Exploratory modeling of the value of Integrated Community Energy Systems for energy communities

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Abstract – **The concept of Integrated Community Energy Systems (ICES) captures attributes of many energy system integration options. It tries to reach a better synergy between the different energy carriers such as heat and electricity. To find the value that the ICES approach can have for energy communities, an exploratory simulation model of the energy system of Buiksloterham in 2034 is made. Scenarios, containing different integration levels of ICES related technologies, are run under different future developments. It is concluded that RES and energy efficient building mainly decrease CO_2 emissions. Capital investments in heat pumps are high but this technology is needed to reach the most ambitious sustainability goals. Depending on the beneficial future developments, higher investments in heat pumps can be made. For grid-defected communities, other thermal energy technologies and energy storage can be of value. Mainly the future development of electricity demand influences the results of ICES compositions.**

Keywords – **Energy communities, energy system integration, renewable energy, energy transition, smart cities**

1. Introduction

The energy consumption and the organization of the energy supply in urban areas have changed drastically over the last years. Scientists that study the pattern of greenhouse gas (GHG) emissions and the climate, agree that rising CO_2 and other greenhouse gas emissions are causing climate change (EPA, 2016). According to estimations, cities can be held responsible for 75% of global CO_2 emissions (UNEP, 2016). A response strategy for this that has been developed is the smart city development concept (Chourabi et al., 2012). Cities that are going through this smart city development try to maximise their social and environmental capital by making use of amongst others modern technologies, infrastructure and citizen participation (Gladek et al., 2014). The development of smart cities covers all subjects that influence the social and environmental. In this paper, the energy subject of smart city development is investigated. A development that is interesting because of the value that it could offer to the energy sector of smart cities is the energy community development. Community initiatives change the way in which the energy system of a city or a community is organized; from hierarchical top-down system to a bottom-up system where the end-users are more prosumers than consumers, as they are not only consumers, but also generate energy. Community initiatives are decentralized initiatives of local communities and citizens, focusing on the successful implementation of renewable energy sources (Oteman, et al., 2014).

A. Energy communities

The implementation of these initiatives is taking place more often. In Germany over 700 registered community energy initiatives have come up in the last years (Holstenkamp and Müller, 2012) and in the Netherlands there is a total of almost 500 of these initiatives

(HIERopgewekt, 2015). The most important incentives for creating a community energy system are first of all return of investment, because of the possibility to sell generated electricity to neighbouring grids. This can generate local income, together with the creation of employment that energy communities push (Walker, 2008). Community initiatives also lead to a better local acceptance than projects that are managed in a hierarchical way. Load management of an energy system involving renewable energy sources is also likely to be clearer and less problematic in smaller-scale projects than on a national scale (Hain et al., 2005).

B. Integrated Community Energy Systems

Many frameworks and concepts that have been created in the last years could make these community initiatives possible. The most well-known concepts are community micro-grids (Koirala et al., 2015), virtual power plants (Ravindra, et al., 2014), energy hubs (Koirala et al., 2015) and community energy systems (Walker et al., 2012). A different concept, that tries to find solutions for the drawbacks that can be found with the optimal integration of renewable energy sources, is the Integrated Community Energy Systems (ICES) concept. ICESs provide local energy systems with the possibility to optimize themselves, depending on the conditions in which this local community is settled (Koirala et al., 2016). The ICES approach can be seen as a 'multifaceted smart energy system that optimizes the use of all local distributed energy resources, dealing effectively with a changing local energy landscape' (Koirala, 2017, p.366). It captures attributes of many energy system integration options such as virtual power plants and energy hubs and applies them to a community level energy system (Koirala, 2015). ICES wants to reach a better synergy between different energy carriers such as heat, gas and electricity. Two general forms of ICES can be distinguished: a grid-integrated ICES, and a grid-defected ICES. A grid-integrated ICES is connected to the national energy system and thus has dependencies with it. A grid-defected ICES has no interconnections with the outside grid and is completely independent of this grid (Koirala et al., 2016). The energy demand either can be met with imports from other energy systems (grid-integrated) or needs to be met locally by own power generation, without energy import (grid-defected).

