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| Author(English) | Amanda Grace Ahl |
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Tokyo Institute of Technology
東京工業大学

School of Environment and Society
*Department of Innovation Science*

# **Digital innovation in the energy value chain**: An analysis of prospects for distributed, renewable energy in Japan

**Supervisor:** Mika Goto

**Co-supervisor:** Kazuyoshi Hidaka

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**Candidate:** Amanda Ahl

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Abstract

What is the next phase in the sustainable energy transition? The integration of renewable and distributed energy resources is essential, but also presents several complexities that call for resource control and coordination. This can be supported by digital technologies, such as blockchain and artificial intelligence, which will likely be a key competitive differentiator in the energy sector. Indeed, energy is undergoing digitalization in addition to decarbonization and decentralization. However, the implementation of digital energy solutions remains complex in practice. **Energy systems involve social, economic, and institutional processes in addition to technology.** Despite the multidimensional nature of energy innovation, energy-related research has often focused on individual technologies and technical issues. There are several grey areas in the strategic landscape of digital innovation in the energy transition, and a need for further research and practical insights integrating economic, social, environmental, and institutional dimensions.

Based on a multi-dimensional approach, this thesis explores how digitalization in the energy value chain can facilitate renewable, distributed energy in Japan. **The focus is on 1) renewable energy exemplified by woody biomass, and 2) distribution networks exemplified by blockchain.** The overall goal is to develop a holistic framework for the assessment of digital strategies in the renewable energy value chain, which may be further built upon in academia as well as industry and government. **An exploratory, qualitative approach was adopted, leveraging semi-structured interviews with experts and case studies.** Case studies and expert interviews can be valuable for data collecting, mapping, and theory induction in new academic areas, as these methods can support insight creation and manifold perspectives. Based on these insights and discussion with a strong foundation in recent literature, implications for digital strategies in the energy value chain are identified.

From the perspective of 1) **renewable energy**, key challenges across the **woody biomass supply chain** as well as potential for digital technologies to contribute to overcoming them are identified. The challenges include transportation infrastructure; biomass quality monitoring and control; stakeholder respect, relationships and trust; local community revitalization and socioeconomic development. It is found that digital technologies can contribute to solving the challenges via various mechanisms such as improved transparency, information-sharing, accountability, automation, and value maximization. However, digitalization would also call for new approaches in management and policy, such as education and community outreach programs. From the perspective of 2) **distribution networks**, an analytical framework for **blockchain-based peer-**

**to-peer (P2P) microgrids** is developed. The framework is titled TESEI, and incorporates 1) Technological, 2) Economic, 3) Social, 4) Environmental and 5) Institutional dimensions. Based on this framework, a blockchain-based P2P microgrid case in Urawa Misono, Japan, was analyzed. Concrete challenges of scaling this case and opportunities to overcome them are identified and discussed. Examples of key challenges include blockchain throughput, subsidy-dependence, behavioral change among consumers/prosumers, emissions reduction scheme uncertainty, and grid interconnection regulations. Opportunities include blockchain consensus mechanisms development, platform markets, business model innovation, user-friendliness, enhanced user choice, renewable energy-trading transparency, emissions-tracking, and regulatory sandboxes.

Findings indicate that digital innovation in the renewable energy value chain faces multi-dimensional and inter-related challenges and opportunities. The incorporation of this multi-dimensionality and interoperability between current and future systems can be important in supporting innovation. A framework of pathways for digital innovation, or a digital toolbox, based on challenges and opportunities identified across the renewable energy value chain is created. In addition, a digital innovation process is suggested, based on 1) concept creation rooted in this digital toolbox and challenges in the energy value chain, 2) multi-dimensional experimentation, and 3) scaling. Living Labs and regulatory sandboxes can support this experimentation, multi-stakeholder innovation ecosystems, and decision-making in both the private and public sectors. **This thesis offers holistic conceptualization, contributing with research to support more substantiated strategies for digital innovation in the renewable energy value chain in Japan.** These implications would be of interest in academia, business, and among policy-makers that are working to support the energy transition.

While exploratory findings and an initial assembly of aspects are shared, further research would be needed on the nexus of renewable energy and digital technologies. This may include how digital technologies can contribute to social, economic, and environmental sustainability in regional woody biomass supply chains. An important question is also what regulatory and policy support would be needed to facilitate the nexus of digital innovation and woody biomass. An additional suggestion for further research is the development of the TESEI framework as well as its application to different cases, such as off-grid microgrids. Finally, further research is also needed in terms of governance to support digital innovation in the energy transition. Such research may delineate a future development route that assimilates digital technologies, the renewable energy value chain, and impactful, sustainable development.

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# Chapter 1. Introduction

## 1.1 International momentum for sustainable energy

The world as we know it is undergoing extraordinary change. On the one hand, change has been positive. Hundreds of millions of people have been pulled out of poverty (UN, 2015), and global electricity access increased to approximately 89% in 2017 from 78% in 2000 (World Bank, 2019). The rapid spread of information and community technology (ICT) has expedited development, accelerated innovation, and bridged digital divides (UN, 2015). On the other hand, the energy systems powering such advancements have at large been based on fossil fuels. Approximately 2/3 of global greenhouse gas (GHG) emissions are attributable to fossil fuel combustion for energy purposes, including power, heat, transport, and industry (EEA, 2017). GHGs caused by human activities have thus far led to global warming of approximately 1.0 °C above pre-industrial levels (IPCC, 2018). Examples of resulting impacts are environmental degradation, bio-diversity loss, and health risks such as heat-related mortality (IPCC, 2018). Climate change clearly poses significant risks, and as put by Spratt and Dunlop (2019), is an “existential threat to human civilization.”

In order to reduce climate risks, no or limited overshoot of a 1.5 °C global warming limit would be necessary, as estimated by the Intergovernmental Panel for Climate Change (IPCC) (IPCC, 2018). To attain this goal, anthropogenic $CO_2$ emissions would need to reach net zero by 2050 (IPCC, 2018). For this, a both rapid and extensive energy transition is needed, including enhanced energy efficiency, electrification, and renewable energy growth (UN, 2015; UN, 2018 a; IPCC, 2018). For example, in its 1.5 °C pathway, the IPCC projects renewables to account for 70-85% of global electricity by 2050 (IPCC, 2018). Indeed, global efforts for sustainable development in the energy sector have been rising. This can be seen, for instance, in the United Nations (UN) Sustainable Development Goals (SDGs), in which “access to affordable, reliable, sustainable and modern energy for all” is included as SDG 7 (UN, 2015). This is an important development, as SDGs communicate global political ambitions, including energy innovation (Arent et al., 2017).

There is clear emphasis in the international agenda on sustainable development in the energy sector. For example, numerous countries have set 2050 targets for 100% renewable electricity, such as Spain (Morgan, 2018), Germany (Klaus et al., 2010), and Denmark (Brittlebank, 2016). With rising interest in the public and private sectors as well as in civil society, the pace of innovation for efficient and renewable energy technologies is undoubtedly accelerating (IRENA, 2019 a). Technical advancements have enabled capital cost declines for renewable and distributed energy technologies, such as 75% for solar power, 20% for onshore wind power, and 50% for battery storage since 2010 (IEA, 2019). In 2017, renewable electricity increased globally by 178 GW, accounting for 2/3 of total net capacity additions (IEA, 2018 a). In fact, when adjusted for 2018 cost levels, investment in renewable electricity has risen by approximately 55% since 2010 (IEA, 2019).

While the renewable electricity share has increased, the transportation and heat sectors have shown slower growth, as seen in Figure 1 (IEA, 2018 a). There is still a need for expanded and accelerated renewable energy development. While final investment decisions (FDIs) in coal- and gas-fired power have indeed declined since 2014, low-carbon systems constitute approximately 35% of all energy investments (IEA, 2019). Investments in electricity grids have also decreased in the past two years (IEA, 2019). Based on these trends, energy systems would be insufficient in ensuring supplies for rising demands and reaching sustainability goals (IEA, 2019). Delayed efforts to limit global warming to 1.5 °C would pose significant risks, such as escalated costs, lock-in in high-carbon infrastructure, stranded assets, and a lack of system flexibility (IPCC, 2018).

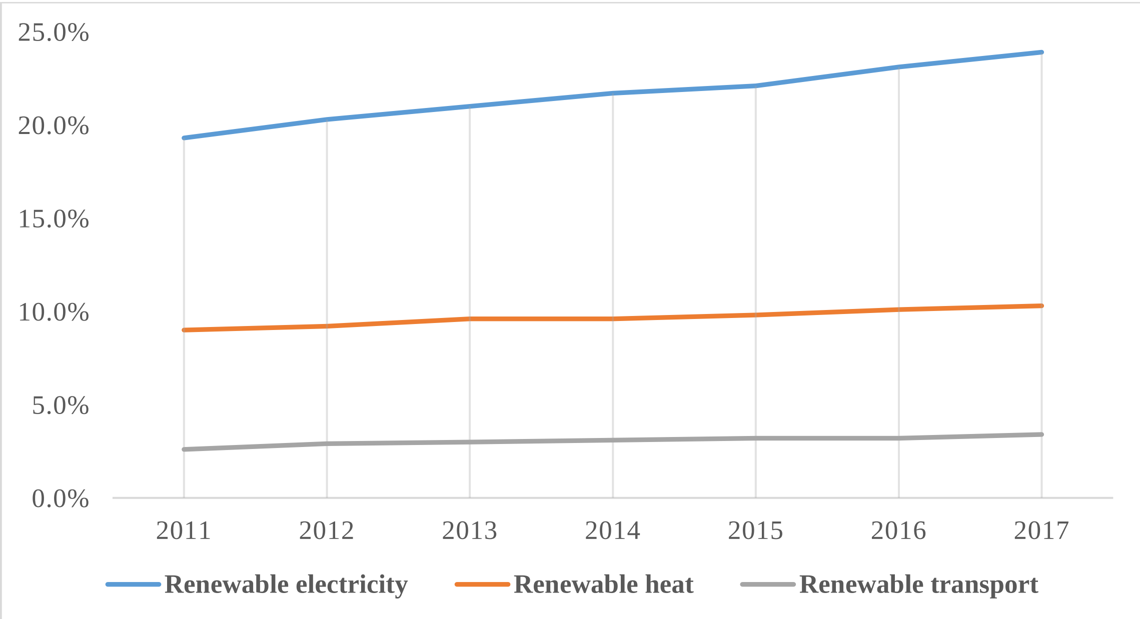


**Figure 1** Global share of modern renewable energy per sector (IEA, 2018 a)

This means that it would be vital to reallocate capital and resources (IEA, 2019). It can be suggested that short- and long-term national strategies for low-carbon energy expansion, coupled with supporting physical and digital infrastructure, are needed to accelerate sustainable development and avoid climate change risks. A key question in such strategies is, how can "universal access to affordable, reliable and sustainable energy" (UN, 2015) be supported? To address this, there would be a need for innovation and transition management on multiple fronts in the energy sector.

**1.2 Energy decarbonization, decentralization, and digitalization**

Prior to elaborating on energy innovation, it would be important to expand on innovation per se. There is a common misconception that innovation only relates to new product development (Goffin and Mitchell, 2017). However, services, processes, business models, and markets can all also be subject to innovation (Goffin and Mitchell, 2017). Rogers (1962) broadly described innovation as "an idea, practice, or objective that is perceived as new by an individual or another unit of adoption." Schumpeter (1934) explained innovation on five concrete fronts, as a new 1) product or product species, 2) process (for product production/sales), 3) market, 4) sources for raw material or semi-finished goods, or 5) industry structure. At large, innovation presents new means for problem-solving among firms (Rogers, 1962). It can be placed in the broader context of the Schumpeterian Trilogy: the flow from invention to innovation to diffusion (Mahdjoubi, 1997). