Frugal Eco-innovation for Addressing Climate Change in Emerging Countries
Case of Biogas Digester in Indonesia

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Contents

Abstract

Technological innovation is considered to be one of the key strategies to maintain the global temperature below 2 °C. Since emerging and low-income countries are now responsible for reducing greenhouse gases (GHGs) under the Paris agreement, there is an implied need to balance their development mandate and climate change policies. This chapter highlights frugal eco-innovation as a means of providing basic needs while including the requirement to urgently address climate

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change in these regions. The characteristics of frugal and eco-innovation are explored to identify the appropriateness of technologies within the context of emerging and low-income regions. These characteristics are applied to demonstrate the economic and social benefits of the low-carbon technologies at the local level. Meanwhile, the eco-innovation's characteristics demonstrate a potential for cascading positive impacts at a larger scale. Finally, the Alternative Pathways framework is applied to describe the trajectory of frugal eco-innovation through low-carbon narratives. This framework also helps to make explicit the dominating fossil fuel pathway and powerful actors while identifying alternative technology pathways and different (nondominating) actor groups that could potentially transform the rural energy system. Portable biogas is identified as a frugal eco-innovation that represents an alternative pathway which can potentially lead to wider transformation for the cooking energy sector in rural Indonesia. The innovation can create knock-on socioeconomic benefits for lower-income communities while contributing to GHG emission reduction at national level. This frugal eco-innovation process is led by the private sectors with the support of policy environment and acceptance and implementation at the local community level.

Keywords

Frugal eco-innovation · Clean cooking energy · Alternative pathways · Indonesia · Climate change

Introduction

Addressing Climate Change in Emerging Countries Through Frugal Eco-innovation and Alternative Pathways Framework

Every continent is under serious threat of climate change. Particularly, emerging and lower-income countries are more vulnerable to climate change risks as they still strive for economic growth. Emerging countries with high economic growth like China, India, Indonesia, and Brazil have voluntarily committed to reduce GHG emissions in their respective Nationally Determined Contributions (NDCs) as part of the Paris Agreement. These emerging countries highlighted the concept of sustainable development and promoted clean energy as part of their strategy to deal with climate change while maintaining economic growth. So far, most of the strategies proposed are technology-centered while other innovations, such as those in agriculture, have also been considered.

A set of sustainable strategies to reduce GHG do not only employ the low-emission technologies that are available today but also encourage the innovation of required new technologies (Rubin 2011). In early innovation studies, the process of technological innovation has been motivated by an urge to solve certain economic problems within a silo, thus giving limited attention to the interplay with external forces (e.g., social, cultural, and environmental factors) (Kemp et al. 1998). In contrast, current energy transitions literature provides more insights on the need for socio-technical change. For instance, the maturity of technological innovation in addressing environmental problems such as air pollution and water pollution is a more recent development unlike other industries such as electronics or automotive (Rubin 2011). The complex nature of issues related to climate change drives innovation studies to new directions, from solely supporting economic growth to finding innovative technologies as responses to anthropogenic climate change, i.e., low-carbon technology (Geels 2004). Often, these novel low-carbon technologies may initially have low performance or are more expensive and thus are not able to compete with the existing or mainstream technologies. These technologies act as "incubation room" – called niches (Geels et al. 2018). Thus, through a complex and lengthy innovation process, these technologies become impactful once they achieve larger scales. Furthermore, the technological innovation is also linked with the change not only in the business space, but also in the institutional and even the cultural context as enabling factors (Cooke 2012). Here, barriers and challenges remain in the deployment of low-carbon technologies, particularly in regard to the energy sector in developing countries.

Although there has recently been remarkable progress in providing energy services for poor and emerging countries, it is reported that 2.6 billion people still live without clean cooking and approximately 950 million people still do not have access to electricity. Specifically, in Indonesia, as the focus of this chapter, about 9% of the population fall below the poverty line (Badan Pusat Statistik 2018), with 30% of the population still relying on traditional biomass fuels (IEA 2019a, b). Thus, the world still remains short of the target of SDG No. 7 to provide clean and affordable energy (IEA 2019a, b). Given the complex nature of this issue, there is a necessity to address nearly all other SDGs. One of the reasons for slow adoption may be the inadequate understanding of local cultures and their institutional capacities (Murphy 2001). It was studied that the cost of the technology is a more sensitive decisive factor for low-income households, as opposed to, for instance, quality of the technology (Takama et al. 2011). Thus, in terms of the affordability of clean energy, an increase of the technology's cost leads to the reluctance of a pervasive adoption (Takama et al. 2011). The lack of modern and clean energy access then induces the use of unsustainable alternative fuels, such as firewood and kerosene, which are responsible for deforestation and indoor air pollution that leads to GHG emissions and premature death, respectively. Energy for cooking is still one of the largest forms of energy consumptions in countries of the global south. For countries that rely on firewood, most of the energy is used for cooking because of weaker industry and transportation sectors as well as less demand on the heating in the house (Food and Agriculture Organization of the United Nations and Stockholm Environment Institute 2010).

In the last decade, there has been an increasing focus on low-carbon innovations beyond the energy sector to address climate change as well as to meet the needs of the low-income community. Indonesia has perceived adverse climate change impacts in economic sectors such as agriculture, which cuts across energy and food. Fluctuating rainfall and increased temperature have been affecting the agriculture productivity, for example, rice paddy production in Bali (Takama et al. 2014). This is far from the conventional narrative on how innovation was initiated in industrialized countries and transferred to the "rest" of the world. Many reports indicate that innovations from emerging markets such as Brazil, India, and China are focused on addressing negative environmental impacts. An example being the scale-up of renewable energy, such as solar, wind, and biogas for households in China and India (Spratt et al. 2014; Bond and Templeton 2011). Because of the importance of improved energy services to poor communities, on the one hand, and the crucial role of technological innovation in addressing climate change, on the other, this chapter aims to better understand how innovation processes in poor communities differ from industrialized countries in addressing climate change impacts.

Frugal eco-innovation presents an innovative way to address the challenges of satisfying basic needs while mainstreaming climate change initiatives in rural areas. Emerging countries, including Indonesia, are now responsible to reduce greenhouse gases (GHGs) under the Paris agreement, requiring the government to balance their development mandate with climate change policies. The concept of frugal eco-innovation was introduced by Vilchez and de la Hiz (2018) to reduce negative environmental impacts in resource-constraint areas in Europe. The frugality appeared initially as a promising solution to tackle the poverty gap by providing affordable products and services that employ minimal resources. This concept is highlighted and later emphasized by the role of the interaction between private firms in making change possible in a niche and the effort to create systemic change (Prabhu 2017). Following the predecessor of frugal innovation concept, this chapter applies the concept as an approach done by Prabhu (2017), rather than a specific form of innovation. Meanwhile, eco-innovation serves the need of socio-institutional change at the national level (top-down approach) while closely engaging their consumers (bottom-up approach). This reduces the negative environmental impacts on a larger scale. The study bringing together *frugal eco-innovation* is at the present limited, particularly in emerging countries. Thus, this chapter is expected to better understand how frugal eco-innovation could potentially accelerate the adoption of low-carbon solutions in emerging markets to assist with meeting their NDC targets.