C. Buiksloterham

Buiksloterham is a district in the North of Amsterdam. It has the ambitions of becoming a sustainable circular community. The district of Buiksloterham is currently mainly used as a business site with only a number of 234 registered residents in the year 2014 (Gemeente Amsterdam Noordwaarts, 2009). Figure 1 shows the area of Buiksloterham.

Figure 1: Area of Buiksloterham.

This district is an example of an energy community that is going through smart city development. The transition in Buiksloterham is still in start-up phase. The governance behind the energy supply of the community has had little development yet (Gladek et al., 2014). The energy supply could be developed as a decentralized community energy system, in order to reach the sustainability goals of the community. The ICES approach can provide guidance in (re)forming the energy system of this community. The community of Buiksloterham will be used as case study in this research.

2. Problem description

The research in this paper is aimed at finding possibilities in improving community energy systems. The application of the Integrated Community Energy Systems approach is investigated.

A. ICES technologies and compositions

Different technologies are involved with ICES. These technologies will be called 'ICES related technologies'. Technologies on generating renewable energy via renewable energy sources, such as solar panels and wind turbines are an example of this. Next to this, technologies that provide flexibility in a system, such as energy storage or thermal energy technologies such as heat pumps and solar boilers are also related to the design of an ICES. Other technologies, that are part of the electrification of the energy demand, such as the penetration of electric vehicles, can also be linked to the design of ICES. Figure 2 shows the conceptual design of an ICES and the technologies at the community or at the household level that are related to this.

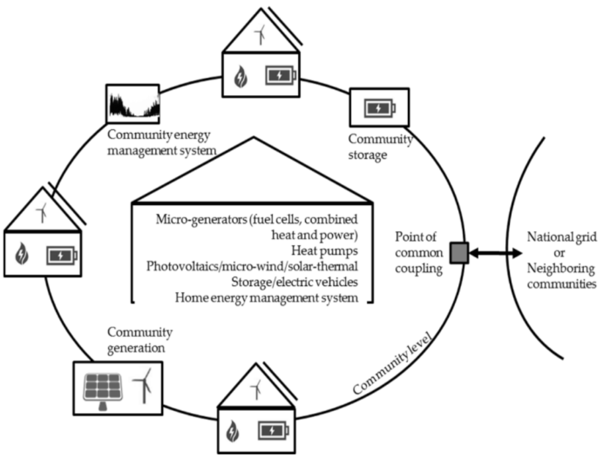

Figure 2: Conceptual design of an ICES (Koirala et al., 2016).

Previous studies on the application of ICES on energy systems (Koirala et al., 2016, van den Hil, 2015) have focused on the optimization of an energy technology set for specific households in an energy community to reach for instance low CO_2 emissions or high self-sufficiency of the energy community. In this research, an exploratory focus is taken. The focus is at the community level of the energy system, not at the household level.

For communities it is valuable to know which technologies of ICESs and thus what type of ICES composition can lead to certain results in the trend of becoming a sustainable energy community. The case of the energy system of Buiksloterham is used to find the value that different ICES applications can have for a specific energy community. As the community largely still needs to be formed, this means that in advance there not any ICES compositions that are more or less desired for implementation than others.

B. Research question

The research that is presented in this paper wants to answer the following research question:

'What value does ICES have for the community of Buiksloterham, to reach the sustainable energy goals of their smart community development?'

In order to answer this question, a simulation model on the development of an Integrated Community Energy System of Buiksloterham has been developed. The exact method and how this will answer the research question of this paper, is described in more detail in section 3.

3. Method

The method that is used in this research, is analysing the outputs of a simulation model of an ICES in an energy community. The energy community that is used as a case study is the energy community of Buiksloterham. To create this model, a system demarcation needs to be made. The households and the demand patterns of Buiksloterham form the energy community. The year 2034 in which a certain ICES is implemented is simulated in the model. This is because 2034 is the year for which the municipality of Amsterdam has set certain ambitions in their circular city development. The target for this year is to have developed a self-sufficient energy grid with a fully renewable energy supply. The choices that are now made for the energy system, will determine what the energy system will look like in this year. 3500 households will be included in the energy community of Buiksloterham, as this is the expectance and target of the municipality (BIES, 2016).

