Renewable micro-generation of heat and electricity—Review on common and missing socio-technical configurations

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A B S T R A C T

A widespread adoption of distributed generation (DG) technologies in energy systems can play a key role in creating clean, reliable energy and support the targets of emission reduction. A transition from current modes of production to a significant deployment of renewable energy technologies can fundamentally affect the structure of the industry and change the way energy is produced, transmitted and sold. The current paper provides an extended review of the socio-technical configurations of micro-generation based on journal publications and reports during the 21st century. The paper analyses currently existing and missing configurations and discusses technology and policy implications to support proliferation of micro-generation technology and local energy production from renewable sources. The potential for new configurations can be found particularly in heat producing micro-generation with solar heat, heat pumps, and biomass. Developing further the operations and maintenance of distributed generation technologies and business models appears an area that calls for further innovation, and corresponding innovation policy measures. Third party service and community-driven deployment models can aide the proliferation of distributed generation and further innovation therein, justifying the introduction of feed-in-tariffs to attract such models during their early diffusion.

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1. Introduction

Decentralized energy production based on renewable sources is a commonly presented vision and solution for future energy needs [1]. The exponential growth in distributed photovoltaic installations has been accompanied with a widening range of their deployment models. Other decentralized renewables appear to feature fewer alternatives to the deployment models. As a fuller range of available models could also help the proliferation of these technologies, it is worth examining whether these technologies have hitherto been deployed in a more limited array of models, and if so, are these limitations inherent or could they be subjected to targeted measures for innovation and for energy policy. After an analytic review it appears that only some of the limitations are inherent and there is room for development.

According to recent research, distributed generation (DG) technologies may yield significant benefits in terms of energy efficiency and reduced carbon emission. This is due to the fact that DG combines geographically dispersed decentralized generation from preferably renewable sources [1,2]. DG can reduce losses in energy distribution [3], improve energy security by producing energy close to the point of consumption [4], facilitate an increase of energy services in remote rural areas in developing countries [5–9] and consequently it may foster social equity by providing energy services and capacity for households and villages to reduce extreme poverty and advance standards of living [10]. In addition, DG from local renewable sources, also called micro-generation, can reduce dependencies on foreign energy sources.

Energy technologies are not just material objects, they also can be seen as embedded components of socio-technical systems—in which energy final users, producers, infrastructures, regulators, and other intermediaries are all embroiled [11–14]. A transition from current modes of production to significant deployment of renewable energy technologies will fundamentally affect the structure of the energy industry and change the way that energy is produced, transmitted, and sold [15–19].

Technologies emerge through active development, linkages, and the alignment of various heterogeneous, social, and technical elements into working configurations [20]. Science and technology studies (STS) have revealed a wide variety of different “configurations” of renewable energy technologies and the elements of social organization involved in their deployment. Socio-technical configurations comprise assembles of technological components, and non-technological components such as human factors. A configuration can be seen as an unique assembly of components built up to meet the particular requirements of organization [21,22]. These organizational interacting mechanisms around energy technology include dimensions such as ownership, management, operation, and infrastructure [11].

Another stream of literature and research has been interested in value chain(s) in the renewable energy business and deployment models [4]. Especially the issue of utilities’ business models for renewable energy has been addressed by a number of recent reports [18,23–26] and academic studies [27].

Both streams of literature show how organizing a micro-generation is in constant change and new configurations are emerging. Production of renewable energy is becoming multifaceted and clear demarcation lines between centralized and decentralized, grid-connected and off-grid, and producer and consumer, are increasingly becoming blurred. New configurations consist of different sizes of networks that underpin the energy consumption of consumers and communities [2].

This paper is interested in the deployment of micro-generation technologies. The article departs from the framework introduced by Walker and Cass [11] in 2007, and adapts it to discuss renewable micro-generation, the covering technologies, ownership, financing, production, and the distribution of energy. Our contribution is twofold. First, we review current academic literature complemented with up to date documents to reveal existing socio-technical configurations of renewable micro-generation technologies. Second, we analyze technological and organizational combinations that create configurations which remain unrealized or marginalized cf. [28]. Our findings offer insight for policy makers in the field of energy, and help companies and user groups to understand various opportunities and current restrictions when enhancing the diffusion of micro-generation technologies and scaling up local renewable energy production. Such insight and opportunities have been hitherto discussed mostly with regard to the solar photovoltaics (PV) domain only, and we expand on this.

The article begins with opening up the concept of decentralized generation, micro-generation, and the methodological approach that will be used in this study. We then describe different types of socio-technical configurations taking place in the micro-generation of heat and electricity. In Section 4 we analyze marginal and missing configurations and the reasons that hinder the emergence of certain configurations. Finally, we discuss innovation and energy policy implications and how these could speed up the proliferation of micro-generation technologies.

1.1. Concept of micro-generation

Decentralized or distributed energy supply refers to the generation of energy close to the place where energy is used. It can mean a range of generator sizes; from residential households to community or district-level [3]. Micro-generation is the term given to small-scale local energy generation, and it has various definitions, which vary from country to country. The key characteristics of these definitions are that micro-generation occurs at a local scale, it can include both the generation of heat or electricity or both, and it generates small amounts of energy compared to centralized plants. Furthermore, there is often a requirement of environmental friendliness in the production. For example in the UK, the Energy Act section 82 defines micro-generation as generating plant with a capacity of less than 50 kW. Most residential installations are in the range of 2.5–3 kWp [3,27]. In the case of electricity, it can be for the sole use of the building’s occupants or it can feed the National Grid.