Within this chapter, the development and deployment of biogas digesters in Indonesia is used as an example of a frugal eco-innovation in the energy sector, focused on cooking applications. In order to describe the trajectory of frugal eco-innovation in the case study, a framework of Alternative Pathways is applied (Lieu et al. 2020). The path that leads to innovation is a conscious process initiated by the firm innovator. It is one that recognizes the complex nature of innovation that involves other stakeholders to bring larger scale of changes. Thus, Alternative Pathways is used as an analytical framework to identify different narratives and provide an empathetic understanding of the process of frugal eco-innovation in potentially transforming the rural economy (i.e., energy-agriculture sector) in Indonesia.

This chapter first discusses the appropriateness of frugal eco-innovation by describing the integrated characteristics of frugal eco-innovation that strengthen the unique innovation of the case study. Subsequently, the importance of Alternative Pathways is portrayed after introducing Indonesia's context for the framework application. In the third section, the Alternative Pathways framework narratives conceptualize the energy options for rural households that lead to the introduction of frugal eco-innovation. The narratives of the energy options are explored by using the pathway classification proposed in the Alternative Pathways framework: a mainstream pathway, on-stream and off-stream pathways, and a transformative pathway. Finally, section four emphasizes opportunities of future application for frugal eco-innovation that represent an alternative pathway. This represents the potential for a wider transformation of the cooking energy sector in emerging markets such as Indonesia, namely as a means to improve their capacity to address climate change.

The Appropriateness of Frugal Eco-innovation to Describe the Case Study

Initially, frugal innovation emerged as a promising solution to tackle resource scarcities in low-income contexts by providing affordable products and services for low-income people to meet their needs that were not attended to by regular business (Numminen and Lund 2017; Albert 2019). Frugal innovation aimed to reduce complexity and lower technology cost. One of the first scholarly discussions of frugal innovation was in a relatively small section of a book about economic development strategy in India and China by Gupta and Wang (2008). Here, frugal innovation was defined as: *"innovation that strives to create products, services, processes, and business models that are frugal on three counts: frugal use of raw materials, frugal impact on the environment, and extremely low cost."* It was further stressed that the rapid rise of emerging markets is the prime motivation behind the critical need for all three types of frugality (Gupta and Wang 2008). This was followed by substantive coverage in a special report by *The Economist* in 2010, which described frugal innovation as "*not just a matter of exploiting cheap labor, it is a matter of redesigning products and processes to cut out unnecessary costs"* (Bhatti et al. 2018).

Scholars have defined the concept of frugal innovation in different ways. In 2012, Navi Radjou coined a new term for frugal innovation in his book "Jugaad Innovation: Think Frugal, Be Flexible, Generate Breakthrough growth" (Radjou et al. 2012). Based on the Hindi word that means "improvise fix," Jugaad underlies three principles of doing more with less: 1) keep things simple, 2) do not reinvent the wheel, and 3) think and act horizontally; scale out instead of scale up. Here, scaling up means to grow vertically, which is commonly referred to as institutionalization, while scaling out takes current resources and replicates it to the other regions (Pachico and Fujisaka 2004).

Despite having various definitions, Numminen and Lund (2017) attempted to outline three main criteria for frugal innovation. First, the use of resources in the concept of frugal innovation, such as raw materials, energy, and water, is conserved or reduced. Product simplifications could also lead to considerable energy and cost savings, creating affordability. Resource efficiency, substitution (with local and sustainable materials and processes), and sufficiency are described as part of the ecological sustainability of frugal innovation (Albert 2019). Second, frugal technologies should be robust and durable, especially when products are used in remote or resource-constrained areas. When the frugal product or service is placed in resource-constrained areas, the needs of the locals are addressed through a product that is user-friendly, accessible, and affordable. This includes accounting for the availability of skills in the area to ensure consistent and stable maintenance by locals. Finally, the frugality principle is also applied to energy usage, having modest energy output levels that are monitored. Frugal innovation addresses issues in several sectors, such as healthcare, water, energy, and communication (Bhatti et al. 2018). Focusing on the energy sector, Numminen and Lund (2017) emphasized that frugal innovation should contribute to create access to affordable and sustainable energy resources for low-income and rising middle-income segments.

Due to its characteristics of frugality, the product or service of frugal innovation is perceived as having a lower carbon footprint compared to conventional technologies (Albert 2019). However, the concept of frugal innovation itself is not inherently sustainable (Wohlfart et al. 2016; Weyrauch and Herstatt 2017), as reducing resources does not directly translate into environmental protection (Rosca et al. 2018). For frugal innovation to be more in line with sustainability, Baud (2016) suggested several conditions to be fulfilled: 1) Firms should commercialize affordable frugal products and services, 2) low-income actors should be engaged in value chain activities, and 3) natural resources should be employed in a frugal manner. Since the technology described in this chapter contributes directly to addressing climate change, frugal innovation becomes an insufficient term to describe the technology. Hence, the concept of eco-innovation is introduced.

The term eco-innovation (used interchangeably with sustainable innovation) has been used in diverse contexts. The focus of this idea is on technological change that contributes directly to reducing negative environmental impacts. In addition, when developing eco-innovation, social considerations are highly prioritized (Rennings 2000; Cooke 2012). In addition, Carrillo-Hermosilla et al. (2009) proposed four characteristics or dimensions of change in eco-innovation: design, user innovation, product service, and governance. These characteristics of change have been used as factors to determine the success or failure of an eco-innovation.

In the first characteristic of eco-innovation, *the change of design*, integrating environmental factors, becomes an emerging trend besides cost and profitability. This characteristic emphasizes how design dimensions can maximize positive impacts on the environment. In frugal innovation, this is recognized as minimizing negative environmental impacts by reducing excess resource use and implementing user-friendliness for products in rural areas. To assess the impact of eco-innovation, Carrillo-Hermosilla et al. (2009) further suggested three approaches of design change: component addition, subsystem change, and system change:

1. *Component addition* refers to the development of additional components of the technology or end-of-pipe technologies to curb the negative impacts of the existing system on the environment, for example, carbon sequestration.
2. *Subsystem change* is defined as system performance improvements to reduce negative impacts on the environment. This component is associated with eco-efficiency. This involves producing economically valuable goods and services while reducing the ecological impacts of production (producing more with less). Examples include efficiency improvements in energy and water use.
3. *System change* refers to the redesigning of unsustainable systems by considering the positive and negative impacts on the environment. These moves toward making peace with the environment (biocompatibility) include, for example, closed-cycle production through recycling.

The second characteristic of eco-innovation is *user innovation*, which emphasizes a change in the behavior of individual users or organizations. The users play a key role not only in applying innovations, but also in making improvements to the innovative product or service. The role of users in improving the product or service is observed using two components: (i) *User Development*, where innovation is inspired from the users' ideas, and (ii) *User Acceptance*, where behavior changes are evident in adopting eco-innovation. The contribution of users in modifying or improving a product or services determines the direction of the innovation, even toward environmentally benign practices. On the other hand, the behavior change of users could result in the acceleration of eco-innovation adoption in the socio-technical system where the product and/or service evidently move to meet the community's basic needs. In some cases, change of behavior could be achieved when a technology is proven to solve social issues or fulfill social needs (Wüstenhagen et al. 2007).