A. Simulation study

In the simulation, the energy community has a gas and electricity demand profile that is linked to the number of households. The demand has to be fulfilled by a supply every hour of the simulation. The electricity demand can be, depending on the applied ICES related technologies, (partly) fulfilled by the generation of renewable energy sources installed at the community or household level of the energy system. In this simulation, solar energy installations represent household renewable energy sources (RES) and wind energy installations represent community RES. Heat demand can be fulfilled by various options such as natural gas or electricity via thermal energy technologies. The main working principles of the simulation model are that when the locally generated supply of electricity cannot fulfil the demand, the supply has to be met by buying electricity from the central energy grid. Electricity can be locally generated, while the supply of gas is arranged via the traditional way of central supply by natural gas. An oversupply of locally generated energy can be sold at APX price level to the central grid.

The modelling approach that is taking for this simulation study is to create the model in the computer program MATLAB. MATLAB is a computing environment in which simulation models can be developed. With MATLAB, large datasets of information can easily be imported and complex calculations and simulations can be run. By varying the inputs of this model, and creating scenarios in which the implemented technologies of the ICES differ, the values of the ICES approach for the energy community of Buiksloterham can be investigated. By analysing these results and taking it to the bigger picture of ICES application to energy communities in general, an answer can be given to the research question of this study.

B. Key performance indicators

The simulation study is exploratory and with the outputs of the simulations, the value of different ICES compositions on the key performance indicators (KPIs) of the energy community of Buiksloterham is compared. The KPIs are the following:

- CO_2 emission [Ton CO_2/year]
- Self-sufficiency [%]
- Total energy demand per household [GJ/household/year]
- Yearly cost of the ICES [€/household/year]
- Total renewable energy exported to the central grid [GJ/year]
- Self-consumption [%]
- Maximum line capacity flow [kWh]
- Capital costs of the ICES components [€/household]
- Payback time of ICES related capital costs [Years]

C. Scenarios in the model study

The simulation model contains the following parts: demand (heat and electricity), supply (household RES and community RES), the energy efficiency level of buildings, the exchange of energy between the central energy grid and the community energy grid and thermal energy technologies to meet heat demand (electrical heat pumps). Data about model factors such as variable costs and CO_2 emissions is gathered and assumptions are made, to model the energy system in the year 2034 and create trustworthy output. The output of the simulations is of course also dependent on the input of the simulations. This input is determined by the scenarios that are run in the simulation study.

The scenarios are formed by choosing the level of integration of the following four ICES technologies: (1) Energy efficient buildings, (2) household RES (solar panels), (3) community level RES (wind turbines) and (4) thermal energy technologies (electrical heat pumps). The results of these scenario runs are also analysed by taking into account uncertain future developments. Integration of energy efficient buildings can be none, medium or full, meaning that none, half or all of the buildings are built with high energy efficiency standards, lowering the energy demand of these buildings. Household RES investments can be low (30% of total rooftop capacity covered with solar panels), medium (50%) or high (80%). Community RES investments can also be low, medium or high, with these three categories corresponding with the same installed capacity levels as with household RES. The integration of heat pumps can be none, medium or full, meaning that none, half or all of the buildings make use of electrical heat pumps. These buildings then use electricity for heating instead of gas.

Because of the fact that the model simulates the energy community in the future, it is unsure which value some factors will have in 2034. It is therefore valuable to see what the influence of these future developments is on the simulation results. The uncertain future developments that are included in the modelling study are the following: (1) The electricity demand by end-users of the energy system in 2034, (2) the ICES technology related capital costs in 2034, (3) the APX electricity price in 2034 and (4) the natural gas price in 2034. There are multiple directions that these developments could take in the future, and different motivations can be found behind these directions.

4. Simulation results

Ten scenarios are simulated in the model study to see the effect that different ICES compositions have on the functioning of the energy system of Buiksloterham. The scenarios are based on penetration of the ICES technologies.