Various renewable energy sources are used for micro-generation. These include solar, wind, biomass power (e.g. wood, wood pellet, bio waste), and the utilization of outdoor and ground source heat. Hydropower can also be built on a small-scale, the capacity defined as small, mini or micro-hydropower [29]. It is noteworthy that micro-hydropower definitions of size and capacity differ from other sources, and a hydropower plant with the capacity of between 50 kW and 10 MW is still considered as a micro-hydropower [30,31]. Definitions of small-scale Waste to Energy (WTE) systems have some variations. There are studies that define small-scale WTE as capacity
below 100,000 t of waste per year, which equal to 33–67 MW thermal capacity. In some other studies [34,35], a small-scale WTE definition is more inline with typical micro-generation definitions i.e. below 50 kW output.

In this article we focus on the above common technologies that are available as established commercial systems in many markets, even if not necessarily globally.

2. Analytical framework

2.1. Organizing around micro-generation

Different types of deployment models of micro-generation have received attention in studies of energy policy. These models include business model like considerations, but also take into account different ways of organizing the production, such as community energy [4]. As micro-generation is gaining momentum, new types of actors and ways of organizing around micro-generation are emerging.

In earlier studies, by Walker and Cass [11] and Sauter [36], the authors make a division between technology and social and infrastructural actors in their conceptualizations of socio-technical configurations of the renewable generation. Technologies generate usable energy in the form of heat or electricity. The social and infrastructural actors utilize the technologies. These actors take care of functions such as generation, distribution network, ownership, operation, management, service, consumer-supplier relationship and supply chain. How the energy technology is used also includes considerations of learning, skills and the function for which the energy is used. Walker and Cass examine all sizes of renewable energy production and list five implementation ‘modes’: public utility, private supplier, household, community and business [11]. These modes especially reflect the ownership dimension of production. Walker and Cass [11] framework is the most comprehensive attempt to analyze socio-technical configurations of renewable energy productions. Thus it has been taken as starting point in this study to create a practical tool for analyzing micro-generation technologies. For the purposes of the present study, the Walker and Cass framework has been adapted for what can be analyzed regarding the variety of socio-technical configurations in micro-generation reported in reliable published sources as of 2014. This has required altering, further focusing and developing the earlier model in the following aspects:1

1. Nuanced examinations on function and service have been left out of this model. Function and service is electricity or heat is always produced primarily for local consumption and sometimes also fed to grid. Questions of final energy consumption purposes such as comfort, warmth, visibility, or mobility would require further research that goes beyond literature review of presently available information.

2. Micro-generation implementation model variations are more limited. In practice three implementation modes takes place, namely household, community, and business (aka company-driven, utility or third party business) [38].

3. Locality can be seen as a key dimension in conceptualizing micro-generation and has been added as second dimension to our analysis framework. Dimensions of ownership and financing, operation and maintenance, and distribution of energy can be viewed from the point of locality; i.e. what is the physical and institutional distance between the local site of production and the site of service consumption [11]. The degree of locality depicts energy autonomy or self-sufficiency, which is the ability of an energy system to function based on own local energy generation, storage, and distribution systems without the need of external support [39]. The proximity levels (user/household, community, business) follow widely used approach in the literature. An abstraction level of analysis has been put to a position that can be answered and filled by a rigorous literature review.

The socio-technical configurations framework for micro-generation is presented in Fig. 1. The vertical axis presents increasing locality in three steps, and horizontally the figure is divided in to three separate dimensions; ownership and finance, management and operation, and distribution as described above.

2.2. Methodology and procedure

In this paper, our analysis follows the socio-technical configurations framework for micro-generation. The analysis of socio-technical configurations can make visible both the options of organizing around renewable micro-generation and the value network around local small-scale energy production.

In the study of configurations, the micro-generation of energy is scrutinized without particular actors’ viewpoints (corporate, community, or user/consumer/citizen). How actors take different positions in a socio-technical network within which they operate then becomes interesting. The actors include individual users, communities, and corporates2. The configuration depictions show how different dimension can be configured in multiple ways.

The concept of shared value creation has received limited attention in traditional energy business model analysis, which is based on a top-down hierarchy from generation to distribution and the final use of energy. A value chain perspective is presented in Fig. 2. In the value chain, actors follow each other in the marketplace. However, decentralized energy systems can be characterized as value networks cf. [40]. To understand the roles and engagements of actors within the energy system requires a multidimensional conceptualization [11]. A configuration can be seen as the conceptualization of a network wherein actors take a position, connect to each other, add value, create and share knowledge, and make transactions.

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1. Bracken et al. propose “environmental dimension” to be added to Walker and Cass original model to take into account ecological impacts such as biodiversity [37]. For the purposes of this study inclusion of environmental dimension would complicate the analysis beyond what can be achieved through literature review of materials available to date. Taking into account various aspects of ecological impacts both locally and globally (in supply chain) of technologies would arguably require separate study focusing to this dimension with each micro-generation technology examined.

2. In the network of actors policy makers also play a role, especially in the formulation of (dominant) configurations. However, if production-based support mechanisms such as FIT are not used, the role of regulation may be rather limited in a socio-technical configuration that is running a daily operation.
Our analysis is based on two separate information sources or sets. There has been increasing interest in research to address different aspects of micro-generation technology and business and development models. Thus, a logical point of departure in this study was to review recent (from 2000 to 2014) academic articles on micro-generation in the areas of business and deployment models. These models explain the key characteristics of organizing around the technology, define points of control, and help to construct depictions of socio-technical configurations that have already been recognized in research and academic literature. The literature review includes an extensive set of empirical studies both from the developing countries and from developed industrial countries. However, renewable micro-generation is an emerging area: academic literature is scant and most of it is too constricted to thoroughly address the issue. Moreover, many of the models are emerging as we speak, and academic publications appear to lag behind the new configurations and value networks that are emerging. Thus, other sources available on the Internet were consulted in order to gather further information relevant to the analysis and to fill the gaps in academic publications. The additional material includes reports, documents, company pages, and material from cleantech news sites.

This study has two main research questions:

1. What kind of socio-technical configurations have been established around renewable micro-generation technologies?
2. What are the missing configurations and the underlying limitations and barriers affecting the absence of certain configurations?

The literature review began by searching with 12 relevant keywords5 from two main academic search services. First, a full text search was carried out in Ebsco for Financial Times 45 list business journals. Second, both Ebsco and Sciverse ScienceDirect full text searches were carried out for a wider range of business, economics, technology, and energy specific journals. The initial round resulted in 1246 articles from 171 journals. The duplicates of articles, conference proceedings, non English journals and outside of scope tech journals (e.g. hydrogen or fuel cells technology) were removed, which reduced the number of journals to 154 with 925 unique articles. Finally, based on an examination of abstracts6, 101 academic publications were found that were relevant for this study, of which 23 articles had a significant contribution in the area of business or deployment models (discussed in Section 3.2).

3. Existing configurations—Technical and non-technical aspects

3.1. Technologies of micro-generation

Micro-generation technologies are small-scale systems that generate energy in usable form from heat or electricity or both. In the historical perspective, the oldest form of micro-generation is wood burning fireplaces, but available technology alternatives, product models and solutions are steadily increasing. To give an overview of commonly7 used technologies, Table 1 presents energy sources and technological alternatives of micro-generation. Micro-generation is a technology that converts a source energy to a form that can be utilized for certain functions, which, for example, can be warmth or comfort [11].

3.2. Ownership and financing

Various legal and financial models of ownership have been adopted for micro-generation. One hundred % public ownership is not common, but public involvement in supporting schemes is widely present. A whole range of combinations between public and private ownership exists: projects can be community owned, or may be developed under co-ownership arrangements (e.g. public–private sector partnerships [43]). Projects can involve the ownership of energy generation that is grid-connected or off-grid, or can combine the locally owned production and consumption of energy (e.g. where heat is generated for local use for one or several buildings) [44].

Ownership issues are inseparable from organizing the financing for energy production. There is an extensive literature on financial subsidies for energy projects. Through the use of

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5 Emerging technologies (e.g. micro-CHP and fuel cells) without significant market adaptation have not been listed.

6 The abstract addressed topics of business and deployment models, financing, operations, management, distribution of heat or electricity, or storage of energy.
subsidiess, government aims to lower the cost of energy provision either through incentives for energy generation or price reductions to consumers. In recent research, the main interest has been to study energy generation incentives, namely feed in tariffs (FIT), to enhance the diffusion of the technology \([45,46]^{6}\). Table 2 presents an overview of recent literature on business, financing and deployment models.

Ownership models can be divided in to different categories by looking at the distances from operational technology and energy production site to an actor or an institution that holds the ownership of the production equipment. From this viewpoint ownership can be divided in to a local ownership at site of the production or to ownership outside the site of production. Both ends include various kinds of models. Friebe et al. \([51]\) examine solar PV technology and divide options along the lines of cash, credit, leasing, and fee-for-service. Based on the literature review, business and ownership models of solar PV has been most widely studied among micro-generation technologies. The existing models are also most diverse in solar PV technology.

However, similar models may also be applied, in principle, to other micro-generation technologies, but certain technology characteristics do set limits and hindrances to this, which we will discuss later. The traditional ownership model is where house owners, or similar, own the production unit and use upfront cash or credit (e.g. home-equity loan) to purchase equipment\(^7\). Both of these options are popular in the developed countries. In regards credit based model in the developing country context, microfinance has been used (especially with biogas based generation \([57,66]\)).

When the ownership of production is outside of the production site, third party financing is used. Third party financing models i.e. service-based models include both Power Purchase Agreement (PPA) and lease \([52]\). There are no clear-cut definitions and implementations have some variation, and models can also be mixed and have various local marketing terms. For example, solar PV lease can be called “rent-a-roof” and PPA as fee-for-service, which can be marketed as “free solar on your roof” \([67]\). Fee-for-service and lease customers have different payment structures.

With a lease consumer pays monthly fee, which is not tied to level of production, and with a fee-for-service the payment can be fixed or based on variable production. The details of third party financing can vary, e.g. a lease contract can allow the consumer to purchase the system over a certain period defined by the initial equipment owner. The homeowner can feed an oversupply of electricity back to the grid and sell electricity to an electricity service provider. Third party financing has become the dominant form of financing for domestic solar PV in the U.S. \([52]\).

In the developing countries, the fee-for-service model is receiving increased attention. Next to all of the studies of fee-for-service focus on these markets. Using micro-credit for building new energy capacity, or implementing a fee-for-service utility model, is now considered as two desirable options to create a dynamic self-sustained market for solar home systems \([55]\). Donation models \([10,58]\) in which the technology is transferred to the community as a gift is hardly in practice in the most developing countries these days \([9]\). The donation logic is discontinuous, by nature, which makes it hard to succeed in a long run.

On the other hand, in developed countries with FIT programs, PPA (rent-a-roof) are gaining momentum. Third party companies can lease the equipment, and large utilities have entered the market and provide DG technology to commercial users and private consumers \([63]\).

In summary, while DG is growing, and new types of business models are entering the field, the field includes a range of different models of financing and ownership \([52]\).

### 3.3. Operation and management

In the operation and management configuration, interest is on who manages, controls and maintains the hardware, and how is this organized \([11]\). Ownership of micro-generation equipment and control of operation and management are typically tightly coupled, thus ownership has a high influence on socio-technical configurations. To keep technology operating and energy output high is primarily the owner’s responsibility. However, ownership and operations can be also separated via outsourcing \([49]\), whereby ownership is purely a control and financing issue, without material responsibilities.

Feasible operation and management configurations are highly defined by the operation needs of the technology. The operation needs vary significantly from one micro-generation technology to another. While electricity generation from solar requires relatively low maintenance depending on environmental conditions such as

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Energy technology</th>
<th>Output power type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro power</td>
<td>Small hydro-turbines</td>
<td>Electricity</td>
</tr>
<tr>
<td>Wind</td>
<td>Micro-wind power</td>
<td>Electricity</td>
</tr>
<tr>
<td>Solar</td>
<td>Solar PV</td>
<td>Electricity</td>
</tr>
<tr>
<td>Solar</td>
<td>Solar thermal collector</td>
<td>Heat (water)</td>
</tr>
<tr>
<td>Solar</td>
<td>Solar air collector</td>
<td>Heat (air)</td>
</tr>
<tr>
<td>Biomass: wood</td>
<td>Fireplaces</td>
<td>Heat (air or water)</td>
</tr>
<tr>
<td>Biomass: wood</td>
<td>Wood burning boiler</td>
<td>Heat (water)</td>
</tr>
<tr>
<td>Biomass: wood pellet</td>
<td>Wood pellet boiler</td>
<td>Heat (water)</td>
</tr>
<tr>
<td>Biomass: bio waste, e.g. straw</td>
<td>Small-scale combustion</td>
<td>Heat (water), electricity, CHP</td>
</tr>
<tr>
<td>Biomass: bio waste</td>
<td>Gasification</td>
<td>Heat (air/water), electricity, CHP</td>
</tr>
<tr>
<td>Solid waste</td>
<td>Thermolysis</td>
<td>Heat (water)</td>
</tr>
<tr>
<td>Outdoor air heat (+electricity)</td>
<td>Air source heat pump</td>
<td>Heat (air)</td>
</tr>
<tr>
<td>Outdoor air heat (+electricity)</td>
<td>Air to water heat pump</td>
<td>Heat (water)</td>
</tr>
<tr>
<td>Ground heat (+electricity)</td>
<td>Ground source heat pump</td>
<td>Heat (water)</td>
</tr>
<tr>
<td>Indoor air heat (+electricity)</td>
<td>Exhaust air heat pump</td>
<td>Heat (air)</td>
</tr>
</tbody>
</table>

\(^6\) Due to the complexity and the set of issues involved, it is not possible to include public policy support mechanisms, such as subsidies and regulations, in the analysis of this paper.

\(^7\) This basic model has been called also as “dealer model. Cf. Sustainability—Business Models for Rural Electrification (Source: The ACP-EU Energy Facility http://capacity4dev.ec.europa.eu/system/files/file/23/04/2012_-_1736/sustainabil ity_ruralelectrification.pdf, accessed Nov 27 2014.)
## Table 2

<table>
<thead>
<tr>
<th>Author(s)/year of publication</th>
<th>Publication name</th>
<th>Journal</th>
<th>Business or deployment models covered</th>
<th>Type/empirical study area or country if applicable</th>
<th>Technologies included to empirical work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boon and Dieperink [47]</td>
<td>Local civil society based renewable energy organisations in the Netherlands: Exploring the factors that stimulate their emergence and development</td>
<td>Energy Policy</td>
<td>Community business models; collective procurement of energy and technology, education and facilitation, delivery of energy, collective generation</td>
<td>Empirical/ Netherlands</td>
<td>Wind, solar, biomass, geo-thermal</td>
</tr>
<tr>
<td>Drury et al. [50]</td>
<td>The transformation of southern California’s residential photovoltaics market through third-party ownership</td>
<td>Energy Policy</td>
<td>Customer owned, Third party owned</td>
<td>Empirical study/ California, United States</td>
<td>Solar PV</td>
</tr>
<tr>
<td>Friebe et al. [51]</td>
<td>Exploring the link between products and services in low-income markets—Evidence from solar home systems</td>
<td>Energy Policy</td>
<td>Sales model (cash and credit), service model (leasing and fee for service)</td>
<td>Empirical study/ several emerging and developing countries.</td>
<td>Solar PV</td>
</tr>
<tr>
<td>Huijben and Verborg [53]</td>
<td>Breakthrough without subsidies? PV business model experiments in the Netherlands</td>
<td>Energy Policy</td>
<td>Customer-owned, Community shares, Third party</td>
<td>Review and empirical data/Netherlands</td>
<td>Solar PV</td>
</tr>
<tr>
<td>Lemaire [54]</td>
<td>Fee-for-service companies for rural electrification with photovoltaic systems: The case of Zambia</td>
<td>Energy for Sustainable Development</td>
<td>Fee-for-service (by ESCOs)</td>
<td>Empirical study/ Zambia</td>
<td>Solar PV</td>
</tr>
<tr>
<td>Mainali and Silvera [57]</td>
<td>Financing off-grid rural electrification: Country case Nepal</td>
<td>Energy</td>
<td>Fee-for-service, leasing of energy-generating products, credit (credit from local cooperatives, revolving funds, credit from commercial banks)</td>
<td>Empirical study/ Nepal</td>
<td>Micro-hydro and solar PV</td>
</tr>
<tr>
<td>Nieuwenhout et al. [58]</td>
<td>Experience with Solar Home Systems in Developing Countries: A Review</td>
<td>Progress in Photovoltaics: Research and Applications</td>
<td>Donations, cash sales, consumer credit, fee-for-service,</td>
<td>Empirical/ Developing countries</td>
<td>Solar PV</td>
</tr>
<tr>
<td>Okkonen and Subonen [60]</td>
<td>Business models of heat entrepreneurship in Finland</td>
<td>Environmental Research Letters</td>
<td>Lease (utility), cash</td>
<td>Empirical/United States</td>
<td>Solar PV</td>
</tr>
<tr>
<td>Provance et al. [61]</td>
<td>Institutional influences on business model choice by new ventures in the microgenerated energy industry</td>
<td>Energy Policy</td>
<td>Plug and play, company-driven, community micro-grid</td>
<td>Conceptual</td>
<td>Generic</td>
</tr>
<tr>
<td>Sovacool [10]</td>
<td>Design principles for renewable energy programs in developing countries</td>
<td>Energy &amp; Environmental Science</td>
<td>Cash, credit, mixed finance, donation model, fee-for-service, leasing, ESCO</td>
<td>Empirical/ developing countries</td>
<td>Generic</td>
</tr>
</tbody>
</table>
soiling rate, heat production technologies using biomass can require weekly (e.g. wood pellet heating) or even daily (e.g. wood heating) intervention. Fig. 3 shows how operation and maintenance frequency separates electricity from heat producing technologies. Management and operation can be organized privately, collectively, or publicly, but viability of these options is tied to an actor’s (maintenance worker) proximity to the technology and to the frequency of a required site visit.

3.4. Distribution of energy

Although the basic principle of micro-generation is to produce and consume energy at the same location, a distribution network enables the transfer of energy and proximity between production and consumption. This solid infrastructural connection is an essential dimension in the analysis of the socio-technical configuration.

In Fig. 4, electricity distribution is used as an example to demonstrate the multitude of distribution configurations. Electricity distribution occurs through different types of organizations, with country variations and ownership combinations. Traditionally the ownership of the distribution network has been traditionally concentrated to large organizations such as those of the state, municipality, or energy utilities. For example, in the U.S., electricity distribution occurs through three main types of organizations—public utilities, investor owned utilities, or distribution cooperatives [52]. These very same distribution networks are used when micro-generation is connected to the grid.

Social public–private partnerships or customer trusts are examples of new forms of ownership used with distribution networks. In New Zealand there is a local electricity distribution company having the form of a customer trust, it is owned and governed by consumers [68]. In Germany, within the last five years over 450 new energy cooperatives have emerged that are not only setting up energy generation but also have taken an important role in running local grids [69]. When local distribution wires are owned locally, the need to regulate wholly privately owned network monopolies and mitigate the need to regulate long term contracts for locally produced electricity and heat services is reduced [68].

Mini-grids and Micro-grids are smaller scale infrastructures between the universal (or national) network and off-grid solutions. Developing mini-grids for decentralized needs is a very important concept for promoting rural electrification in the developing countries, since the spread of the national grid is very low or almost absent in remote rural areas. Thus, renewable DG provides an opportunity not only for GHG emission reductions but also for improving the quality of life in rural communities [71]. Micro-grids are increasingly important where production is based on distributed resources, multiple electrical loads, and meters. These connected generation units can form an autonomous grid. The micro-grid can be either a parallel island from the wider national grid or connected to it. In the most common configuration, micro-generation inside a micro-grid is tied together with its own distribution feeder and that micro-grid is linked to the national grid or connected to it. In the most common configuration, micro-generation inside a micro-grid is tied together with its own distribution feeder and that micro-grid is linked to the national grid at a single point of common coupling. In “islanded mode” there is no connection to the grid. Micro-grids can enhance energy security and reliability in various ways. They can reduce distribution losses, support local voltages, provide increased efficiency or provide stable power supply functions [72]. Micro-grids are gaining momentum, with hundreds of individual projects already implemented or under construction worldwide [73].

Production and consumption of all produced energy at the same site without connection to external networks is a special case. In the case of electricity, an off-grid system works standalone. All of the produced energy is used at the site of production and the system is self-reliant. Recently, off-grid electrification has been promoted for rural electrification as an answer to the growing energy needs in developing countries [74]. In many developed countries with an extensive national grid, off-grid and micro-generation has been used widely in special cases, such as on summer houses and holiday homes. For example, in Nordic countries in the case of remote houses there is a trade off between new grid extension and solar PV, which favors solar PV because constantly falling panel and installations costs [75]. In terms of the
micro-generation of heat, production without external distribution and connection is even more popular. Most small-scale installations are not equipped with thermal network connection to the other consumption units. Because of the losses in distribution distance between production and consumption becomes limited. Thus current heat distribution networks connect buildings in urban area or within-community. District heating networks can be considered as equivalent to electricity micro-grids. Both provide medium proximity distribution.

The electricity infrastructure types presented in Fig. 4 provide high-level depictions of distribution configurations. In terms of economic considerations, how electricity is measured becomes interesting with regard to how monetary transactions are carried out and how an established market price is formed. These concepts have the potential to change how micro-generation in the context of the community can be organized. Current micro-generation community energy is based on close proximity users co-operating in energy production. In the future a community could be seen in a new way in the smart-grid environment, where the peer-to-peer approach spreads out from a close proximity community to a group of remote households generating and using, and selling and buying their own energy to each other and using the national grid for their electricity distribution.

Energy generation from renewable sources is seldom constant over time; moreover, electricity demand is never constant. Therefore, connecting and utilizing an energy storage within a system becomes important [78]. In addition to the stochastic nature of local production, the volatility of the market price in a grid-connected DG environment may also create a need to shift the consumption of produced energy.

The heat storage of hot water in boilers is a traditional and widely used method with micro-generation of heat. Batteries have been used to store DG electricity and there are various technologies at different stages of maturity and with a wide range of technical characteristics that can provide heat or electrical storage [79–84]. It is likely that several solutions will continue to compete in the future due to the wide variations in possible applications [84,85].

Local energy storage is an additional new dimension in energy systems, which will also have an impact on energy usage. Users can change their energy behavior not only based on local production or market price, but also according to the local storage situation. While research of micro-generation and storage has mostly addressed the technical or economical aspects of local electricity storage, less attention has been paid to heat storage [84] and the behavioral or socio-technical aspect of storage and how it impacts electricity production and usage in daily life.

Local storage is not typically present in current micro-generation networking configurations because of the high price...
3.5. Summary on existing socio-technical configurations

We have gone through renewable micro-generation technologies and reviewed literature on the financing, ownership, operation, maintenance, and networking aspects of energy production. In Figs. 5–9 we use the socio-technical configurations framework to depict currently existing and currently missing socio-technical configurations for each technology as a means to summarize our findings on existing configurations. Each technology has been analyzed separately and the existing configurations have been marked with a solid line. The index numbers in the figures refer to footnotes which explain the sources. In heat distribution there are hitherto unfeasible areas, which have been marked on the pictures.

Let us use micro-hydropower as an example case to explain how the analysis framework visualizes existing and missing socio-technical configurations. In Fig. 5 diagrams of currently existing configurations for the technology are summarized. For micro-hydropower we have not been able to identify third party ownership or third party management and operation models, which leaves these section empty. Community energy deployment has been used, for example, in Nepal [9,57], and it covers all three dimensions, hence the green community energy line connecting these areas at the community level. Cash and credit financing models, where the owner takes care of management and operation, can be found and all possible electricity distribution forms leaves these section empty. Community energy deployment has been used, for example, in Nepal [9,57], and it covers all three dimensions, hence the green community energy line connecting these areas at the community level. Cash and credit financing models, where the owner takes care of management and operation, can be found and all possible electricity distribution forms

of battery technology. Feasible options for local storage increase in conjunction with the proliferation of electric or hybrid vehicles that can be connected to the grid [2].
difficult. In all likelihood, community-driven micro-generation of electricity or hydro, solar PV, and micro-wind is also often connected to the national grid, but nowhere in the reviewed literature is this explicitly documented.

In all of the heat systems, national networking has been cut off because of heat losses that would occur through distribution. Third party ownership models exist for solar thermal deployments, but as yet, only solar thermal has had modest trials with regard to leasing.

Heat pump, wood and pellets biomass feature a similar relative lack of development in their possible socio-technical configurations. Company-driven models, including fee-for-service and ESCO service for ground source heat pumps have been trialed. For biomass-based production community energy models are also in place, but fee-for-service has been in modest wider use.

Finally, we have analyzed Waste to Energy (WTE) for micro-generation use. Managing solid waste is a big challenge both in developing and developed countries. WTE technologies can reduce both use of virgin raw materials and carbon emissions. WTE has been widely deployed in large and medium scale plants [88]. However, WTE based on small-scale units is less used as the smaller-scale facilities are less efficient than the larger-scale systems. WTE based on small-scale technologies are particularly feasible for communities in rural or semi-urban areas or regional centers. In less densely populated areas the volume of waste, transportation costs or public disapproval may rule out large-scale solutions [32]. Small-scale thermal energy production has been traditionally based on combustion concept, which has been almost abandoned, because of its problems: very low energy efficiency and high dust and polluting emissions [34]. Currently small-scale units have been piloted and used for special purposes in community level providing waste treatment in developing countries for refugee camps, rural villages, and institutions like hospitals utilizing for example crop residues in farming [91] or hospital waste [92]. The smallest units of WTE technology can be found deployed in the developing countries. These units are used at homes to provide heat for space heating and cooking.

In our analysis, technologies have been analyzed separately. However, in real life setting many technologies are used in hybrid setups as combination of technologies, which reduces problems associated with intermittence, randomness, and uncertainty of renewable energy sources. In their current deployments, hybridization has not forced different micro-generation technologies to take similar non-technical positions. This type of isomorphism of socio-technical configurations could come about with the maturation of the micro-generation business field.

4. Missing socio-technical configurations

Viable business and deployment models on energy generation are often applied (copied) to new areas, environments and technologies. This development has been visible among micro-generation technologies. At the same time, there are various limitations and barriers that hinder proliferation of certain models, at least “as is” to certain other micro-generation technologies. Based on our review, however, we can recognize several missing socio-technical configurations, which may open doors for alternative new business models with micro-generation, despite the limitations. These issues are discussed in the following.

4.1. Technological limitations

Operation and maintenance needs vary significantly between technologies, and in general heat production requires more frequent operation than electricity production. Service based
business models have gained popularity with technologies that require infrequent operation. Solar PV provides the richest set of configurations and includes several third party, community and end-user driven models. The technology requires relatively little maintenance after installation, but in some extreme conditions an active user can influence output. In cold climate during the winter, the removal of snow from panels becomes important. Similarly, high soiling rate can be an issue in dusty dry areas. In service-based models with technologies requiring frequent operation requirements, operation maintenance challenges can be addressed by shared responsibilities where incentives for energy users are created.

Micro-generation typically provides a competitive energy price in comparison with external energy sources, i.e. market price. When a (residential) energy user receives locally produced energy (at discount rate), the user also benefits from the high output level. A local ownership option, cash and credit, gives full authority to the user to control the production of the unit and full reward to maximize the production of the unit. Strengers [93] proposes enabling co-management relationships with consumers for peak electricity demand. Similarly co-management can be expanded to production equipment in order to enable the mutual benefits that maximize local energy production. However, co-management applicability is highly dependent on general skills and knowledge of the population to operate domestic technologies, which may be insufficient for example in bottom of the pyramid (BOP) markets.

4.2. Service-based models and limited market demand

Although micro-wind and micro-hydropower can be seen as self-sustaining technologies, they have not attracted third party business models. Khennas and Barnett [94] who researched hydropower deployment in developing countries explained this as a market size issue. A third party model is not used because the extent of project developers is largely a function of whether there is sufficient work for them; i.e. are there sufficient number of new micro-hydro constructions taking place each year. Natural conditions, such as unharnessed rivers, define where it can be deployed at all. In the case of micro-wind and solar thermal, an under-developed market and limited current market size can limit viability of the business, whereas the solar PV market has grown large enough to provide companies with economies of scale in operation and possibility to create profitable business around the third party ownership model. It should be noted that especially in the case of a solar thermal collector, a market lease could be an applicable model if the gained heat production vs. cost of equipment ratio is sufficiently high. Because subvention mechanisms have been generally directed towards electricity production, solar PV has been the starting point and entry technology to provide service-based models such as lease and fee-for-service. In the countries without government subvention, these models are practically nonexistent as yet. Nonetheless, service-based models of solar thermal collectors appears to be a missing configuration which is hard to rationally account for. The concepts of the model can be dated back to 2006 [95] and some commercial deployments have been planned but commercial providers are still very rare. Similarly, a missing configuration without clear explanation, apart perhaps from a poor fit with extant business models, is that utilities do not appear to provide fee-for-service solar PV.

Energy Service Company (ESCO) models have been applied to some heat generating technologies, but the operations are often difficult to apply successfully on a small-scale [60]. For heat pumps, microESCO models have been tested but commercial success has been limited to date. However, for biomass systems, third party ownership is an established model and service providers can be found, for example, in the UK.

4.3. Opportunities with community energy

Community energy as a concept consists of a diverse set of activities and includes more than energy production [96]. Community-energy initiatives can improve energy systems via renewable energy; energy efficiency, and behavior change [97]. In this paper our interest in community activities is solely on energy production from renewable sources, and we grouped under community energy initiatives those that have community ownership and production benefitting multiple households. Micro-generation refers to small-scale energy technologies and often community energy production exceeds the micro-generation scale.

When energy output from micro-generation is distributed to multiple households, the technical capabilities of distribution become essential. In electricity distribution micro-grids can be used, but in heat distribution heat losses can be significant thereby creating limitations in community production. Solar thermal collectors and biomass, are used in community-scale deployments. The visions for using the district heating network for transmitting solar heat imply models of distributed privately owned collectors and third party owned distributed solar heat generation. To make these models viable may require regulatory forced unbundling of heat production and distribution ownership in a company level in a similar manner that has been done in electricity generation and distribution earlier.

To date community-scale experiments with ground source heat pumps have remained mostly trials, and present a missing configuration. Shared collector fields, potentially heated with solar collectors in the summer, as well as trials with seaborne heat for district wide heat pump installations, point to the technical forms this can take [28]. Similarly, multiple heat pump combinations in shopping malls provide excellent examples for how the technology could be managed at a community-scale. In terms of business models, only cash/credit has been available to date, but due to their easy maintenance and the capacity of being monitored remotely, other business models could suit community ground source heat as well.

Finally, we may note that sources to date have not addressed community energy possibilities from the point of view of separating ownership, operations and maintenance, and networking, with distant proximity and close proximity combinations (distant proximity networking being ruled out due to technical limitations, naturally). An example would be third party lease of biomass generation equipment to a community, which could mitigate the third party barriers in operation and maintenance of e.g. pellet systems.

5. Policy implications of missing configurations

Analysis of missing configurations revealed three key limiting factors: technological limitations, limited market demand, and challenges in distribution in the community energy context. Innovation and energy policy mechanisms can be used to facilitate all these items.

The cost efficiency of energy technologies is highly dependent on the cost involved during the operation phase. New innovations especially addressing the issues of the maintenance and operation of equipment could open new service models for micro-generation technologies that have not attracted service business models so far. We suggest that local innovation trials may [97,98] support manufacturers efforts to find new solutions to drive heat based micro-generation technologies, in particular, towards a more self-sustaining or remotely controlled operation.

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* Centralized community production unit feeds heat to households in surrounding area.
A diverse socio-technical configuration choice set also includes service-based models. Fee-for-service or leasing can boost market development in multiple ways, as has been evident with solar PV. They remove the need for upfront capital investments from consumers, and thus have the potential to increase the popularity of small-scale renewable technology in general. In addition, service companies can gain economies of scale in sourcing of equipment, installation and operation, and maintenance. Moreover, end of life-cycle and recycling services can be organized in a professional manner. Service-based models can add component quality concerns, because this model allows companies to purchase equipment in volume and use low-cost finance to spread customer costs over the lifetime of the equipment. It also appears to promote innovation, as in the case of solar utility companies, which can have enough resources for R&D investments and are large enough to use negotiating power with suppliers [99]. Especially in the developing countries third party ownership and credit models are having special importance to increase affordability among the poorer segments of the market, where lack of capital and loan guarantees are an issue. In these markets leasing and fee for services are particularly important [9,54,55]. Households’ knowledge and capability for taking care of operation and maintenance of micro-generation technology might become an issue, which support idea of service-based models. In fact, in the countries where adult illiteracy rate is high the lack of skilled and motivated local human resources to build, operate and manage may represents a major barrier even for the corporate driven models [100].

In the early market phase where the limiting market size does not attract sufficient commercial vendors, subvention is an important driver to support market takeoff. Especially FIT tariffs have been used widely to support electricity generation from solar. FIT for heat production, such as solar thermal collectors, is less used with a few exceptions (e.g. Spain). Also in developing countries main renewable focus has been in solar PV deployments. Our review echoes earlier research by Karezeki [6] and calls for expanding policy support horizons for various renewable technological options. Efficient micro-generation technologies for the use of biomass, for example crop residues, would, ensure that scarce biomass resources are effectively utilised. In addition to eco-efficiency increases more advanced micro-generation would alleviate the negative impacts that burning biomass can affect on women and children’s health. Increased productivity level in basic energy generation could also improve women’s participation possibilities in different economic activities other than household work. Furthermore, in regards energy policy and supporting mechanisms of renewable micro-generation, attention in developing countries should be paid not only to solar PV but also to solar thermal, windpumps, micro-hydropower. We emphasize the importance within technology and innovation policy, both in developing and advanced industrial countries, to drive development towards carbon emissions reduction and remain technology agnostic so as to allow winning innovations to come about on multiple fronts.

Finally, let us address financing issues that can support the proliferation of micro-generation technologies. Cash, credit, or community ownership options give high autonomy and control to production for individual users or groups. These options are applicable especially among wealthier segments in the developing countries and developed countries. For financial institutions there is space to develop new financing instruments (credit schemes) in order to remove the upfront payment. There are also possibilities to develop other types of mechanisms as an example of Francisco DeVries, also known as Property assessed clean energy (PACE), from California shows. In this Sustainable Energy Financing District, the municipality takes part in financing by issuing bonds whose proceeds could finance the upfront costs of photovoltaic systems. The participating homeowners could use the money they save on their utility bills to pay a tax assessment, thereby achieving payback. Unlike in third-party financing, the ownership of the energy production unit rests with the building owner under this model [52,101]. In California PACE model has been expanded from initial solar PV technology to cover also HVAC systems, and energy efficiency renovations such as more efficient windows [10]. In principle the same model can be utilized for all renewable micro-generation technologies.

6. Conclusions

There is a range of options to deploy micro-generation. In this study we developed the socio-technical framework for renewable micro-generation and used it to make visible the currently existing and missing configurations in small-scale decentralized energy production. Micro-generation takes three main ownership models; consumer (household), community, and company ownership. We showed how the versatility of socio-technical configurations within these ownership models has, to date, varied significantly between technologies. Some configurations appear to be impossible due to physical limitations, such as distribution limitations in heat production because of heat losses, but most configurations are a result of a combination of social, technological and economical factors. Earlier literature has recognized the impact of various factors on how socio-technical configurations emerge and diffuse in the local marketplace. Within the micro-generation sector, the choice between alternatives is a reflection of consumer involvement in the acquisition process, and that variation or a combination of these models is possible [36]. In addition, both politico-institutional and socio-institutional forces have an impact on the choice between these models as explanations of the variation in level of the activity and business model choice between countries, ventures, and technologies [61]. Our contribution is to extend this thinking and show that differences in technological characteristics, which have a direct impact on operation and management needs, play a key role in socio-technical configurations and enable or hinder proliferation of company-driven models and servicetization of micro-generation. We suggest that particular attention should be paid to innovations that improve reliability, increase maintenance-free operation times and provide remote monitoring and maintenance. This applies to heat producing technologies in particular. Alternative possibilities might also emerge from improved ease of use (usability) and the organization of the operation and maintenance at the site of use or at community level so that operations and maintenance could be left to consumers whilst the ownership and distribution of heat might reside with a third party operator. We can also recognize technologies, such as solar thermal collectors, that could well meet operational requirements of service-based models, but which have not yet attracted business interest. At the policy level, there is space to develop new mechanisms for small-scale heat production in manner similar to that which has been used to support the scale up of electricity micro-generation in many markets. In developing countries special focus should be put on expanding energy policy measures from solar PV to other renewable micro-generation technologies.

The present study concentrates on current ways of organizing around micro-generation technologies. Its temporal context is confined to the operation of micro-generation when a certain organizational set up around a technology has been already established. Our

9 Financial institutions may not consider micro-generation products to be valid for collateral security, which increases interest rate in the credit pricing.

contribution opens several avenues for further research on socio-technical configurations. It points out that academic research on micro-generation technologies and related business models requires frequent updates to avoid falling behind the rapidly developing field. It also underscores new points of focus such as how installation work is organized before the socio-technical configuration of energy production has taken its organizational form, or how configuration trajectories have developed over time. There are significant country-specific variations in micro-generation technology diffusion. For example, supporting mechanisms play a crucial role in the early development of servitization. In this study FIT and other supporting mechanisms were excluded in order to be able extensively cover selected dimensions. Servitization may also hinder the development of local energy autonomy from a user perspective, even if it may also provide a boost for market development and lead to increasing popularity, lower prices and reliability of equipment for autonomous consumers in the long run.

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References