The third characteristic, *product service of eco-innovation*, calls for consideration of overall business strategy and logic, including the convergence of supply chains. To achieve radical change, product service innovation requires a rearrangement of the product service concept which is developing sustainable business models. The sustainable business model in question refers to "a system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have lower environmental impact than conventional business models." An example is seen in Radjou's (2012) frugal innovation concept, when addressing the necessity for a less centralized supply chain that allows scalability.

The last characteristic, *the governance change*, is required to allow the eco-innovation to persist in a much higher level of environmental and economic performance when the prevailing socio-technical system of the innovation acts as a barrier. Overcoming such pervasive barriers may require significant governance innovation both in the private and public sectors. The governance innovation for eco-innovation refers to institutional and organizational solutions to resolve conflicts around the innovative environmental-friendly practices. From the innovators' point of view, this dimension challenges the firm to improve its relationships with other stakeholders, especially with the government.

In this chapter, the concept of eco-innovation does not only describe technological development by improving the existing product to tackle environmental concerns, but also incorporates social dimensions. For instance, the interaction of stakeholders (e.g., users and government) could contribute to the technological advancement toward system change or, in climate study, what is commonly known as transformative pathways toward sustainability (Lieu et al. 2020). In addition, embodying frugal innovation in the product's (or service's) sustainable development is imperative in emerging countries due to well-being and resource constraints. To merge the two complementary innovation concepts, this chapter applies the concept of *frugal eco-innovation* to describe a biogas technology innovation in Indonesia. The concept of frugal eco-innovation is introduced by Vilchez and Leyva de la Hiz (2018), and it is defined as:

"[. . .] ecologically sustainable business approach that strives to create products, services and even productive processes that are easier to use, have a clear orientation for reducing operational costs and decrease (and even eliminate) the negative impact on the environment."

Based on the scholarly discussion above, Vilchez and Leyva de la Hiz (2018) emphasize some core characteristics of frugal eco-innovation. First, frugal eco-innovations focus on diminishing negative environmental impacts through simple and efficient means. Second, frugal eco-innovations are designed to promote the reuse, recycling, and revalorization of by-products. This means that the innovation is easier to disassemble for recycling and reuse. Frugal eco-innovation also promotes environmental-friendly business models for revalorization of by-products, derivatives, and waste with the additional advantage of obtaining extra revenue. Last, the cost of developing the innovation product or service is low.

The concept of frugal eco-innovation can be consolidated by integrating separate characteristics of frugal innovation and eco-innovation, as well as the characteristics suggested by Vilchez and Leyva de la Hiz (2018). Additional characteristics are identified in Indonesia's case study to provide further understanding about how the impacts of a frugal eco-innovation could bring cascading effects to support economic growth and tackle climate change issues. The additional characteristics include inclusiveness and reusability, which can also be perceived as place-bound characteristics. In terms of inclusiveness, the case study describes how a technology aims to reach the needs of communities in remote areas, especially during the covid-19 pandemic, when physical distancing is required. Reusability illustrates how the case study technology addresses the limited resources of remote areas by providing an easy-to-use and easy-to-remove technology that could be used for multiple purposes. In sum, frugal eco-innovation, as defined in this chapter, should possess the following core 11 key characteristics, including their indicators to measure the change, as described in Fig. 1.

For the indicators of design and process development, as mentioned, the extant potential technologies are assessed based on the indicators of design change: component addition, subsystem change, and system change. In respect to frugal design and manufacturing, the case study highlights the material and installation time to demonstrate the frugality of the technology. To connect the design change in

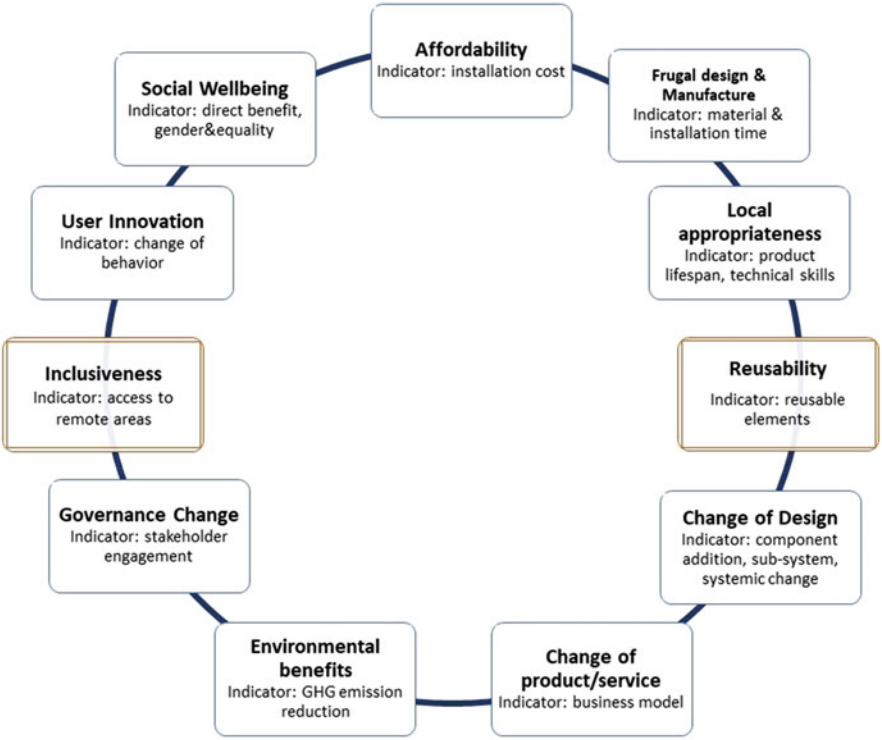

Fig. 1 Characteristics and case study indicators for the evaluation of frugal eco-innovation

technology and environmental impacts, this chapter also underlines the reusability of the technology by looking at the element that can be used in other product variants or for multiple purposes. In order to demonstrate the affordability for the low-income community, the indicator of the technology's installation cost is used to compare the extant technologies with the potential transformative technology (i.e., portable biogas). Additionally, the change of product service explores how the innovator firms design their business models in order to have lower environmental impacts as well as to maintain and even improve the benefits for users. The business model in question could be, for example, value prepositions of the product or service offering to meet the users' needs in a sustainable way.

Given that "rural and remote areas" typically have limited access to knowledge and resources, this chapter provides a measure on whether or not the technology fits with local conditions (local appropriateness) by looking at the product lifespan and the required technical skills. Moreover, the indicator used for inclusiveness is accessibility. Accessibility emphasizes how the frugal eco-innovation should be accessed by communities in rural regions that are poor and marginalized. Focusing on the environmental benefits, this chapter uses the GHG emission reduction as the parameter to measure the impact of the innovation in addressing climate change. Furthermore, the characteristics of social well-being, change of behavior, and governance change serve to demonstrate the impacts of frugal eco-innovation on a large scale. The indicators of social well-being include direct user benefits and gender equality. Gender equality is included in addition to the primary benefits because this parameter is often underexplored, and the focused technology has evidently illustrated this issue. To observe the change of behavior, the value added by the technologies is used as the indicator, because a technological innovation and its clear potential to resolve relevant issues commonly lead to good acceptance of the end users or wider adoption. Last, the benefits of stakeholder engagement are highlighted to illustrate the change of governance so that the frugal eco-innovation has the potential to bring the impacts to a large scale, in this case by addressing climate change.

