ancillary services. ICES can defer grid reinforcement required for accommodating increasing penetration of DERs or demand. These avoided costs and generated revenues are the benefits of ICESs.

ICESs costs involve capital costs for DERs and energy management system, fuel cost, operation and maintenance cost, as well as network costs for interconnection infrastructure. DER capital costs involve the cost of household- and community-level DERs and cost for corresponding energy management system. Operation and maintenance cost involves the cost of operating local energy exchange as well as the cost associated with operation and maintenance of DERs. Moreover transaction cost is associated with making contracts and billings. The cost of network interconnection and operation should also be considered.

The success of ICESs largely depends on the fair allocation of these costs and benefits. The cost must be paid by those who cause it and the benefits must accrue to those who previously made the investment. In ICESs, this is sometimes difficult to achieve because parts of the facility have the character of a public good.

4.4 Future-Proof Institutional Design

As discussed in Section 2, the complex sociotechnical system, such as ICES has to adapt and operate in changing energy landscape where new technologies will become available, new institutions will emerge, and role and responsibilities of the actors might also change. ICESs should be open for new interactions and experiments to allow further technological and social innovation.

Different actors of the ICESs will have important roles to steer and transform activities of ICESs. These activities namely consumption, storage, exchange, and collective purchasing are influenced by attributes of the technical world, such as available technologies, grids, as well as the environment, attributes of community in which actor and actions are embedded, and institutions which guide and govern actors behavior. This leads to patterns of interactions and outcomes, which could be judged by technical, economic, social, and environmental performance evaluation criteria. Policymakers should steer right transformation of ICESs through suitable policies, incentives, and support schemes.

5 CONCLUSIONS

ICESs are emerging in an environment that was designed for a centralized, top-down, unidirectional network with regulation assuming full reliance on the common network. Now prosumers have options that do not fit the old model and their aggregation in the form of ICESs need fertile support to get established in an otherwise hostile environment. It is important to create dedicated policy space for ICESs within climate and energy framework for the next decades. Policymakers should steer right transformation of ICESs through suitable policies, incentives, and support schemes.

ICESs offer strategic choices for households and communities to transform their energy system and become active prosumers. Households and communities need to understand the trade-offs between self-consumption and local energy balance, as well as to provide system services for the larger energy system. ICESs also address the desire of local communities to contribute toward sustainability and energy security locally.

This chapter has highlighted several institutional precursors for the emergence of ICESs, such as regulation, support incentives, grid access, and local balancing, as well as the alignment of technologies and institutions. Advancing ICESs requires supportive institutional environment for integrated operation as well as interactions among different actors. Unbundling should be relaxed for the long-term financial viability of ICES and partial rebundling is required for local ownership of energy supply infrastructure and energy grid. The local energy exchange platform should be developed to ensure further emergence of ICESs.

Several institutional design recommendations for ICES based on techno-economic perspectives are provided. Technical perspectives considered are flexibility, energy storage, energy services, as well as the autarkic design of grid-integrated and grid-defected ICESs. Collective financing and new business cases involving value of flexibility and ancillary services, as well as hedging against price fluctuations are important. The clear understanding of the changing roles and responsibilities, community ownership and self-governance, design and coordination of local energy exchange, as well as the fair allocation of cost and benefits are important institutional settings for the success of ICESs. These institutional settings need to adapt to the changing energy landscape.

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Willingness to Participate in Integrated Community Energy Systems

Abstract

In order to decarbonize the energy sector, there is widespread consensus that the role of end-users in the energy system should change from passive consumption to an active engagement. This is of particular importance as an increasing number of technologies and business models are focusing on the end-users. These developments provide new opportunities for further technical and social innovation to smarter, flexible and integrated systems such as integrated community energy systems (ICESs). Through system integration and community engagement ICESs assists in transition to a low-carbon energy system. Despite the high importance, there is limited knowledge on willingness of local citizens to participate in the local energy systems such as ICESs as well as associated factors determining such willingness. Through a survey among 599 citizens in the Netherlands, this research analyses the impact of demographic, socio-economic, socio-institutional as well as environmental factors on willingness to participate in ICESs. Factor and multi-variate regression analysis reveals the importance of environmental concern, renewables acceptance, energy independence, community trust, community resistance, education, energy related education and awareness about local energy initiatives in determining the citizens' willingness to participate in ICESs.

Keywords: Energy communities, Distributed energy resources, Energy transition, Citizen participation

1. Introduction

Transforming societies into sustainable patterns of production and consumption is a key challenge of this century [1]. In addition to individual behavioral change, system wide transformation through collective action is required to solve the challenges of the present energy systems and collective action has historically been a successful motor of social transformation [2]. In this regard, local energy systems can potentially contribute to the efficient overall energy production and distribution and also help meeting climate objectives by helping reversal of energy consumption and emissions trends [3]. The energy system, providing heat and electricity to houses and businesses, is transforming from a centrally coordinated fossil-fuels powered system towards a bottom-up and decentralized low-carbon systems [4,5].

These developments provide new opportunities to create smarter, flexible and integrated systems such as integrated community energy systems (ICESs) creating value both for whole energy systems as well as the end-users [3,6,7]. ICESs provide new roles for local citizens and communities putting them at the centre of the energy system [3,8]. The acceptance, support and participation of citizens is essential to successfully manage these ongoing energy transitions [9].

Integrated community energy systems (ICESs) are considered an important modern development for low-carbon transition of the local energy system through energy system integration and community engagement [3]. ICESs are multi-faceted energy systems for supplying a local community with its energy requirement from high-efficiency co-generation or tri-generation as well as from renewable energy technologies coupled with innovative energy storage solutions as well as electric vehicles and demand-side measures [6]. Households which are part of ICESs can balance their energy requirement through local energy exchange. ICESs focus on better synergies among different energy carriers as well as among local households. ICESs aim not only at the self-provision for the local communities but can also provide system services to the energy systems such as balancing and ancillary services bringing additional revenue to the communities.

Local energy initiatives are becoming a societal movement in Europe, which indicates rapidly growing societal demand for sustainable and 'self-owned' energy with potentially significant impact on the energy system [10]. With more than 500 local energy initiatives, local communities are expected to play a significant role in the transformation of the Dutch energy system [11]. However, with only 5.5% of its primary energy generated by renewables, The Netherlands is lagging behind all other EU member countries except Malta and Luxembourg [12]. This lag can be partly attributed to delays in offshore wind projects as well as to lagging energy efficiency projects in buildings. Yet, the role of the built environment, which consume approximately one-third of the total Dutch primary energy, and citizens participation therein, cannot be neglected [13]. This makes the Dutch case particularly interesting for analysing citizens' willingness to participate in local energy initiatives.

Moreover, the local energy initiatives are emerging with varying numbers, success rate and strategies in the Netherlands and Europe [14]. The diversity in success of these community initiatives could be partially attributed to prevailing structural, strategic and biophysical conditions. Community spirit, co-operative traditions and the norms of locality and responsibility as well as environmental concerns are central drivers behind the emergence and constitution of these local energy initiatives[15]. Demographic and socio-economic factors such as age, education, tax deduction, income are important determinants for renewables adoption in households[16] These socio-institutional features along with other demographic, socio-economic and environmental factors might influence the way the citizens participate in the local energy systems.

The willingness of local citizens to engage in such local energy systems is vital. The willingness is defined as 'the quality or state of being prepared to do something [17]. For energy systems to provide more value to the society, different energy sectors at the local level have to be integrated with the engagement of the local communities. Local citizens and communities engagement could lead to a low-carbon, affordable and secure energy system. Local communities are well-placed to identify local energy needs, take proper initiatives and bring people together to achieve common goals such as the reduction of energy costs, CO_2 emissions and resiliency [18,19]. In the energy domain, literature to date that focusses on willingness, ranges from willingness to pay, willingness to accept, willingness to participate and willingness to adopt [2,9,16,20,21]. To the best of our knowledge, there is limited research to capture the opinion and attitude of Dutch citizens on the ICESs formation, their willingness to participate and their determinants.

This study aims at determining the willingness of Dutch citizens to be part of local energy initiatives such as ICESs. The influence of different motivations such as economic incentives, environmental concerns and energy independence as well as demographic and socio-economic characteristics in the willingness to participate in such systems is studied. The drivers which help emergence of ICESs and the barriers which inhibit ICESs are also investigated.

The main research questions for this study are:

a) What is the willingness of local citizens to participate in ICESs?
b) What are the most important socio-institutional and environmental factors associated with willingness to participate in ICESs?
c) To what extent can people's willingness to participate be predicted using demographic, socio-economic, socio-institutional and environmental factors? What are the main influential factors?

These research questions are answered empirically by surveying a sample of Dutch citizens. In order to have detailed understanding of willingness to participate in ICESs multivariate regression and factor analysis is performed.

This paper is organized as follows. First, a brief review of literature and our research framework is presented in Section 2. In Section 3, methods and measures used in this study is reported. Section 4 presents the results of descriptive statistics, factor analysis and multi-variate regression analysis. Finally, section 5 provides conclusions and policy recommendations.