The ten scenarios that are simulated are the following:

1. Minimum ICES investments
2. Maximum ICES investments
3. Medium ICES investments
4. Maximum RES and full energy efficient buildings
5. Maximum RES and full heat pump investments
6. Maximum RES investments
7. Full heat pumps and energy efficient buildings, low household and community RES
8. Maximum ICES investments, but low community RES
9. Maximum ICES investments, but low household RES
10. Maximum ICES investments, but medium heat pump investments

The simulation results of the scenarios with the most important outputs on the key performance indicators will be analysed, after which the influence of the uncertain future developments on the scenarios is discussed.

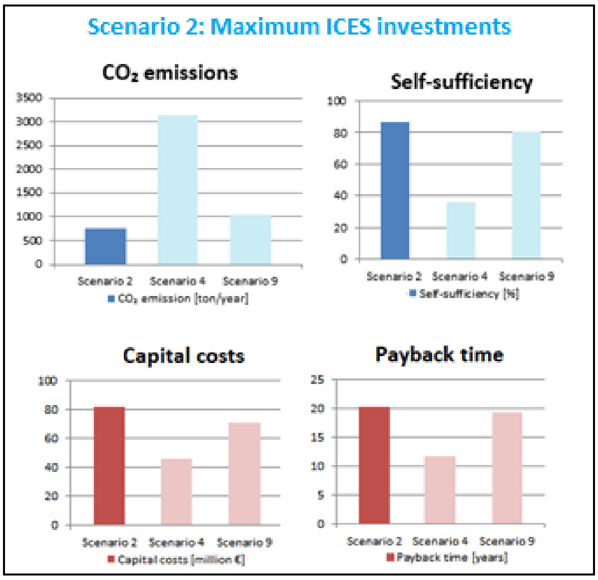

Figure 3: Most important results of scenario 2.

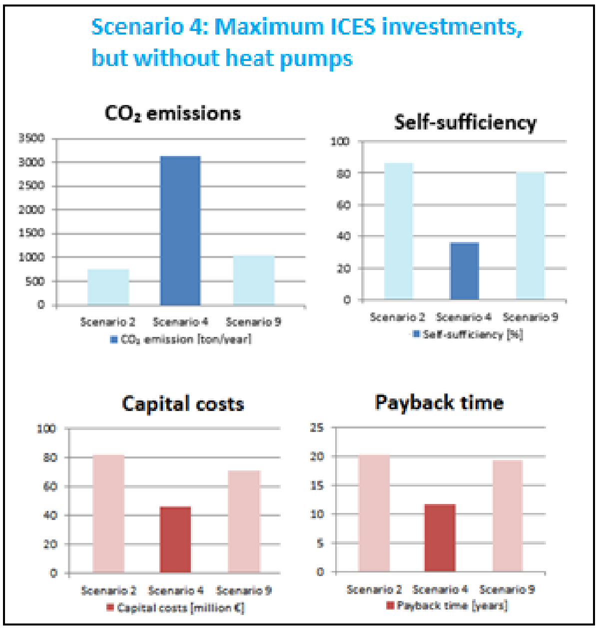

Figure 4: Most important results of scenario 4.

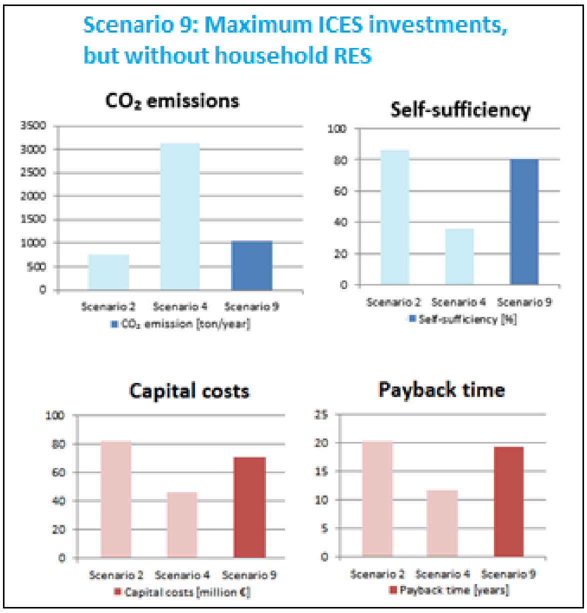

Figure 5: Most important results of scenario 9.