Enacting the Potential of Frugal Eco-innovation for the Transformation of Rural Energy System in Indonesia

Indonesia stands out as the largest economy in ASEAN as well as one of the top ten greenhouse gas (GHG) emitters in the region, where the energy sector contributes approximately 314 $MtCO_2e$ due to extensive use of fossil fuels. The country has already pledged to reduce its carbon emission to 29% by 2030 to meet the Paris Agreement. This indicates the increasing pressure on government spending allocated to managing economic development while contributing to the global transitions toward sustainable development. Many national reports have showcased the progressive adoption of clean energy in the recent years; however, the focus is on electrification and often excluding the use of traditional biomass in the energy mix (e.g., DEN 2019; MEMR 2019).

In response, there have been many clean cooking movements since the early 200 s, such as wood-pellet cookstove, biosynthetic gas, and biogas initiated by private sectors working closely with local community in rural areas (Thoday et al. 2018). However, many of these technologies failed in the uptake process mainly due to financial and social factors, including heavy reliance on subsidies and a lack of suitability. This led to the reluctance in adopting the clean technology from end users, who perceived those technologies to be more expensive than conventional energy. Among these technologies, biogas, the interest in this chapter, has been recognized by the government as a suitable clean energy option in Indonesian rural areas (Silaen et al. 2019a).

The socioeconomic benefits of biogas for rural communities are evident and well documented (Devisscher et al. 2017; Silaen et al. 2019a). However, the technology uptake is relatively low and slow, where the installation of biogas in 2020 is reported to have only met 5% of the installation target set by the country to contribute to its NDC (489.8 Mm^3 by 2025) (Dilisusendi 2020). If biogas installations meet the target, an emission reduction of approximately 391.8 $MtCO_2$ could be obtained, simply from installing a 4-cubic size (Rumah Energi 2020a). This implies that biogas potential is being overlooked by current policies. Biogas development in rural areas is then perceived as a half-hearted movement within national GHG mitigation programs, particularly compared to other popular clean technologies such as solar PV (Dilisusendi 2020). Furthermore, the policy environment often urges an ambitious clean energy target with less understanding on the drivers of change in low-income context, e.g., basic necessities. Hence, there is a misalignment in the strategies of implementation. This indicates that the coevolution of institutions and technologies is required to pursue sustainable development that ties with economic growth. Since much of the Indonesian population still live under the poverty line and without clean cooking energy, Indonesia becomes a hub for frugal eco-innovation that can transform rural energy systems that are still dominated by unsustainable sources. With wider acceptance of such innovation in rural areas, it is expected that the impact will be global, i.e., taking action toward maintaining the temperature below 2 °C (Creutzig et al., 2015).

Alternative Pathways Framework

In this chapter, the alternative pathways framework (see Fig. 1, see Lieu et al. 2020 for details) was used to explore the potential for frugal eco-innovations as niche low-carbon technologies to potentially contribute to a sustainable transformation. Here, transformation is defined by Roggema et al. (2012) as the capacity to transform the stability landscape itself to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable. Niches are defined as “incubation rooms that protect novelties against the mainstream market selection” (Kemp et al. 1998). Here, the technology is a flexible and portable biogas digester currently codeveloped by su-re.co and farmers with the potential to disrupt the current carbon-intensive biomass used for cooking in rural Indonesia. The framework conceptualizes the three types of energy transition pathways for the frugal eco-innovation biogas case study in Bali, including the mainstream and its corresponding on-stream pathway, the off-stream pathway, and the transformative pathway (as seen in Fig. 2).

The mainstream pathway represents the dominant energy system currently followed by incumbent stakeholders. The on-stream transition pathway operates in a niche space within the mainstream but does not disrupt the dominant, mainstream fossil fuel energy sector. Policies within the on-stream pathway can promote niche technologies that may bring out societal or environmental benefits, as compared to the current high-carbon sector. There are dedicated energy policies that promote niche energy technologies by providing niche stakeholders with a more equal playing field in the energy system regime, through means such as energy subsidies. Mainstream and on-stream pathways consist often of incumbent and dominant stakeholders within the system who maintain positions of power in the energy system and in respect to household decision-making processes that impact energy choices. These stakeholders tend to represent the mainstream perspective, which can include the official government or policy stance, the largest and most influential institutions, and/or the largest market players in the system.

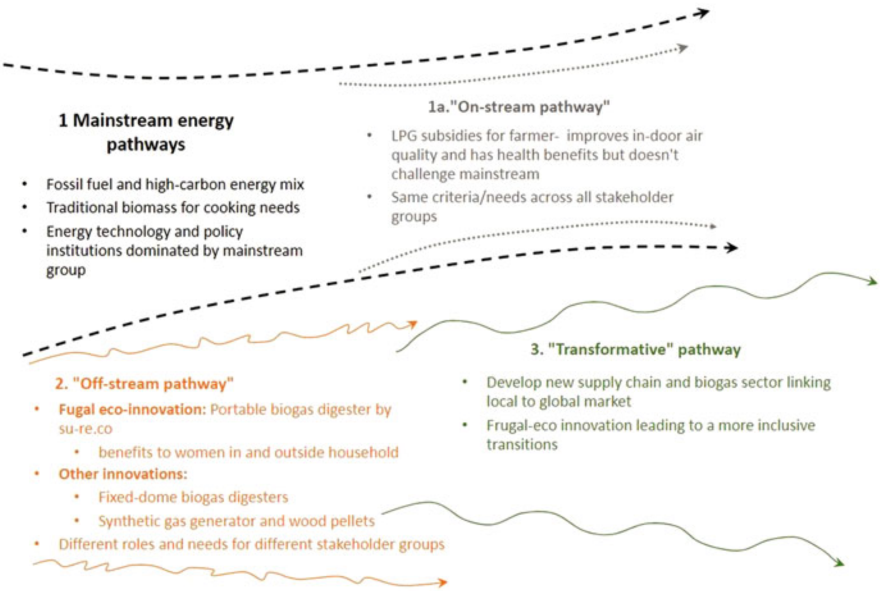

Fig. 2 Alternative pathways framework to analyze frugal eco-innovation for potential transformation. (Adapted from Lieu et al. 2020)

The off-stream transition pathway promotes niche low-carbon energy innovations in a dedicated space that is separate from the mainstream technologies. Policies or other programs are needed to create protective spaces for niche technologies and stakeholders, which may potentially challenge the mainstream high-carbon technologies. Since niche technologies are outside the mainstream energy system, new infrastructure may need to be developed. Often, these technologies have higher barriers to entry, and breakthroughs could be supported through grants and subsidies. Off-stream innovations also include innovations and innovators (niche stakeholders) that might not be part of the mainstream regime. Therefore, stakeholder groups with alternative perspectives, including women and other groups that are marginalized, are often promoted in off-stream narratives. This dedicated space for alternative perspectives can potentially be more inclusive than the on-stream pathways as it recognized that women and groups traditionally marginalized have different and important needs and priorities.