2. Literature review and research framework

2.1 Community engagement in ICESs

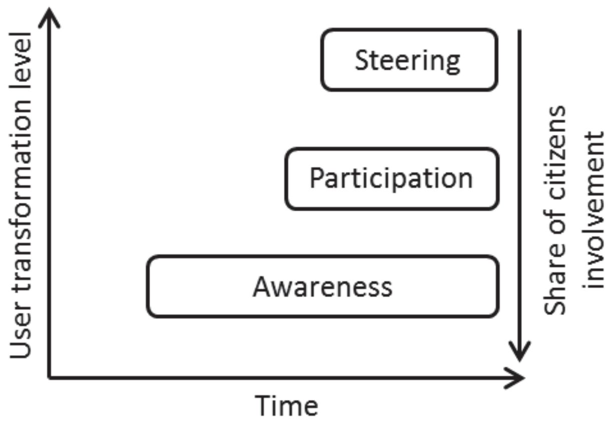
There is a substantial amount of literature indicating the importance of more deliberative and inclusive participation of consumers in the energy system [22,23]. Increasing numbers of consumers are becoming co-providers by engaging themselves in generating, storing, conserving, importing and exporting energy locally thanks to recent developments such as implementation of suitable policies, cost reduction of renewables, emergence of information and communication technologies (ICTs) and environmental awareness [24]. When consumers have more control, they tend to self-organize and co-operate to form a community energy system [15,25–29]. This makes more energy options at community level feasible, like community solar, wind farm, district heating, community energy storage and biogas production. Sometimes an integrated energy system at community level can be pursued when electricity and heat are generated together or when waste heat from nearby industry as well as flexibility of electric vehicles and storage systems could be utilized.

Local citizens can be engaged in ICESs through several means subjected to particular ICESs activities. Some examples of ICESs activities are supply side activities, such as collective purchasing of solar panels or collective ownership of wind farms, and demand side activities, such as energy conservation, retrofitting of dwellings or energy awareness raising activities [10]. Although there are many benefits associated with citizens engagement in ICESs, they also have several challenges [27] [26] [14] [10]. In this research, the focus is on citizens' engagement through investment, volunteering as well as exchange of energy and the related demographic, socio-economic, socio-institutional and environmental factors.

2.2 User transformation

End-user transformation is a gradual process. As presented in figure 1, the different levels are awareness, participation and steering [30]. User transformation in energy system can be achieved through providing them with information, choice, and engaging them to provide flexibility to manage demand as well as supply. Local communities are being transformed by challenging their traditional identity as passive consumers to active prosumers, which are both consumers and producers. User engagement in implementation of local energy systems supports acceptance and diffusion of novel technologies. End-user transformation also favor the emergence of innovative business models and technical solutions [30].

Figure 1: User transformation in local energy system



Local energy initiatives such as ICESs emerge due to ongoing restructuring processes and changing energy landscape [3]. Figure 1 also suggests that not all end-users will we driven by the process of user transformation and the level of involvement of citizens shrinks from awareness to steering. Nevertheless, user transformation has potential to steer the energy system transformation [30]. In this research, the focus is on citizens willingness to participate in ICESs and their willingness to steer transformative energy system such as ICESs as well as their determinants.

2.3 **Factors affecting ICESs participation**

Willingness to participate is vital for the success of novel community-based energy systems. In addition to community related factors for collective action, it is also affected by different factors affecting citizens' willingness to participate in renewable energy and energy efficiency projects. [9,16,31]. For example, despite large number of benefits of energy renovations, there are challenges to motivate Danish home-owners to participate in renovation of their homes [31]. Although community objectives such as economic incentives, environmental concerns and resiliency are important, different demographic and socio-economic factors such as age, family situation, home ownership, occupation and income affect citizens' willingness to participate. Similarly, financial incentives such as tax deduction, energy price, age, household welfare status as well as perceived maintenance costs of renewables are statistically significant factors for willingness to adopt microgeneration in UK households [16]. Despite a general positive attitude of local citizens towards community energy in Germany, the willingness to participate in such systems is also affected by several socio-institutional and environmental factors such as social norm, trust in community, and environmental concern [9]. Therefore, a critical first step is to hypothesize what factors affect or might determine the willingness of Dutch citizens' to participate in ICES initiatives.

Demographic factors: The willingness to participate may be affected by citizens' current position in life. Some of the key demographic factors that influence citizens willingness to participate in ICESs are gender, age, education and income level [9,31,32] .

Socio-economic factors: Socio-economic factors may play important roles in citizens' willingness to participate in local energy systems. Some of the key factors that influence citizens willingness to participate in ICESs are home-ownerships and energy bills [16].

Socio-institutional factors: Socio-institutional factors such as sense of community and trust may affect citizens' willingness to participate in ICESs [9].

Environmental factors: Several environmental factors may play role on citizens willingness to participate in ICESs. Pro-environmental factors such as ownership of distributed energy resources (DERs), resiliency, desire to reduce CO_2 emissions are expected to impact citizens willingness to participate in ICESs [2,9,33].

These different demographic, socio-economic, socio-institutional and environmental factors are assumed to affects the Dutch citizens' willingness to participate in ICESs. This research is set to determine the impact of these factors in willingness to participate in ICESs and also to investigate which factors are more important in determining such willingness. Moreover, difference in factors affecting willingness to participate and willingness to steer local energy initiatives such as ICESs will be determined.

3 Materials and Methods

The research method is a statistical data analysis based on an empirical survey conducted among a sample of the Dutch populations. The important factors affecting the willingness of local citizens to participate in ICESs are determined through a factor analysis. Using the factor scores resulting from the factor analysis, a multi-variate regression analysis is estimated.

3.1 Survey data

Data were collected in December 2015 using an online survey collector tool of Faculty of Technology, Policy and Management, Delft University of Technology, the Netherlands. The online questionnaire was send to 956 Dutch citizens of which 599 completed the survey. The response rate is 63 %. The demographic and socio-economics of the respondents is summarized in Table 1.

3.2 Measures

The online survey consisted of 37 questions about demographics, socio-economic conditions, socio-institutional issues and environmental concerns as well as perceived drivers and barriers to participate in ICESs.

Table 1: Demographic and socio-economic characteristics of the respondents

Variables	Sample(N=599)	
	Frequency	
	Numbers	%
Gender		
Male	294	49
Female	305	51
Age		
15-24	85	14
25-34	74	12
35-44	56	9
45-54	232	39
55-64	116	19
65+	33	6
Education		
Basic education	5	1
High school	54	9
Secondary vocational education	59	10
Higher vocational education	196	33
University education	282	47
Working hours per week		
0 (unemployed/retired)	91	15
1-10	41	7
11-20	59	10
21-30	76	13
31-40	173	29
40+	156	26
Income level		
basic	14	2
Less than € 28500	27	5
28500	62	10
Between €28500 and € 57000	151	25
Greater than € 57000	263	44
Do not want to disclose	79	14
House ownership		
Owners	478	80
Renters	121	20
Type of community		
Urban	452	76
Rural	147	24
Solar Panels ownership		
Yes	83	14
No	516	86

3.2.1 Demographic factors

Among the respondents, 51% were female and 49% were male. Most respondents were of the age group between 45 and 54 years (39 %); 26% were between 19 and 34 years, 9% between 35 and 44 years, 9% between 55 and 64 years, and 6 % above 65 years. Regarding education level, 47% had university degree, 33% had higher vocational education, 10% had secondary vocational education and 9 % had high school. The majority of the respondents were working full time (55 %), 30% were working part-time and 15% had either no jobs or retired. As far as household level income is concerned, 44% reported income higher than € 57,000, 25 % between € 28,500 and € 57,000, 17% below € 28,500, whereas 14 % respondents did not disclose their income. Majority of the respondents (76%) live in urban area whereas 24% live in rural area.

3.2.2 Socio-economic factors

80% of the respondents are owner of their house. The monthly energy (gas and electricity) bills of the majority of the households (52%) was higher than € 125.

3.2.3 Socio-institutional factors

Sense of community: The sense of community is measured based on citizens involvement in the neighbourhood and number of neighbourhood activities. The respondents were asked how strongly they feel involved in their neighbourhood. Almost 47% of the respondents were neutral, whereas around 24 % feel not involved in their neighbourhood and 29 % feel strong involvement with their neighbourhood. The respondents were also asked regarding the numbers of neighbourhood activities organized per year. Almost one third (34.2 %) of the respondents reported no neighbourhood activities, 30 % reported one neighbourhood activities whereas 36% reported two or more neighbourhood activities per annum. Among the respondents, 79% are willing to work with their neighbourhood in the field of energy.

Community Trust: The respondents were asked how much trust they have to the people of their community. Among the respondents, 24% have no trust in their community, 29 % neither trust nor distrust their community and 47 % have trust in their community. The respondents were further asked if they have objection with the neighbours giving much less time in ICESs project than themselves. Among the respondents, 14% will be so much offended that they will not like to participate in the ICESs anymore, 47 % will be objected but will continue to participate in ICESs and 39 % will not be affected at all.

3.2.4 Environmental factors

In order to measure environmental concern of Dutch citizens several questions related to environment were included in the questionnaire. The respondents were asked about their interest in community-based energy system in general as well their acceptance towards local renewables based production such as solar PV and wind. The attitudes for local renewables were assessed on a Likert-type scale from 1 (very negative) to 5 (very positive) and summarized in Table 2. The respondents find the sight of solar panel less disturbing than the sight of wind turbines whereas the noise of wind turbines is the most disturbing. These questions helped to understand acceptance of general public towards renewables in general and community-based energy system in particular. Among the respondents, 14% also own solar panels on their rooftop. 80 % of the respondents showed positive interest in the local energy systems such as ICESs.