A. Results on KPIs

The capital costs and payback time of the ICES related capital costs show what the 'price' of the different scenarios is. The results of all scenarios 2, 4 and 9 on these key performance indicators are displayed in figures 3 to 5.

The output on the key performance indicators can show the value that the ICES compositions have for the energy community of Buiksloterham. The most important of those KPIs are the CO_2 emissions and the self-sufficiency percentage of the energy community. The capital costs and payback time of the scenarios are important to show the unbeneficial conditions under which this ICES is developed.

What can be seen is that scenario 2, with maximum investments in the ICES technologies, is that it has the best results for the sustainability goals. Scenario 4 differs from scenario 2 because it has no integration of heat pumps. The payback time and capital investment costs are significantly lower and could become closer to acceptable. The self-sufficiency however is around 36% and the CO_2 emissions are four times higher. The simulations show that community RES is more beneficial for the sustainable key performance indicators than household RES. Scenario 9 is therefore based on full integration of the ICES technologies, except for the integration of household RES, which is low. Looking at the KPI results, scenario 2 and 9 seem to, relatively to the costs, achieve the same level of favorableness. The results on the CO_2 emissions and self-sufficiency are slightly less beneficial, but the payback time and capital costs of scenario 9 are about 15% lower than in scenario 2.

The results show that for energy communities in general, RES capacity is important for meeting the electricity demand and lowering the variable yearly costs of energy supply, which again will lower the payback time of the total investment costs. The integration of heat pumps lead to a high self-sufficiency, while the integration of RES lead to a low CO_2 emission and a small increase in self-sufficiency. Investing in energy efficient buildings has a more beneficial influence, relative to the capital costs, on decreasing the CO_2 emissions than integrating RES. Investing RES increases the self-sufficiency of the community which the integration of energy efficient buildings does not.

The results are now used to look at other energy communities and the application of ICES in general. In a grid-defected energy community, the ICES is not selling or buying electricity from the national grid; other investments in for instance electricity storage here are needed to balance demand and supply. Other thermal energy technologies, such as solar boilers or city heating are less dependent on the integration of renewables, as they provide sustainability by nature already. For energy communities, the value of energy efficient building is dependent on the possibilities of being able to easily build or change new or existing buildings. The future electricity demand is mostly influencing the value of ICES technologies on the energy system of a community. The developments of natural gas- and electricity prices are not important for grid-defected ICESs, as they are not buying energy from the central energy system.

B. Results on future developments

The direction of the development of the electricity demand in the future has the largest influence on the result on the KPIs and thus on the performance of the energy system. A 30% lower demand of electricity would lead to an almost two times lower CO_2 emission in the scenarios with large ICES investments. Concerning the investment costs and payback time, a lower electricity price and of course a development of lower capital costs of ICES related technologies would lead to lower investments and a lower payback time in the scenarios. Lower future ICES investment costs have more influence on this than a lower energy demand. The other way around, the price of natural gas and the APX price of electricity can increase the payback time, but this effect is rather small.

5. Conclusions

For energy communities, it is recommended to invest in renewable energy sources to both reach a high self-sufficiency and low CO_2 emissions, while the investments costs can be earned back. The RES adoption should be focused first on community RES and only when community RES would not be available, also on household RES. Without heat pumps, the results on the sustainability goals are decent, but not as ambitious as the municipality of Amsterdam wants to be. Better results are reached with electric heat pumps, but the downside is the large investments costs and high payback times. Dependent on the direction of the uncertain future developments, a number of heat pumps could still be implemented in some or all of the houses, to achieve this much higher self-sufficiency level and lower CO_2 emissions. A better exploration of uncertain future developments, that influence some of the output values of this research, could help to get more insight in the exact value and costs of these heat pumps in the future, in combination with the other ICES related technologies. For energy communities that are not integrated with the national energy grid, investments in energy storage are needed to balance supply and demand.

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