Transformative pathways involve radical technological innovations and a fundamentally new way of reorganizing the energy system. This new mainstream pathway no longer resembles the previous mainstream system and may include a diversity of stakeholders. A transformation could potentially stem from off-stream pathways and lead to more just and sustainable decision-making processes. Transformation pathways are supported by diverse stakeholder groups and a range of policies, programs, and actions that lead to change energy regime. This new energy regime is to be dominated by a low-carbon and sustainable energy system, and its transformation process could include a new network of stakeholders, including groups that have historically been marginalized.

Narrative of Development and Deployment of Biogas in Indonesia

Mainstream Pathway: Unsustainable Biomass and Kerosene

The mainstream narrative focuses on traditional biomass use for cooking. Firewood-only households in rural Indonesia use approximately 153 kilograms of firewood per month, as collecting it bears no direct cost and the resource is locally abundant (Thoday et al. 2018). However, environmental and health risks of traditional biomass fuels are evident. The use of traditional fuel such as firewood and crop residues is responsible for deforestation and indoor air pollution that leads to GHG emissions and premature death, respectively (Silaen et al. 2019b). However, these risks are not fully realized by rural communities in Indonesia. Poor farmers do not care about indoor air pollution as much compared to other groups (Takama et al. 2012). Each year, there are approximately 165,000 premature deaths from illness attributable to household air pollution that results from inefficient cooking practices and solid fuel cook stoves (IRENA 2017; OECD 2019). In addition to the lack of awareness around health risks, smallholder farmers do not perceive climate change as an immediate threat to the sustainability of their activities. Furthermore, the risks of energy-poverty, energy-related challenges, and health dangers are particularly endured by rural women and children. This is due to cultural norms where women and girls are responsible for collecting firewood as a means to support the "man of the family."

In addition to firewood, kerosene was once a part of the mainstream energy use as a primary cooking fuel in Indonesian households for many decades. Kerosene consumption was supported by the government through energy subsidies and was a large state expenditure. To reduce the burden of the subsidy and reliance on this costly fossil fuel, the Indonesian government introduced the Kerosene-to-LPG Conversion Program in 2007. Although subsidy of LPG was more expensive than kerosene when the program was introduced, LPG was cheaper than kerosene given its higher calorific value (Thoday et al. 2018). As a result, the use of kerosene has declined drastically in the last 10 years, though it does still have a significant role in certain areas of Eastern Indonesia such as in East Nusa Tenggara, Maluku, and Papua, due to limited knowledge and access of LPG (Thoday et al. 2018).

On-Stream Pathway: LPG

A small but growing space was carved in the mainstream pathway when the Indonesian government's program of the Kerosene-to-LPG Conversion Program was introduced. It has resulted in a fivefold increase in the number of LPG users since 2010, mainly in urban areas. In 2008, the government initiated the city natural gas network program as a complementary program in order to reduce the reliance on oil. Currently, the urban population has more options of primary energy for cooking, including the electricity stove. In terms of environmental benefits, the GHG emission reductions due to this conversion program are estimated at approximately 31% compared to the 2007 level. However, this number represents only a 5% emission reduction from overall household cooking due to the major use of traditional biomass. Furthermore, the impact of these programs has been limited in rural households that are located far from the LPG distribution network, as around 40% of the rural households in Bali rely on firewood (BPS Indonesia, 2018). This implies that rural and remote households are unlikely to switch to modern fuels on a large scale until an affordable option becomes available. Therefore, these households are more likely to remain reliant on traditional biomass cooking energy for the foreseeable future. This on-stream innovation and related policies did not consider the diverse needs of end-users in urban and rural areas.

On the other hand, the use of LPG has seemingly been facing a challenging period where the demand is growing while domestic supply is plummeting. In 2007, only 11% of LPG was imported. However, in 2018 imports reached 73% to meet the increasing demand (Thoday et al. 2018; MEMR 2019). The subsidy for LPG was seven trillion Indonesian rupiahs (ca. 500 million USD) in 2019. Currently, the Indonesian government is seeking energy alternatives such as dimethyl ether (DME) from coal gasification to be blended with LPG to reduce the reliance on imports of this energy carrier. However, further assessment is needed to achieve full deployment due to challenges such as a more corrosive property of DME if this compound is used for long term.

Based on the facts above, it is concluded that firewood, kerosene, and the on-stream LPG niche technology cannot be considered as a frugal eco-innovation option. Certainly not for rural areas of an emerging archipelagic state like Indonesia given their affordability, environmental benefits, reusability, and inclusiveness. Although the use of LPG and kerosene evidently reduces indoor air pollution from firewood use, they cannot be considered affordable given the current subsidies for these products (Thoday et al. 2018), which becomes a burden to the state expenditure. At the local level, a survey conducted under the World Bank Clean Stove Initiative (CSI) reported that more than 50% Indonesian households use both LPG and firewood for cooking on a regular basis. The findings implied that, although there are opportunities for clean cooking fuel, the baseline condition might not change completely in the coming future (Durix et al. 2016). It can be seen that these types of cooking fuels are highly dependent on subsidies and dominant in some areas of Indonesia.

Off-Stream Pathway: Synthetic Gas, Wood Pellets, and Biogas

There are a few existing off-stream cooking energy technology pathways in Indonesia with potential to replace the mainstream technologies: 1) synthetic gas generator, 2) wood pellets, and 3) biogas. In the first technology, synthetic gas (generated by heating firewood instead of burning it) is promoted by a local organization that makes turbines to generate electricity from the gas. This reduces indoor house pollution and has the potential to make off-grid village electricity systems which would be a perfect alternative for villages whose electricity is run by diesel engines (Abdurrahman et al. 2018). The system appears to be sufficiently simple, and the cost could be as much as the conventional biogas digester. Although synthetic gas uses firewood, it could still be considered as an eco-innovation if the wood supply is managed sustainably. One issue includes the fact that organizations implementing this technology are completely reliant on donations to promote corporate social responsibility from private banks. Furthermore, although community-based projects may be attractive in theory, they face implementation challenges as the project requires knowledge-transfer, not only for technical operations, but also to manage the system (Puzzolo et al. 2019).

The second potential off-stream pathway of wood pellets is pursued by a group in West Bali and East Java. The pellets can be used to replace coal in power plants to generate electricity at a large scale or, alternatively, used as a replacement for firewood (Xian et al. 2015), potentially in conjunction with efficient rocket stoves at the household level (Kotrba 2016). Since each pellet is small (ca. 5 mm), they can be treated like a viscous liquid, hence controlling energy usage and heat is manageable. These pellets are made of Kaliandra, fast-growing trees that the government has promoted in East Java and Madura Island. However, they are not being marketed for domestic consumption, rather for exports to Asian and European market where quality issues have arisen. Other pellets in Sweden are made of sawdust from dry wood (a waste material), thus the quality of pellet is standardized. In comparison, the pellet group of West Bali is grown from trees, cut and chopped into pellets, and shipped abroad, which increases both economic and environmental costs (Puzzolo et al. 2019).