Table 2: Overview of renewables acceptance

Measures (N=599)	Renewables acceptance (%)					Mean	SD	Scale
	Very negative	negative	Neutral	positive	Very positive			
Sight of solar panels	6.2	10.9	17.9	24.9	40.2	3.82	1.242	5-point
Sight of wind turbines	16.5	22.4	25.9	20.5	14.7	2.94	1.295	5-point
Noise of wind turbines	19.2	28.0	25.5	16.5	10.7	2.71	1.25	5-point

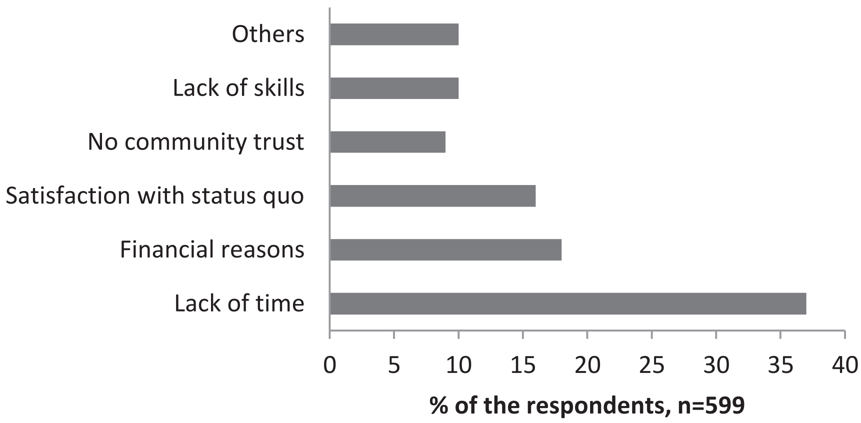
The respondents were also asked to rate the environmental and socio-economic-institutional drivers in Likert-type scales of 5 or 7 points. Table 3 summarizes the responses regarding the environmental and socio-economic-institutional drivers to participate in ICESs.

Table 3: Drivers to participate in ICESs

	(N=599)	Drivers(%)							Mean	SD	Scale
		Entirely disagree	Mostly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Mostly agree	Entirely agree			
Environmental	Good for the environment	4	2.3	4.7	9.8	21.9	27.7	29.5	5.45	1.55	7-point
	Climate change	-	2.5	4.2	16.0	35.9	41.4	-	4.10	0.98	5-point
	Less fossil-fuels consumptions	-	2.5	4.7	16.5	36.9	39.4	-	4.06	0.99	5-point
	CO2 emission reduction	-	2.0	3.2	10.7	36.2	47.9	-	4.25	0.91	5-point
Socio-economic-institutional	Economic benefits	3.5	3.5	5.5	16.0	22.5	27.5	21.4	5.19	1,54	7-point
	Community identity	14.5	11.5	12.5	22.9	22.2	11.9	4.5	3.80	1.72	7-point
	Democratic decision-making	-	6.2	7.7	26.2	32.9	27.0	-	3.67	1.14	5-point
	Regular updates on state of affairs	-	4.3	3.2	17.4	37.7	37.4	-	4.01	1.03	5-point
	Independence of national grid	18.7	14.2	14.0	18.9	14.9	12.9	6.5	3.62	1.87	7-point
	Independence from big energy suppliers	-	8.7	16.2	33.7	24.2	17.2	-	3.25	1.17	5-point
	Plenty of leisure time	38.7	21.9	14.4	13.9	5.3	3.3	2.5	2.45	1.59	7-point
	Awareness of local energy project	23.4	17.7	15.4	21.9	11.9	6.7	3.2	3.14	1.70	7-point

In addition, participants were asked what they think will inhibit them the most to set up or participate in ICESs. The perceived barriers to participate in the ICESs as presented in Figure 2 are, lack of time (37%), financial reasons (18%), satisfaction with the current energy systems(16%), no trust in neighbourhood to develop ICESs (9%), not enough skills to support ICESs (10%) and other reasons (10%). The other reasons reported are, too much focus on the environment, trust in the government, limited thinking space, too big risk, already ownership of solar panels and heat-pumps, expectation of government initiative, financial sustainability, inclusive rent, old age, moving in near future, renting, no interest in initiative and leadership, lack of experience and already participating in a local energy system. The perceived barriers are in line with what has been reported in the literature which are lack of financing and technical expertise as well lack of technical support [23,34,35].

Figure 2: Perceived Barriers to participate in ICESs



4 Results

The result of the survey is reported in the following three sub-sections. First, general descriptive statistics with respect to willingness to participate and willingness to steer is presented. Second, important factors affecting the willingness to participate are determined using factor analysis. Finally, a model to predict willingness to participate in ICESs is developed using the results of factor analysis in multi-variate regression analysis.

4.1 Willingness to participate and steer

First of all, the respondents were asked about their interests towards local energy initiatives such as ICESs and their willingness to participate in such systems if the option is available at the local level in 5-likert type scale. The respondents were then asked regarding their willingness to volunteer and invest in the activities of ICESs as well as their expectation regarding the payback period.

Among the participants, 80% of the respondents showed positive interests towards ICESs. As far as willingness to participate in ICESs is concerned, 53% of the respondents showed positive willingness whereas 31 % of the respondents were undecided and choose the option to be neutral, and 16 % of the respondents showed negative willingness to participate in ICESs, as presented in Table 4. As illustrated in Table 5, 73 % of the respondents are willing to invest in ICESs and approximately same amount of the citizens are willing to volunteer. Majority of the respondents expect return in investment within 10 year. In fact, only 14 % of the respondents are fine with payback period higher than 10 years.

Table 4: Willingness to participate in ICESs

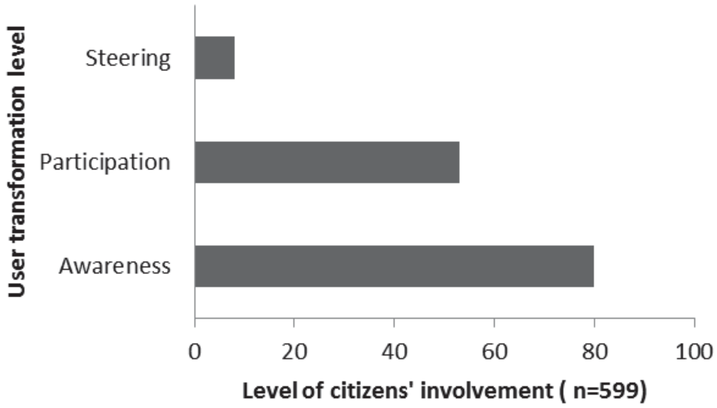
Measures (N=599)	Willingness (%)					Mean	SD	Scale
	Not very willing	Not willing	Neutral	Willing	Very willing			
Willingness to participate	6.2	9.5	31.4	44.9	8.0	3.39	0.98	5-point

Table 5: Willingess to invest and volunteer in ICESs

Measures (N=599)	Willingness (%)		
	Low	Medium	High
Willingness to volunteer	27.7	41.6	30.7
Willingness to invest	27.0	42.9	30.1

The survey participants were also asked which organizational responsibilities they are willing to undertake to steer ICES activities. Among the respondents, 25% are not willing to participate at all, 37% are willing to participate but without organizational responsibility, 30 % are willing to participate with minor responsibility such as attending member meeting, and 8 % are willing to participate with substantial responsibility of steering the ICESs such as member of the board. In accordance with the Figure 1, the latter represents the respondents willing to steer the ICESs, thereby transforming the energy system. The hypothesis on decreasing share of citizens' engagement with user transformation level is also validated, as presented in Figure 3.

Figure 3: User transformation vs. level of citizens' engagement



4.2 Factor analysis

Factor analysis is used in order to simplify the data and to identify the underlying dimensions of willingness to participate in ICESs. Initially, the factorability of the 17 variables was examined. It has been observed that 14 out of 17 variables correlated at least, suggesting reasonable factorability. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.783. This indicates that the patterns of the correlations are relatively compact and factor analysis should yield distinct and reliable factors. The Bartlett's test of Sphericity was also significant ($x^2(136) = 3218$, $p < 0.001$). This means that the correlation matrix is not an identity matrix and there are some relationships between the variables being tested. Both KMO test and Bartlett's test confirm that the factor analysis is appropriate.

The initial eigenvalues associated with each factor represent the variance explained by that particular component and indicate the substantive importance of that factor. Initial eigenvalues indicate that the first five factors, , have eigenvalues just over one and explain 25%, 12%, 11%, 9 % and 6% of the variance respectively. The five factor solution, which explains 63 % of the variance is preferred because of the levelling off of eigenvalues in the scree plot after five factors.

The extraction method used is principal axis factoring. It is preferred over the more common principal component analysis when using factor analysis in causal modelling. In this research the focus is on the dimensions of willingness to participate in ICESs and therefore the principal axis factoring method is used. After extraction, the five factors explained 22%, 10%, 9%, 6% and 3% of the variance respectively and 49% of the variance cumulatively.

The factors are rotated to approach a simple structure. As the factors are expected to correlated, direct oblimin rotation method is used. Then, the factor labels were proposed after carefully looking at the related variables in the analysis and presented in Table 6. These are environmental concern, renewables acceptance, energy independence, community trust and community resistance, respectively. Factor scores were created for each of the five factors so that it can be used in subsequent analysis such as regression in the following sub-section.

Table 6: Factor analysis

	Environmental concern	Renewable Acceptance	Energy independence	Community Trust	Community resistance
Willingness to participate					
Good for the environment	,591				
Economic incentives					
Familiarity with ICESs					-,635
Plenty of time					-,461
Grid independence			,623		
Positive sense of belongingness to the community					-,514
CO2 reduction	,906				
Fossil fuels reduction	,855				
Climate change	,868				
Independence from big energy suppliers			,847		
Sense of community				,821	
Neighborhood activities					
Trust in community				,667	
Acceptance of solar panels		,461			
Acceptance of wind turbines		,969			
Wind turbine noise tolerance		,601			

4.3 Regression analysis

A multi-variate linear regression model was estimated to predict willingness to participate in ICESs based on the factor scores from the previous section as well as demographic and socio-economic variables. This is specifically done in order to make the regression analysis as representative as possible.

According to the results reported in Table 7, a regression equation is found which represents a substantial share of variance *(R^2 = 0.41, F(15) = 21.88, p < .001)* in the willingness to participate in ICESs. According to the standardized coefficients, the statistically significant predictor in the order of importance are community trust, community resistance, energy independence, environmental concern, energy-related education, education and awareness about local energy initiatives. Age, gender, solar PV ownership, house-ownership, income, type of community as well as economic incentives are not statistically significant. The case of solar PV ownership is particularly interesting as many respondents with solar panels perceived that they could not take part in other local energy initiatives such as ICESs.

A closer look at residual statistics and case-wise diagnostics showed the three cases as outliers for the regression analysis. However, no case with Cook's distance greater than one is found. It can be concluded that the influential data point(s) does not exist and the result of the regression analysis can be trusted.

Table 7: Coefficients of the regression analysis

	Unstandardized Coefficients		Standardized Coefficients
	B	Std. error	Beta
(Constant)	2,480***	,278	
Environmental concern factor	,151***	,041	,149
Renewables acceptance factor	,066	,037	,066
Energy Independence factor	,166**	,055	,152
Community trust factor	,308***	,051	,273
Community resistance factor	-,259***	,060	-,228
Age	-,001	,003	-,008
Gender (female =1)	-,074	,071	-,039
Education	,114**	,037	,117
Income	,007	,040	,007
Type of community (rural=1)	-,046	,079	-,021
Energy education	,098***	,029	,133
House ownership (owner=1)	,162	,114	,063
PV ownership (owner=1)	-,143	,102	-,052
Awareness (Aware=1)	,173*	,071	,090
Economic incentives	,013	,024	,021
			Adjusted R square 0.388

Dependent variable: Willingness to participate in ICES

Notes: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

5 Conclusions and Discussions

Citizens' participation in the energy system is essential to sustain the ongoing energy system transformation. In this research, we introduced and tested a conceptual framework focusing on demographic, socio-economic, socio-institutional and environmental factors affecting the willingness of local citizens to participate in novel community-based energy systems such as integrated community energy systems (ICESs). A large share of the surveyed citizens are aware of local energy initiatives and exhibited positive interest towards ICESs. The percentage of the respondents willing to participate in such systems is slightly above the majority whereas one-third still remain undecided. Respondents exhibited similar willingness to volunteer and invest in ICESs. Although education and income level positively impacted the willingness to investment, the willingness to volunteer does not seems to be correlated with a part-time or full-time employment of the respondents. Citizens' with house ownerships and male citizens are more likely to participate in ICESs. The percentage of respondents willing to steer such systems, however, is rather small.

The perceived barriers from local citizens in participation in ICESs are lack of time, financial resources, technical expertise. Many respondents who already owned a PV installation perceived that as a barrier to participate in ICESs.

The willingness of local citizens to participate in ICESs is driven by environmental factors such as environmental concern and climate change as well as by community related socio-institutional factors such as community trust, and energy independence. The factor analysis exhibited that environmental concern, renewables acceptance, energy independence, community trust and environmental resistance are important factors in determining the willingness to participate in ICESs. These normative positions of local citizens might partly guide their decisions and practices, thereby strongly affecting their willingness to participate in local energy initiatives such as ICESs. The multi-variate regression analysis exhibits that community trust factor is the most important and statistically significant predictor of willingness to participate in ICESs followed by community resistance, energy independence, and environmental concern factor as well as education, energy-related education and awareness about local energy initiatives. Age, gender, solar PV ownership, house-ownership, income, type of community are not statistically significant predictors.

Although the survey was based in the Netherlands, the results of this study could be useful in implementation and successful operation of ICESs in other parts of the world as well. In particular, important factors such as community trust, environmental concern, energy independence as well as community resistance should be taken into account in such initiatives. The positive interests in local energy projects and higher acceptance of renewables could be useful to increase the share of renewables through community-based initiatives such as ICESs. Despite the large share of the population in local energy initiatives such as ICESs, the research also showed that the share of citizens' involvement diminishes from participation to steering. As the survey was mainly focused on intention of citizens to participate in ICESs, the share of citizens could be even lower in ICES implementation.

The European and its member state policy on end-users involvement are still based on the traditional and centralized energy systems focusing on individual consumers-suppliers relations and undermines the possibility of collective action through local energy initiatives. A level playing field for enabling collective action should be provided. Policy makers should focus on removing the perceived barriers through empowerment of local communities and on increasing citizens' willingness to steer local energy systems. Nevertheless, this study showed that different demographic, socio-economic, environmental and socio-institutional factors should not be neglected while initiating local energy initiatives such as ICESs. The relevance of these factors highlights the dynamics of citizens' participation in ICESs which play transformative role in transition towards more sustainable and inclusive society. Increasing citizens' participation in ICESs will transform it from a niche to a more mainstream system with higher relevance for the whole energy system.

Acknowledgements

Binod Prasad Koirala has been awarded Erasmus Mundus Joint Doctorate fellowship on sustainable energy technologies and strategies. The authors would also like to acknowledge the students of the course TB232 on research methods at the Faculty of Technology, Policy, TU Delft.

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Assessment of Integrated Community Energy Systems

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***Abstract*—Integrated Community Energy Systems (ICESs) are emerging as a modern development to re-organize the local energy systems allowing integration of distributed energy resources (DERs) and engagement of local communities. Although local energy initiatives such as ICESs are rapidly emerging, assessment and evaluation are still lacking on the value these systems can provide both to the local communities as well as to the whole energy system. In this paper, we present a framework to assess the value of ICESs for local communities. We apply this framework to assess the value of ICES in Spain. For a block of 10 households, investments and operations of DERs together with local exchange is simulated in DER-CAM model. For the considered community size and local conditions, ICESs are beneficial to the alternative of solely being supplied from the grid. An ICES that gets remunerated the excess energy to the grid has higher benefits than the system where energy exports are not remunerated as currently in Spain.**

***Index Terms*—Distributed Energy Resources, Energy Communities, Smart Grids, Multi-carrier Energy Systems**

I. INTRODUCTION

The imperative to low-carbon transition is challenging the traditionally centralized energy system. The recent surge of distributed energy resources (DERs) such as local generation, demand response and storage as well as advancements in Information and Communication Technologies (ICTs) which enable the development of smart grids is putting the energy system again at the cross-roads [1] [2].

Integrated Community Energy Systems (ICESs) are multifaceted smart energy systems, which optimize the use of all local DERs, dealing effectively with a changing local energy landscape and local communities. ICESs represent a comprehensive and integrated approach for local energy systems where communities can take complete control of their energy system and capture all the benefits of different integration options. The concept of ICESs is further elaborated in detail in [3] [4] [5]. ICESs are capable of effectively integrating energy systems through a variety of local generation inclusive of heat and electricity, flexible demand, e-mobility as well as the energy storage. Such integrated approach at the local level helps the efficient matching of local supply and demand. Integration of DERs and demand side management through smart-grid technologies not only facilitate an increase in reliability and efficiency of such local energy systems but also affect the existing system architecture and influence the way the smart grids evolve.

Local communities are well placed to identify the local energy needs, and bring people together to achieve common goals such as self-sufficiency, resiliency and autonomy. ICESs are implemented with the aim of reducing energy cost, CO_2 emissions and dependency on the national grid. The national grid, however, makes ICES economically viable with an acceptable security of supply. Local energy projects also lead to job creation and economic growth, foster the transition to a low-carbon energy system, help to build consumer engagement and trust as well as provide valuable flexibility to the market.

Although local energy initiatives are rapidly emerging, they are not without challenges. For example, they may depend on subsidies, as illustrated by the stagnation in the growth of energy co-operatives in Germany after the reduction of feed-in tariffs [6]. Alternative business models such as local balancing and ancillary services as characterized also in the ICESs are needed to continue their growth. Other challenges include split-incentives problems, financing, operation and complexity in decision-making. Moreover, ICESs might encourage opportunistic behavior by contributing less towards network and policy costs.

It is clear that ICESs have both benefits and challenges. However, the assessment and evaluation of ICESs is still lacking. Specifically, the value of block of households being organized as a single entity such as ICESs to the local communities as well as the whole energy system is yet to be determined. The main aim of this paper is to develop the assessment framework for ICESs and present a model-based analysis on the value of such system for local communities.

This paper begins with the assessment framework for ICES in section 2, elaborating changing energy landscape, different costs and benefits of ICESs as well as Spanish regulation affecting ICESs. Section 3 presents the model-structure used to analyze the value of ICES. Section 4 presents various results such as a cost-benefit analysis of ICES. Finally, Section 5 concludes and provides policy recommendations.

II. Assessment Framework

Increased interests in ICES are due to its technical, economic and environmental potential for improving local energy systems. In this section, we account for different benefits and costs to assess the value of ICES, see Figure 1. Benefits come from satisfying local energy needs and providing services to the utility or external system. Costs come from households and communities' investments in DERs, energy imports and network infrastructures.

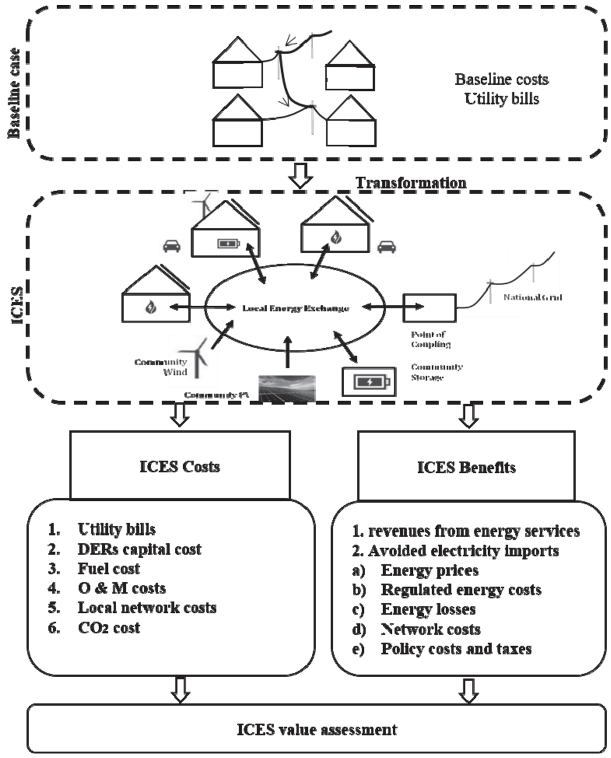

Figure 1: ICES assessment framework

A. Changing Energy Landscape

Traditionally, the energy industry has been managed by vertically integrated utilities [7]. Due to economies of scale as well as resources complementarity, energy system quickly took a centralized form. Traditionally, few large power plants produce electricity and it is transferred unidirectional to households, industry and commercial buildings through transmission and distribution networks. Before liberalization, the energy system was a monopoly with single company and often public ownership of generation, transmission and distribution infrastructure. However, this is changing from early 1980s with the ongoing restructuring and unbundling in order to introduce competition in the system. Energy networks, however, are still a natural monopoly, because of the economic reasons. This transformation has opened several ways for a plethora of the DERs to be part of the power system. Household and community level energy generation, storage and exchange technologies are expected to gain importance in the future energy system [8]. As a result, the technological and institutional arrangements of the energy systems are also rapidly changing.

B. Baseline Case

The current energy system in which the ICES purchase all the energy from the grid is modelled in the Distributed Energy Resources-Consumer Adoption Model (DER-CAM) as the baseline for the value assessment of the ICES [10]. The DER-CAM model has been used widely for economic and environmental analysis of distributed energy resources [9] [10]. Most of these households demand electricity, heat, natural gas and other (transport) fuel and can optimize their energy systems based onsite conditions, energy prices, available technologies, and preferences such as CO_2 costs and reductions. In this sense, DER-CAM assumes households as economically rational utility-maximizers. Hence, prosumer households can optimize their self-consumption and feed electricity into the grid based on economic and environmental criteria. The economic benefit includes, among others, avoided energy purchase costs and revenue from selling energy surpluses. We use 2015 as the base year and use input data from this year unless otherwise stated.

C. Costs of ICES

ICES costs involve utility bills, capital costs for DERs and energy management system, fuel cost, operation and maintenance costs as well as network costs to interconnect households.

1) *Utility bills:* The deficit demand at ICES is met from the market at retail prices.

2) *DER Capital costs:* It involves the investment costs of households and community DERs and cost for corresponding energy management system. This is the major cost in the ICES and it often forms the barrier for its implementation. Moreover, the allocation of the costs to individual households is complex in case of community investment. The investment for ICESs from community or households could come from the individual savings or from the bank loans, for which a rate of return needs to be accounted.

3) *Fuel costs*: The costs of fuels for running fuel-based technologies including CHP, fuel cells, micro-gas turbines, internal combustion engines, gas-boiler and cars' fuels.

4) *Operation and maintenance costs:* Involve costs for operating the local energy exchange and the cost associated with operation and maintenance of DERs. Moreover, transaction costs associated with making contracts, billings etc. should also be accounted (but not modeled here).

5) *Local network costs :* ICES causes bi-driectional flow in the distribution network. For these flows in both directions corresponsing network charges should be accounted. Within ICES, the existing network might also have to be adapted for ICES. There can be resistance from incumbent grid-operator to transfer the ownership or lease the network to the

community. In such case, local communities might have to develop their own local grid after an evaluation on value of such network from national and community perspective. Moreover, the community can be connected to the national grid through point of common coupling. If this is the case, the necessary network infrastructure should be installed. Sometimes, ICES can be connected directly to the Medium Voltage (MV) – network. These addditional community network costs are not accounted in this paper, instead network costs of the national grid are used.

6) CO_2 costs: Some DERs such as CHP, internal combustion engines and micro-gas turbines emit CO_2. The CO_2 cost for ICES is the product of CO_2 emissions times the CO_2 price.

D. Benefits of ICES

There are many benefits of the ICESs, due to the several services provided to their members and to the system. Some of these benefits are efficient for the whole energy system such as revenues from energy sales, avoided energy imports and corresponding energy losses whereas others benefits such as saving in network charges, policy costs (e.g. contribution towards promotion of renewable energy etc.) and taxes might be opportunistic, for further details on efficient and opportunistic benefits please refer to [11]. Although taxes are not cost to the society, it must be kept at minimum to prevent inefficiency as discussed in [11]. On the other hand, ICES might also increase losses through energy export. When assessing the ICES, these avoided costs should be accounted properly. Although the ICES also has system benefits such as reduced network usage due to local balancing, we focus in this paper mainly on benefits for the local communities. Moreover, transactions between the members are not explicitly accounted. Below we elaborate the benefits of the ICES:

1) Revenue from energy services: The energy surplus is sold to the wholesale energy market at the wholesale price.

2) Avoided electricity import: Local generation avoid imports from the national grid. Due to this, part of the several components of retail prices such as energy prices, energy losses, network costs, regulated energy costs, policy costs and taxes could be avoided. For example, there are transmission and distribution as well as conversion losses in the centralized system. These losses are estimated at 14% for residential consumers in Spain [12]. Such losses can be reduced through local generation. Local generation can also save part of the network' costs. However, efficient system of prices and charges should be developed to remunerate transmission and distribution service providers as disccused in [11][13]. Moreover, signficant costs on taxes and regulated charges could be saved in ICESs. For example, in Spain there is 0.06 Euros/kWh for regulated energy charges, 0.01 Euros/kWh for regulated network charges, electricity tax of 6 % and value added tax of 21 %.

E. Spanish regulation affecting ICES

In October 2015, Spain introduced new regulation on self-consumption (Royal decree 900/2015) [14]. The main aim of this regulation is to ensure same contribution from consumers with onsite generation to system costs as the consumers without DERs as well as to prevent inefficient local exchanges and associated regulated revenue losses. For this purpose, a new charge called self-generated energy charge is introduced in order to recover regulated costs and system costs that otherwise would be avoided and is recovered through volumetric charges. In addition, onsite generation does not reduce the established contracted capacity charges. The regulation defines two regimes of self-consumption, type 1 with no possibility to sell excess energy and type 2 with the possibility to sell the excess energy to the grid at the wholesale price after paying network access tariffs. In both cases, the maximum installed capacity should not exceed the contracted capacity and the maximum installed capacity in type 1 should not exceed 100 kW. However, temporarily, type 1 consumers with installed capacity of less than 10 kW do not pay self-generated energy charges. Cost of energy losses are recognized in both cases. Isolated consumers (i.e. not connected to the grid) are exempted from any regulated system costs. The installation of storage is only possible with hourly energy generation or consumption meters (in this way network or other regulated costs are not avoided). Moreover, the regulation strictly forbids ICES or micro-grids where group of consumers are interconnected and exchange electricity among themselves.

On the other hand, the transposition of the EU Energy Efficiency Directive 2012/27/EU was approved in February 12, 2016 by the Spanish Government in the Royal Decree 56/2016 [15, Sec. I]. This law defines a building with null or low energy consumption as a building that supplies its energy needs with renewable energy produced *in situ*. A multiple apartments building is considered as a type of building that needs to be energy-efficient and self-provide electricity mainly with solar panels.

III. MODEL STRUCTURE

To illustrate the value of the ICES, a DER-CAM-ICES model is used in this study. This model has been adapted from the DER-CAM 3.9 [9]. The main modifications are modelling the operation of a group of households and local exchange among them. For simplicity, in this paper, we consider a block of 10 households with solar PV plus battery storage system. However, the model is applicable to larger number of DERs with multiple energy carriers. Below we describe different components of this model.

A. Weather data

The hourly solar irradiance and temperature data for Madrid area are obtained from [16]. Figure 2 presents the hourly output of a 4 kW PV system in the month of July.

B. Demand Profiles

In this research, 10 representative households are used, 8 simulated and 2 measured due to availability. The hourly demand profiles for the 8 households are simulated using the load profile generator tool **[17]**. This tool calculates demand profiles based on household types, occupant's behavior and geographical location. The annual demand ranges from 3149 to 7961 kWh and variation is mainly due to size of household and their occupancy. The remaining two households data are obtained from the smart-meter measurements from Guadalajara city near Madrid, Spain **[18]**. These two houses (H9 – H10) have annual electricity demand of 4510 and 3639 kWh respectively. These profiles are processed to represent the three typical demand profiles, week, peak and weekend, for each month for each household. For example, Figure 2 shows energy demand for July-peak day for household H10.

C. *Energy Prices*

Data for Spanish hourly wholesale and retail electricity prices for 2015 are obtained from [19]. The retail electricity prices include wholesale price and the regulated costs such as surcharges and taxes. A contracted capacity charge mainly covers network costs.

D. *DERs techno-economic data*

Table I presents the techno-economic data of household level DERs used in this study. The variable operation and maintenance cost is 1 % of the capital cost. The cost of capital is 5 % and the maximum payback period for the investment is limited to 10 years.

Table I: Techno-economic data for DER

DERs	Capital cost (kW/ KWh)	Life-time	Ref.
Solar PV	1300 Euros	30	[20]
Storage	130 Euros	10	[21]

E. *Local Energy Exchange*

Local energy exchange is one of the most important attributes of the ICES. To consider the contribution of ICES to the system costs, we applied the retail price for the local energy exchange. The excess energy is traded with the neighboring communities or the national grid at wholesale price and the residual demand is purchased for retail price. Although not modeled here, ICESs can also provide ancillary services to the national grid [22] [23].

IV. RESULTS

The annualized benefits and costs of ICES are presented in Table II. DER cost includes both annualized capital as well as operation and maintenance costs for DERs. We further distinguish between two cases: Case I, ideal conditions from local communities' perspective, which is closer to situations in countries like Germany where no self-generated charge is applied and contracted capacity costs can be reduced, and Case II the Spanish case with current self-consumption regulation (Royal Decree 900/2015). In case I, there is no regulatory barriers and ICES can import and export from the national grid at retail and wholesale price, respectively. For the latter case, we assume that interconnection of household in the form of ICES is allowed according to Royal Decree 56/2016, assuming all other regulation for type 1 consumers as per Royal Decree 900/2015 including self-generated energy charges.

A. *Investment*

For case I, the model invests in 4 kW PV in each household (constrained by rooftop area of 25 m^2). Regarding storage, for the cost of 130 Euros/kWh, 1 kWh is invested in household H4 and H10, 2 kWh in household H5 and H9, respectively. As General Motors have already reported the li-ion battery cost of 130 Euros/kWh for electric vehicles in January 2016, this cost is not too far to achieve for residential storage [21].

Alternatively, in case II, the solar PV investment in households reduces. Solar PV of 4 kW is installed in household H1, H2 and H4, 1.8 kW in H9. At the same time, electric storage capacity of 1 kWh is invested in household H1, H5, H8, H9 and H10 and 2 kWh in household H7.

B. *Economics of ICES*

Table II presents the total costs for baseline case, case I and case II. Cost reduction in case I is mainly from avoided electricity imports and thereby associated energy losses charges, network regulated cost, policy cost and taxes as well as revenue from electricity imports. In case II, the benefit mainly comes from avoided energy prices and energy losses charges for on-site generation. Both cases are feasible under current market conditions without any additional support.

Table II: Annualized costs and benefits of ICES

Total costs and Revenues (in euros)	Baseline Case	Case I: ideal condition	Case II: current Spanish regulation
Electricity import cost	*9254.28*	*4073.00*	*5650.58*
Self-generated energy charges	*0.00*	*0.00*	*779.93*
DER investment costs	*0.00*	*3818.92*	*1426.15*
Contract capacity cost	*1231.82*	*940.02*	*1416.85*
Revenue from electricity exports	*0.00*	*-2642.69*	*0.00*
Total costs	*10824.59*	*6189.25*	*9273.51*

C. *ICES operation*

Figure 2 illustrates the ICES operation at household level in case I. We present the results for July peak-day for household H9 with PV and storage installed capacity of 4 kW and 2 kWh, respectively. The excess PV generation is first exchanged among other households before ultimately being sold to the grid. Figure 3 represents the hourly net exchange among households, net-import and export from the ICES.

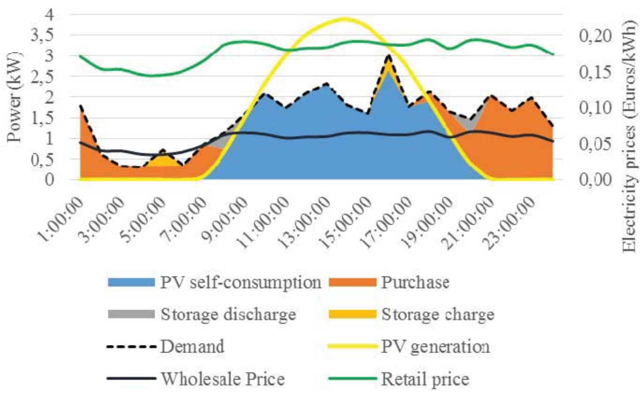

Figure 2: Energy balance in house H9 for July-peak day

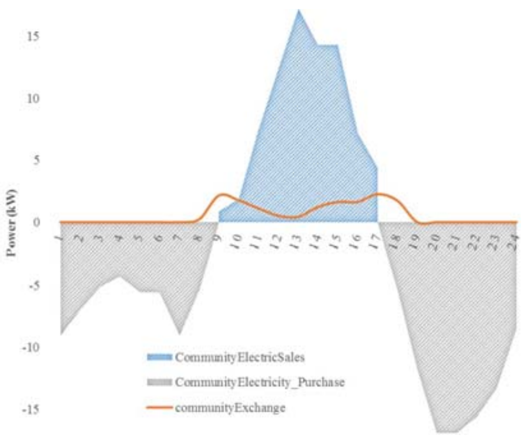

Figure 3: Net community exchange for July-peak day

I. CONCLUSIONS AND POLICY RECOMMENDATIONS

In this paper, a model-based framework considering holistic benefits and costs assess the value of ICESs for local communities. With ideal conditions, ICES is beneficial over current energy system, avoiding system costs. In the other hand, recent self-consumption regulation in Spain makes ICESs less profitable. However, in both cases, ICESs are profitable without additional support by 43 % and 14 %, respectively. Nevertheless, the benefits of ICES are highly subjected to the system of prices and charges.

This model mainly focuses on economic benefits from community perspectives. Provision of system services and other community objectives such as reducing CO_2 and resiliency might affect the value of these systems. Integrating multiple local generation, storage, energy efficiency and demand management system not only provide higher economic benefits but also enable them to play a more active role in achieving low-carbon growth.

The growth of DERs in general and ICES in particular will affect all actors of energy system alike. It is important to avoid opportunistic aggregation and free rider behaviours that avoid paying system costs which otherwise should be recovered through other market agents.

ACKNOWLEDGMENT

Binod Prasad Koirala was awarded fellowship for the Joint Doctorate in Sustainable Energy Technologies and Strategies. The authors would also like to acknowledge the collaboration with the DER-CAM team at Berkeley Lab.

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Opportunities and Challenges of Community Energy Systems: Analysis of Community Micro-hydro Systems in South and South-East Asia (SSEA)

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Abstract

More than 600 million people are still living without electricity access in South and South East Asia (SSEA). Community Energy Systems (CES) can play an important role in providing modern energy access to these remote populations. Micro-hydro if available is the most promising energy systems for rural communities in term of cost and local operation. This research looks into progress of such community based micro-hydro system adoption in SSEA region. Furthermore, opportunities and challenges of these systems are investigated through the careful observation in the published scientific literature, interviews and survey with several local practitioners and organizations from different countries in the region. Although the potential is tremendous, this study finds a need for regional networking and integrated approach for further development of community based micro-hydro systems in the region.

Keywords: Community Energy Systems; Micro-hydro.

Introduction

Electricity has become one of the basic need and a driving force in modern life. However, more than 1.3 billion rural dwellers - one in five globally - still do not have access to electricity (SE4ALL, 2014). Lack of electricity has also hindered access to healthcare, education and employment opportunities for these populations, so that providing energy access to them has recently become a global priority. The United Nations celebrated year 2012 as “Sustainable Energy for All” and aims to achieve universal energy access by year 2030 (UN, 2014). Local communities can have a significant impact on energy production and consumption and can play an important role in implementation of distributed energy (Kelly & Pollitt, 2011). More communities around the globe are generating their own electricity and heat locally thanks to the increasing implementation of favorable policies, cost reduction of renewables, development of information and communication technologies (ICTs) and environmental awareness.

Community Energy Systems (CES) is an integrated approach for supplying a local community with its energy requirement (heating, cooling, electricity and others) from renewable energy, waste or high-efficiency cogeneration sources. It entails the planning, design, implementation, and governance of integrated energy systems at the community level in a way that maximizes energy performance while cutting costs and reducing environmental impacts (Quest, 2012). It also implies looking at existing energy infrastructures and available resources in the community and find innovative ways to use less energy to deliver the same services. When consumers co-operate, more energy options at community level become feasible, like micro-hydro, small wind turbines, community scale integrated solar-photovoltaic systems, district heating or biogas production.

Many communities in developed countries around the globe are taking initiatives through CES to mitigate greenhouse gas (GHGs) emissions and take control over energy generation and consumption whereas in developing countries similar initiatives are flourishing to provide energy access to rural communities. CES initiatives in developed countries is beyond the scope of this paper and here the authors mainly deal with CES in developing countries with special focus on community micro-hydro systems in South and South East Asia (SSEA).

CES can play important role in providing modern energy access to billions of people who still depend on traditional form of energy such as kerosene lamps for lighting, biomass for cooking and diesel generators for irrigation and back-up services. In most of the cases, national grid extension to these areas is both technically as well as economically not viable. Even in the cases when the village has access to grid electricity, there still are many problems in the supply side like low voltages, frequent power cuts, etc. Further, power shortages in the developing countries are very high due to an increasing difference between supply and demand. Utilities usually refrain from extending grid to remote areas because of high investment cost for distribution lines, losses and lower revenue. Moreover, even grid-connected rural areas usually have least priority in case of shortages. This is one of the reasons for poor quality and regular load shedding in electricity supply in rural areas. This happens particularly at times when the need of electricity is highest. Even in the electrified villages, many poor households are still not connected to the grid because of high fees for electricity connection for their houses and unreliability of the electricity supply (Koirala, Ortiz, Modi, Mathur, & Kafle, 2011). Hydro-power by far is one of the most promising form of renewable energy sources, whenever available. It has been widely used since ancient times to meet the energy needs of human civilization. Micro-hydro, which ranges from 5-300 kW[1], when locally available offers one of the promising energy sources for long-term sustainable development in rural areas without energy access (Paish, 2002). Table 1 presents the general incentive and barriers associated with community managed micro-hydro systems.

Table 1: Incentives and barriers of community micro-hydro systems.

Incentives	Barriers
Lower line losses due to local generation	scattered rural dwellings
No direct emissions and very high life cycle energy return on investment (EROI)	Lack of adequate hydro resources
Stronger connection between consumers and energy providers, shared ownership, sense of togetherness	Long term commitment requirement for community-based operation and maintenance
Increased level of energy autonomy, reliability and security of supply	Dependency with community and neighbors
Local employment opportunities through income generating activites	Limited availability of local skills and experience (need assistance, hand-holding and guidance), lack of funding for local capacity building
Potential to reduce per unit cost of energy and very low operating costs.	High up-front investment
Contribution in integrated development of communities through revolving funds etc.	Funding, installation and operation arrangements needed through communities
Locally acceptable and easier permit	Local Conflicts, Local institutional management, e.g. tariff collection by the community

Research Objectives

This paper investigates the status, opportunities and challenges of community micro-hydro systems in South and South East Asia. The main objective is to understand the existing incentives and barriers for implementation of community micro-hydro systems in this region.

[1] The definition of micro-hydro capacity range varies widely in the region and specfic country definitions has been used in this study whenever applicable.

Methods

This research analyses the community micro-hydro systems in South and South East Asia. Most of the discussions in this paper are based on the interactions with participants of the 1st Practitioners Workshop of Hydro Empowerment Network (HPNet) held from 29th August to 1st September 2013 in Borneo, Malaysia (HPNet, 2013)[2]. First of all exploratory research on community energy systems and status of rural energy access in the regions was done. Then, 10 questionnaire surveys (see table 2) with leading organizations and 7 interviews ((Hindrakusuma, 2014) (Lasimbang, 2014) (Maglinte, 2014) (Rahman, 2014), (Sajeew, 2014), (Sharma, 2014), (Shumacher, 2013)) with experts working on this field was conducted to get closer information on status, financial sustainability, productive end uses, capacity building, community motivation, integrated rural development, innovative low cost methods and challenges. Finally, most interesting cases are further elaborated.

Table 2: Details of participant organizations

Organization, Country	Oper-ational years	♯micro-hydro projects	♯micro-hydro (country)
Tonibung, Malaysia	15+	17	~ 23
BGET[3], Thailand	13+	10	~ 60
Practical Action, Nepal	30+	14	~ 1000
AIDFI[4], Philippines	10+	7	~ 100
AEPC[5], Nepal	17+	1120	~ 1287
REPG[6], Bangladesh	2+	planned	-
Odisha, India	8+	5	~ 300
KMHNet[7], India	8+	5	~ 300
SIBAT[8], Philippines	12+	30	~ 100
PT Entec, Indonesia	10+	-	~ 1062

Community Micro-hydro in SSEA

Micro-hydro is playing important role for rural energy access in South and South East Asia already for more than half a century. Population ratio in rural areas and energy access in each countries differ a lot. There is a general trend that countries having lower population living in rural areas have higher electricity access rate. However, countries like Vietnam, Thailand, Philippines and Maldives despite having large portion of the population still living in rural areas have significantly higher electricity access rate.

There are no comprehensive data available for community-based micro-hydro systems in these countries. However, recently there have been initiatives to make

[2] The documentation of this workshop is available on request.
[3] Border Green Energy Team
[4] Alternative Indigenous Development Foundation Inc.
[5] Alternative Energy Promotion Center
[6] Renewable Energy Practitioners Group
[7] Kalahandi Microhydro Network
[8] Sibol ng Agham at Teknolohiya Inc.

database of these systems in some of the countries such as Nepal, Sri-Lanka, Indonesia and Afghanistan from either private sector or government. The status of rural electrification and community micro-hydro in each of the countries in the region is presented in Table 2. The data is based on published articles, survey and confirmation from expert local practitioners from individual countries.

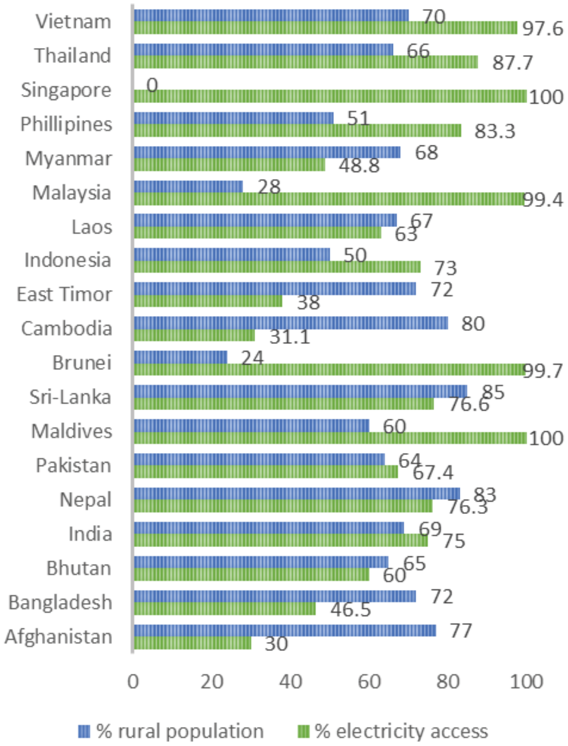

Figure 1: Electricity Access rate (2010) and percentage of population living in rural areas (2010) in South and South East Asia as adapted from (World Bank, 2014)[9].

It is evident that some countries such as Afghanistan, Pakistan, Nepal, Sri-Lanka, Vietnam and Indonesia are doing very well in terms of community micro-hydro whereas countries like East-Timor and Bangladesh are just starting with it. These successful country cases were mainly backed and supported by reputed international organizations such as UNDP, EU, World Bank, ADB, development co-operation organizations from developed countries such as Germany, Japan, The Netherlands, Denmark, Norway and International NGOs such as Practical Action and Helvetas. Moreover, these countries are now capable of autonomously taking it forward. During the HPNet workshop, it became even more evident that these countries can learn a lot from each other and find solutions for existing barriers for community micro-hydro development in the region (HPNet, 2013).

Table 2: Community-based Micro-hydro in SSEA

Country	Installed kW	Source
Afghanistan	46450	(Shumacher, 2013)
Bangladesh	60	(Wazed & Ahmed, 2008)[10]
Bhutan	1480	(Tsering, 2010)
India	6980	(Palit & Chaurey, 2011)
Nepal	25000	(AEPC, 2011)
Pakistan	27000	(Pandey, 2012)
Maldives	-	No data available
Sri-Lanka	1872	(Sajeew, 2014)
Brunei	-	No data available
Cambodia	500	(Sovanna, 2010)
East-Timor	40	(REEGLE, 2014)
Indonesia	21000	(Hindrakusuma, 2014)
Laos	715	(REEGLE, 2014)
Malaysia	178	(Lasimbang, 2014)
Myanmar	-	No data available
Philippines	1236	(Maglinte, 2014)
Singapore	-	No data available
Thailand	1167	(Greacen, 2004)
Vietnam	20000	(Ulfsby, 2004)
Total	**153678**	

Results

Community micro-hydro is already providing electricity access to approximately 1.3 million households[11] in South and South East Asia through numerous projects aggregating to more than 154 MW of installed capacity. All these efforts however have been successful only to provide electricity access to about 1% of the population without electricity access. This shows the amount of effort we need to put together to provide electricity access to all in the region. However, the total micro-hydro potential in the region is huge. For example, exploitation in Indonesia (21 MW out of 230 MW (<10%)), Nepal (25 MW out of 100 MW (25%)), Vietnam (20 MW out of 250 MW (8%)) and Malaysia (178 kW out of 20 MW (<1%)). Below is the summary of the findings from our surveys, interviews and exploratory research on opportunities and challenges of community based micro-hydro systems:

Opportunities for community-based Micro-hydro

There is tremendous untapped micro-hydro potential in South and South East Asia and community-based approach seems to be the best way to tap this potential provided the socio-economics of the region. Further, as national grids approaches the micro-hydro areas or demand becomes too high for the installed capacity, systems can be adapted via grid connection or interconnection of micro-hydro system.

Energy Access: Community-based micro-hydro can play important role in providing electricity to approximately 600 million (IEA, 2012) people without electricity access in SSEA. For example in Nepal, 200000 households are getting electricity through such systems (Sharma, 2014). Moreover, micro hydro can act as a base load generation for renewable energy based micro/mini grids, which are

[9] Electricity access rate for Maldives and Bhutan is adapted from (IRENA, 2014).

[10] Not operational due to faulty design ((Rahman, 2014)

[11] Based on average 120 W connected load per households.

supposed to play a very promising role in enhancing the energy access to rural areas in SSEA in the upcoming years.

Productive End Use: Only two organization out of 10 responded that they do not have productive end uses yet, one of which although made an unsuccessful attempt. Micro-hydro project encourages development of small & micro enterprises, which in turn improves the load factor of the systems during the day, as well as the socio-economics of the communities involved. The common productive end use in the region are rice mills, flour mills, oil mills, carpentry tools, power tools, agro-processing, battery charging, poultry, irrigation, communication center, stone crushers, dryers, chilling plants and coffee processing.

Poverty Alleviation and Gender Equality: It appears that the impact of micro hydro on poverty alleviation and gender issues highly depends on how the hydropower is used by the end-users. Some other qualitative benefits to the society, such as –among others- educational and health benefits from community electrification, improved agricultural yields and drinking water benefits from channels developed for micro-hydro installations remain less understood so far (Khennas & Barnett, 2000). Furthermore, with many male family members of South Asian countries going for jobs abroad, the numbers of female operators have been increased in recent year.

Integrated Rural Development: Seven out of 10 respondent organization work together with other organization to ensure integrated rural development. Some of the experiences includes watershed conservation, community mapping, rural energy development programs, tailrace water for irrigation, revolving funds etc. Projects with integrated rural development approach are able to have community mobilization, hence are more successful. Recently, efforts have been made to develop integrated micro hydro and irrigation projects in countries like Nepal.

Challenges for Community-based Micro-hydro

The location of most of the micro-hydro sites are very remote. Among the 10 organizations we surveyed, one organization has good access road, nine organizations sites has limited access road and one organization has no access road to the project sites. In terms of mobile phones connectivity, four organization sites have no connectivity, two organization sites has occasional connectivity whereas rest have good connectivity to most of its sites. There are numbers of technical, economical, political and institutional challenges associated with implementation of community micro-hydro system in SSEA. Funding and knowledge resources for capacity building as well as innovation needs are the main challenges.

Financial sustainability: Only two organization responded that they are financially sustainable. One of which is charity based organization. This suggests that financial sustainability is still an issue in the region. Although life cycle costs of micro-hydro systems are low, the initial capital cost is very high and ranges from 500-7000 $/kW in SSEA. Within the countries, the initial costs varies a lot depending on the remoteness of the location. For example, in Nepal for the districts which have good transportation network, the costs vary from 3500 – 4500 $/kW whereas for highly remote districts it ranges from 6500 – 7000 $/kW. To overcome this, subsidy from the government exists in many countries in the region for example India and Nepal. For the micro-hydro projects to achieve financial sustainability the tariffs should be set so that it is sufficient to overcome operation, maintenance expenditures and loans At the same time, the set tariff has to be competent with the electricity price from national grid, which might be challenging.

Collaboration between Stakeholders: There is very little collaboration between high-level decision makers, government bodies, funding agency, grassroots NGO's and local communities. Some of the not sustainable micro-hydro projects is not related to lack of enough expertise but more related to not having enough synergy between the stakeholders. Three respondent organizations reported about lack of governmental support.

Community motivation and capacity building: All respondents have faced the motivation problem in some communities and do not want to continue without community motivation in future, as it is extremely challenging. Projects with strong commitment from village leaders and community developer are more likely to get community motivated. When micro-hydro training was integrated in community development activities and communities were involved and informed right from the beginning of the project development, the community motivation was improved. Furthermore, empowerment of community is very important for community based rural electrification. Only three organization responded that they have not done sufficient capacity building training. In addition to technical training for plant operators, some of the remarkable initiatives in this regard are participatory market system development, entrepreneurship development initiatives, community managed electric association and training on community mobilization, account keeping and income generating activities.

Regulatory Framework for Interconnection: Many countries in the region lack suitable regulatory framework for grid connection and interconnection of micro-hydro units. In Sri-Lanka and Indonesia, grid connection has been realized where as in Nepal local grid has been formed connecting seven micro-hydro systems together (Koirala, Schies, Ortiz, Limbu, & Shakya, 2013). Such developments would be a win-win situation with villagers needing more power few years after micro-hydro installations.

Faulty Engineering and Inaccurate Surveys: Engineering related problems, such as -among others- improper site selection, poor surveys, faulty equipment installation, lack of maintenance, improper system sizing and lack of understanding of local market behaviour still play a considerable role in the failure of micro hydro projects. For example, a study by (Khennas & Barnett, 2000) points out that 30 percentage of micro-hydro installations in Nepal were not working due to engineering related problems. Similarly, due to faulty design, the only 50 kW micro-hydro unit in Bangladesh is not operational and it has added acceptance challenges for new micro-hydro installations there (Rahman, 2014).

Fluctuating Demand and Supply: Many micro-hydro power plants have low load factor due to lack of sufficient productive end use during the daytime and most of the electricity demand in rural areas are for cooking and lighting in the evening. To solve the recurring overloading problems, Gridshare® device with LED lights has been installed in 40 kW Rukubji micro-hydro plant in Bhutan so that the consumers know if they can use their rice-cookers or not. (Bucci, 2011). In addition, as most of the micro-hydro installations are based on run-of-river, so the generated electricity varies with the variability of water flow throughout year. In many regions, the water availability reduces drastically during dry seasons. For example, a study by (Palit & Chaurey, 2011) points out that low utilization factor due to insufficient water discharge during dry seasons is one of the key challenges for micro hydro systems in India.

Discussion

Community based micro-hydro systems are small-decentralized energy systems established through joint efforts of multiple-stakeholders and significant participation of local communities involved since from the beginning to the operation of the systems. Although micro-hydro exists in the region for more than half a century, there are still lot of institutional, financial and technical aspects that needs further attention for larger uptake of community based micro-hydro systems.

Higher co-ordination among local communities, social actors, governments, project developers, donor organizations, financial institutions and other stakeholders seems to yield significant impacts in micro-hydro development as observed in countries such as Nepal and Afghanistan. Furthermore, there has been very little co-ordination among countries for micro-hydro technology and policy in the region. HPNet practitioner workshop (HPNet, 2013) was first of its kind and showed that countries in the region can already learn a lot from each other. There is a further need for capacity building and flat and less hierarchical networking within and among the countries. Moreover, it was extremely difficult to gather data for this research, which reflects the need for better database management in most of the countries. Likewise, there is a need for information tools and local practitioners support network for the rural and regional knowledge exchange in micro-hydro.

For the micro-hydro projects to achieve financial sustainability the tariffs should be set so that it is sufficient to overcome operation, maintenance expenditures and loans At the same time, the set tariff has to be competent but should not be referenced with the electricity price from national grid, which might be challenging. The modality of subsidy dissemination should be well developed and transparent. The minimization of the cost should focus more on use of local materials than compromise in standard electro-mechanical components.

Furthermore, there is a need for technology and system innovation. In the community micro hydro work, suppliers/developers are not being enough supported with financing for research and development. If the funding for these projects could also include funds for making the micro hydro technology better, it would help such systems. Further research in the improvement and local adaptation of components of micro-hydro, grid connection, interconnection of micro-hydro systems in the form of local grids and hybrid systems is required. Finally, community micro-hydro should be developed in such a way that it is well integrated in local communities and it contributes in the integral development of socio-economics of the rural communities in the region and ensure success of the projects. Most of the successfully scaled programs have had to rely on and empower the local fabricators and developers from the village level, therefore the focus should be as local as possible. The tremendous opportunities associated with community micro-hydro should be further exploited and challenges should be solved with coordinated efforts.

Acknowledgements

The authors would like to acknowledge Dr. Chris Greacen, Palang Thai (Thailand) ; Chris Wright, HPNet; Owen Schumacher, RemotehydroLight(Afghanistan); Damitha Samarakoon, Janathakshan, Sri-Lanka; Gihan Sajeew, RERED (Sri-lanka); Sanjay Kumar Sharma, Alternative Energy Promotion Center (Nepal), Shen Maglinte, Philippines; and Sentanu Hindrakusuma, Indonesia and all the participant organization who responded to the survey for their contributions and help during the preparation of this paper.

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INTEGRATED COMMUNITY ENERGY SYSTEMS

Binod Prasad Koirala

Energy systems across the globe are going through a radical transformation as a result of technological and institutional changes, depletion of fossil fuel resources, and climate change issues. Accordingly, local energy initiatives are emerging and increasing number of the business models are focusing on the end-users. In this context, Integrated community energy systems (ICESs) are emerging as a modern development to reorganize local energy systems allowing simultaneous integration of distributed energy resources (DERs) and engagement of local communities. With the emergence of ICESs new roles and responsibilities as well as interactions and dynamics are expected in the energy system. With this background, this thesis aims to understand the ways in which ICESs can contribute to enhancing the energy transition.

This thesis utilizes a conceptual framework consisting of four institutional and three societal levels in order to understand the interaction and dynamics of ICESs implementation. Current energy trends and the associated technological, socio-economic, environmental and institutional issues are reviewed. The developed ICES model performs optimal planning and operation of ICESs and assesses their performance based on economic and environmental metrics. This thesis demonstrates the added value of ICESs to the individual households, local communities, and the society. As the added value of ICESs is impacted by the institutional settings internal and external to the system, a comprehensive institutional design considering techno-economic and institutional perspectives is necessary to ensure effective contribution of ICESs in the energy transition

For the KTH Royal Institute of Technology
DOCTORAL THESIS IN ELECTRICAL ENGINEERING
TRITA-EE 2017- 061
www.kth.se
ISSN 1653-5146
ISBN 978-94-6186-827-5