The third off-stream pathway is biogas technology, which has been an emerging technology as a clean cooking alternative and beyond. At the household level, biogas can be generated by feeding manure, food, and crop waste into smaller digesters. It is used as cooking fuel or for lighting lamps. Currently, biogas digesters installed in Indonesia are dominated by the concrete-dome type, followed by the floating type digester, whereas the PVC-type digester has low penetration ($<1\%$) (Rumah Energi 2020b; Silaen et al. 2019a; su-re.co 2018). The cobenefits of using biogas also include reducing unmanaged firewood collection, helping manage animal waste, alleviating food waste by repurposing food scraps, and providing biogas slurry (bioslurry), to be used as organic fertilizer. These benefits are suitable for smallholder farmers as a part of the savings gained from reducing reliance on fossil-fuel-based energy in rural areas (Silaen et al. 2019b).

In the early 2000s, multiple biogas programs with varying types and materials were operated by the national and local governmental agency. However, many digesters malfunctioned, and the program was halted due to lack of budget and attention for maintenance. There were several other challenges to these digesters, such as the fact that maintenance services and training for users were inadequate, which resulted in many digesters going unused after installation due to the insufficient skills of the locals. Another reason for the abandonment of biogas technology was the fact that the wrong incentives were established by these programs, such as full subsidies at the installation stage without consideration for maintenance (Silaen et al. 2019a).

Furthermore, the financing scheme of biogas has become more and more complex. Due to the high cost of the fixed-dome biogas system, a subsidy is needed. Despite that, microfinance is still needed as subsidies often do not suffice. Moreover, to pay back the cost, some farmers need to sell organic fertilizer. In reality, it is difficult to sell bioslurry, because farmers use it for themselves. Thus, without this financial scheme, fixed-dome biogas digesters are still too expensive beyond the scope of wealthy farmers (Devisscher et al. 2017). To address financing and technical issues, the Indonesia Domestic Biogas program (IDBP), initiated by the non-governmental organizations (NGOs) HIVOS and SNV, aimed to support the governmental program in biogas development as an alternative clean cooking fuel. HIVOS then established Rumah Energi to bring biogas back into the spotlight, and the fixed-dome biogas digester was selected to be deployed in different rural areas in Indonesia, including Bali. Meanwhile, su-re.co (an environmental think-do-be-tank based in Bali) developed a portable biogas digester. The project, beginning in 2016, employed research and experiments in addition to integrating the feedback from the farmers as their users. From farmer feedback, the material and dimension of the digester evolved from using water tanks (polyethylene) to more durable materials, and from $4m^3$ to $1\ m^3$. One cubic meter PVC (polymerizing vinyl chloride) digester was then selected to address the technical and economical drawbacks of fixed-dome digesters.

To sustain these biogas projects, each organization employed different methods. For one, Rumah Energi decided to apply a market-based approach (i.e., carbon credit trading), involving corporate social responsibility and microfinance by cooperating with local banks to finance the IDBP program in addition to a participation fee from the farmers to increase the ownership of the users (Devisscher et al. 2017). Moreover, the organization secured a local state-budget, working together with the Bali Government to continue installing fixed-dome biogas digesters to farmers through SIMANTRI's program. However, Rumah Energi reported that 69% of the digesters in Bali are malfunctioning due to mainly nontechnical issues (Rumah Energi 2020a). Meanwhile, the portable digesters of su-re.co serve as a more easily transportable household equipment that is less labor intensive and easier to install. Further, this type of digester is installed aboveground, as Bali's stable temperature, and does not require the digester to be insulated under the soil (Silaen et al. 2019a; Silaen et al. 2019b). Moreover, the portable digester was codesigned with the farmers to fit to their needs. Factors considered were the daily cooking needs of a rural household, and the farmers' skills and capability to utilize and maintain the technology. The frugality of the design allows for a cost reduction of up to 70%, as compared to the fixed-dome biogas digester. Not only that, but su-re.co applied different financial tools such as crowdfunding (CF) and cross-subsidization to unlock private funds. The relatively new phenomenon of CF has been recognized among social enterprises as a method to increase societal awareness and participation of social and environmental issues. In this context, su-re.co successfully utilized this approach to expand the biogas benefits geographically. Meanwhile, cross-subsidization is applied by putting aside a generous sales profit from the farmers' coffee and cocoa products, so the continuation of the activity does not rely on subsidies or funding from governments. This kind of financial instruments is different from the mainstream pathways that are supported by the government and heavily dependent on subsidies.

Another aspect of the off-stream pathway looks at how policy engagement done by niche innovator firms such as Rumah Energi and su-re.co could trigger a systemic change to expand the societal benefits of their innovation toward decarbonization. For this, since 2012, Rumah Energi cooperated with Indonesian Ministry of Energy and Mineral Resources (MEMR) to ensure the continuity of the program and the reliability of technology and secure a local budget for biogas development (Dilisusendi 2020). Simultaneously, su-re.co led a series of policy dialogues and Climate Field School (CFS) for farmers alongside the Ministry of National Development Planning (Bappenas). The goal here was to mainstream biogas development as part of the national development agenda. This attempt then became fruitful when Bappenas included biogas as part of the clean cooking fuel list in midterm national plan (2020–2024). At the local level, su-re.co organized joint activities of climate services, namely CFS for farmers with Indonesia's Meteorological, Climatological, and Geophysical Office (BMKG). In CFS, biogas is introduced to the farmers as a solution for climate change. This activity led to the recognition of biogas as an act of climate change mitigation by both BMKG and the farmers. Furthermore, the portable biogas has gained more acceptance than ever before, transcending its image as just cooking fuel and being recognized as a climate service.

The changes in policy making and the financial scheme in this off-stream pathways disclose that there are emerging niche spaces present outside the mainstream pathways of the cooking fuel sector. The nature of off-stream pathways differed from the current mainstream regime that is exclusive and driven by carbon-intensive fuels and subsidies.

Frugal Eco-innovation Elements as an off-Stream Pathway

Although all the mentioned off-stream technologies provide a low-carbon alternative to fuels in mainstream pathways, they achieve different levels of success. Here, frugal eco-innovation characteristics (as elaborated in sect. 2.2) are used to identify technological innovation with its respective technical, socio-economic, and policy approach to manifest a transformative pathway – a future where the cooking fuel sector is dominated by clean energy resources with socioeconomic sustainability. These characteristics are used as concepts to elaborate the core reasons why the portable digester has the most transformative potential, as depicted in Table 1.

Starting from the frugal characteristics, the biogas digesters' frugal design uses affordable light weight material as opposed to concrete, cutting the manufacturing costs significantly to one-third of the fixed dome technologies' costs. Despite the

Table 1 Comparing technologies in the alternative pathway in respect to the frugal eco-innovation characteristics (Blue = Frugal innovation, green = Eco-innovation, gray = additional characteristics)

Characteristics	Indicators	Portable digester	Fixed-dome digester	Synthetic gas generator	Wood pellets
Frugal design and manufacturing	Material	PVC plastic and pipes	Concrete	Modified small generator & firewood	Wood
	Installation time	1 day	1 week	1 day	1 day
Affordability	Cost (USD)	300	1000	1000	–
Local appropriateness	Product lifespan	5–10 years	15 years	–	–
	Technical skills required	Minimal	High	High	Minimal
Social Well-being	Direct user benefit	Reduced indoor house pollution, energy	Reduced indoor house pollution, energy	Reduced indoor house pollution, energy	Energy
	Gender (in)equality in household	Cocreation process involves women in design and implementation of biogas	New source of fuel influencing women and men's role in household activities	No visible /unknown changes to women and men's roles in household	No visible /unknown changes to women and men's roles in household
Design and process development	Component addition/subsystem change/system change	Subsystem change	Subsystem change	Subsystem change	Subsystem change
Change of behavior	Added value component (in addition to its primary purpose)	Organic fertilizer, waste management, and increasing social cohesion	Organic fertilizer, waste management, and increasing social cohesion	–	–
Environmental benefits	Reduced GHG (per unit)	124 kgCO_2eq/year	2358 kgCO_2eq/year	–	–

Change of product service	Sustainable business models	Self-sustaining financial system	Microfinancing	Subsidies	
Governance change	Stakeholder engagement	Codesigned the technology with the locals	–	–	–
	Policy engagement	Integrated biogas and clean cooking stove to national policy	Part of the governmental initiative	–	–
Reusability	Reusable parts	Removable	None	None	None
Inclusiveness	Accessibility to hard-to-reach communities	Full access	Limited access	Full access	Full access

change in material and cost, which corresponds well to literature (Numminen and Lund 2017; Radjou 2012), it is sufficiently robust and durable, with a product lifespan of 10 years. Thus it is still exceptionally appropriate for the users in rural areas. This simplicity also comes with user-friendliness, where farmers can install the digesters by themselves, which takes 1 day as opposed to 1 week (fixed-dome biogas digester). In addition, the aboveground design allows for easier maintenance for the farmers. This product usability was highlighted in literature as an important frugal innovation characteristic – taking into account local skills (Numminen and Lund 2017). One of the main reasons why farmers abandoned the fixed-dome biogas was their lack of capacity to fix broken underground digesters (Silaen et al. 2019a). Meanwhile, the synthetic gas generator is also not as user friendly, as it requires more advanced technical and management training. In the end, the frugal design and manufacturing of the portable digester itself holds more advantages in respect to catering for local needs, which is important to enact fundamental bottom-up change (Rosca et al. 2018).

With regard to eco-innovation, there are also several characteristics where the portable digester stands out. In terms of design and development, all the technologies fall under the category of subsystem change as they optimize existing technologies. This intersects well with Radjou's (2012) second frugal innovation criterion of not reinventing the wheel. Moreover, compared to the other technologies, the biogas digester seems to have other benefits as it provides additional value on top of its primary purpose. These additional benefits that go beyond cooking fuel are evident and well documented. This leads to the creation of new roles and behavior change of certain stakeholders, particularly the users.

The biogas technology offers less time in collecting firewood, a common requirement in rural areas. It is commonly known that women in rural areas are responsible for cooking, which includes collecting firewood. The reduced need to collect firewood takes off one responsibility of women in the household, which would allow them to spend their time and energy on other activities, such as educating their children and pursuing economic and communal activities. This then increases the participation of women in in the community. Taking into account this additional time, the proposed solution was also designed to support added-value economic activities such as roasting coffee beans or drying cocoa beans. This could improve the value of farmers' agriculture products, which further supports the farmers to expand their income-generation activities beyond farming for (local) market sale (Devisscher et al. 2017). Aside from providing gas, the digesters also produce bioslurry as a by-product. Bioslurry was reported to be used by farmers as an organic fertilizer for their own plants, and some were considering the option of selling it to other farmers to generate additional income (Rumah Energi 2020a). The use of bioslurry as fertilizer compared with commercial fertilizers was observed to increase crop yields, since the slurry is rich in nutrients and much more cost-effective for farmers, who considered commercial fertilizers expensive (Devisscher et al. 2017). In turn, these digesters also reduce much more greenhouse gases from trapping methane, reducing firewood harvesting, replacing synthetic fertilizers, and serving as household waste management.

In correlation with the Covid-19 crisis, MEMR stated that there are four aspects where national biogas programs are affected (Dilisusendi 2020). First, funding for deploying biogas and other renewables is now allocated to handle COVID-19. Second, health is put as a priority over energy, thus energy programs are postponed. Third, with large-scale social distancing measures, technology providers are prohibited to visit villages and install biogas digesters. Finally, the situation prevents farmers from achieving their business targets from selling bioslurry in the microfinancing scheme. However, these limitations do not apply for the case for the portable digester. The MEMR addressed the need for a solution that is easier and faster to install and has an alternative funding method. The portable digester resonates to this call, while also contributing to current health needs by improving indoor air quality, and reduces the risks of respiratory-related illnesses. Women were also the group that is most at risk of respiratory diseases from indoor house pollution from utilizing cookstoves; thus, they receive the benefits of improved sanitary living conditions most. Moreover, with the financial scheme su-re.co has (crowdfunding and cross-subsidization), there are funds to continue installing digesters for the foreseeable future. Running the portable digester program during a time of economic crisis is also important for keeping up with longer term climate targets as well as maintaining and/or creating job opportunities in the community, not only in manufacturing the technology but also in supporting the auxiliary services such as support capacity building in the long run.

Frugal Eco-innovation as Transformative Forces

A transformative pathway is developed from a potential technology that could bring systemic change in rural areas. Drawing from the previous section, biogas is recognized as the most sustainable resource for cooking fuel, particularly to boost rural development in the range of available technologies. Various types of biogas digesters have been developed to address technical and socioeconomic barriers of biogas uptake, especially to substitute conventional digesters (i.e., fixed dome biogas). It is evident that the fixed-dome biogas is not easy to install and operate as well as too expensive for biogas advancement in rural areas. This then led to the invention of the more affordable design of portable biogas digesters. Therefore, the transformative pathway in this chapter includes a discussion of two main frugal eco-innovation characteristics and additional ones that can bring systemic change in rural Indonesia.

In terms of changes in the product services, the portable biogas is more affordable and easier to operate. Next to the tangible aspect of the innovation, the financial innovation system – cross-subsidization – is applied to reduce the economic burdens of the farmers. Coupled with crowdfunding, these methods collect sufficient funds to self-sustain biogas advancement. In contrast, other technologies use microfinancing and subsidies to pay off the farmer's debts, which is proven to be unreliable (Silaen et al. 2019a). Such payment mechanisms are already avoided in the design process of the portable digester, by minimizing initial costs. Thus, the portable digester has a strong advantage in scaling up and out, because the supply chain can be decentralized by replicating the technology in other regions (Radjou et al. 2012). For instance, the frugality of the technological design and financial innovation allows full reach to remote communities, not only in Bali, but also in East Nusa Tenggara in areas that barely have access to LPG and fixed-dome biogas digesters.

The changes in product services then become particularly important during the Covid-19 pandemic where social distancing is enforced. With the modular compact system, no direct interaction is needed between the technological provider (su-re.co) and the farmer, as the biogas can be sent to the farmers who then can install it by themselves, with remote support from the su-re.co team. At the same time, while governmental biogas projects are halted due to the reallocation of funds for covid-19, the portable digester, funded by other means, can keep going.

Both the technological design and the self-financing approach prove that social businesses can simultaneously generate profit to sustain company projects while serving the poor, which was an issue for existing firms that failed to fulfill the needs of both parties by deploying technologies that are financially unsustainable (Dolan 2012). Thus, this approach actually shows that social business can contribute to long-term poverty alleviation by creating more efficient value chains, providing more jobs by expanding the suppliers (Hahn 2012). Overall, this eco-innovation characteristic shows that the financing approach may allow the portable biogas to be transformative, by the promotion of systemic change in the supply chain.

Outside innovative solutions, addressing global threats such as climate change requires multilevel governance solutions. To transform the unsustainable mainstream pathway, governance change is required between the innovation firms with upper-level governance (i.e., government) and lower-level governance (i.e., users). Such relationships should be established simultaneously, in which case innovation firms are expected to serve as mediators. From a user's perspective, Javier Carrillo-Hermosilla et al. (2009) suggested that increasing awareness of the environmental problems coupled with social inequalities and global economic challenges will lead the society to realize the need to rearrange unsustainable systems and social behavioral patterns. An example of this would be a developed market where the customers are more concerned with environmental issues (Vilchez and Leyva de la Hiz 2018). On the other hand, the lack of suitable eco-innovation models (best practices) in emerging markets to influence the users may pose a significant barrier (Javier Carrillo-Hermosilla et al. 2009). Therefore, the innovation firms should not only "recombine the knowledge" but also "commercialize" it to expand the societal and environmental benefits (Philip Cooke 2012).

su-re.co's portable digester becomes an exemplary case as it takes into account the context of rural communities by involving end users during design development process. At the same time, the process is coupled with governmental partnerships such as policy dialogue and education through Climate Field Schools (CFS). Through the policy dialogue, governmental bodies can understand the local solutions so they can be aligned with their higher-level strategies, which in turn ensure the ultimate goal toward sustainability and works to tackle climate change. CFS evidently improved the lower-level governance, in which climate change was not a driver for behavior change in rural communities, pushing them to adopt sustainable solutions. Thus, after these activities, farmers gain an understanding of the importance of sustainable solutions such as biogas that have the potential to reduce their climate vulnerability, while the government can achieve the development and GHG reduction mandate from bottom-up solutions. In the end, the technology fits well with the national agenda and has a direct impact on farmers' livelihoods. Therefore, this eco-innovation characteristic sheds light on how the portable biogas' implementation process supports all stakeholders of different levels involved, making it possible to fundamentally change the whole societal system.

On top of the frugal eco-innovation characteristics, there are two characteristics where the portable digester also stands out compared to other off-stream technologies – reusability and inclusiveness. In terms of reusability, this portable digester can be moved to other locations on the farm or easy dismantlement if any technical issues are encountered. Additionally, if farmers do not utilize the digester, the content can be emptied and potentially installed by another farmer. This minimizes the resource and monetary loss from each biogas digester produced, where this issue cannot be resolved by the fixed-dome biogas. In addition to mitigation and adaptation efforts, there has been increasing attention paid to addressing climate change from human-based perspectives since SDG Agenda 2030. The slogan "leave no one behind" became a good reason for su-re.co to eagerly reach farmers that are "the most vulnerable and the furthest behind first," thanks to the frugal design. This is coupled with multilevel governance changes then leads potentially to increasing awareness and technology uptake. This kind of frugal eco-innovation would contribute to SDG 2030 Agenda, SDG No. 7 that ensures universal access to affordable, reliable, and modern energy services. However, given the extensive nature of the technology, the portable digester would ultimately tackle other SDGs as well such as 4 and 10, by reducing gender inequality at community level and the gap between urban and rural development.

In short, the frugal eco-innovation theories show that the portable digester, as an off-stream innovation, holds promising potential to transform the cookstove sector in rural Bali and potentially wider Indonesia, especially compared to the other technologies. Currently, the permanence and scalability of the portable biodigester in the long run is yet to be seen, as the diffusion of the technology is still currently limited. However, with its current trajectory and the proper policy support to scale up, it has the potential to create a new normal regime, transforming the sector into a sustainable dynamic system in rural regions.

Conclusion

This chapter introduced frugal eco-innovation, a merge of two concepts with complementary characteristics to illustrate how innovations can tackle economic growth and climate change issues in developing countries. These characteristics range from the design of the product itself to the process of introducing the design to various stakeholders. Two more characteristics were identified based on the case study to further show the additional benefits of the portable digester in rural contexts. The case study area, Bali, Indonesia, provides a success narrative on clean energy development that could be beneficial for other countries of similar backgrounds.

The rural energy agriculture system in Bali, Indonesia, constitutes different energy sources to serve the need of the rural households. The alternative pathways demonstrated the importance of the low- carbon technologies in niches that are often underconsidered in the policy making process to contribute significantly toward decarbonization. The mainstream pathways of rural energy system are still dominated by the unsustainable fuels, whereas low-carbon technologies are mainly in the off-stream pathways that could potentially disrupt the mainstream technologies. In this case, biogas digesters emerged as the most favorable low-carbon solution. However, barriers and challenges remain that are slowing down the deployment of low-carbon technologies. First, within the two governance levels, the lack of acceptance from local communities and lack of understanding of the off-stream technologies are there among policy makers. Second, funding barriers are commonly encountered by the private sector to challenge the mainstream technologies that are heavily subsidized and to sustain the continuation of projects.

Using the concepts of frugal eco-innovation sheds light on how a technology in the Indonesian case study can potentially serve the aforementioned challenges. There are two main frugal eco-innovation characteristics that may help innovator firms bring wider impacts of off-stream technologies to address climate change which are: the change of governance and the change in product and services. As a starting point, engagement in the lower governance should happen in the design process to fully take into account the needs and capacities of the local communities involved and affected. Ultimately, this results in a design that is user-friendly and affordable. Then, while educating the rural households about how the technology can help meet their basic need, the social learning about climate change should be instilled as a long-term education project and additional incentive. At the same time, actively engaging the policy makers is imperative to address the financial barriers and slow pervasive adoption. Finally, having a self-sustaining business model is key in scaling the technology so more areas can be reached. The absence of these activities resulted the other off-stream technologies to fail in addressing said issues.

The Indonesian case study showed that the portable biogas digester, as an example of frugal eco-innovation, has the potential to bring about systemic social, economic, and environmental changes in rural areas. This case study also showed the difficulties and crucial roles of making a convincing low-carbon narrative by the innovator firms. The pressure is on building local capacities and improving understanding at the national level adapted to the difficulties of poor and rural populations. Due to its frugality, such technology and approach have the powerful potential to be applied to other regions that have similar challenges.

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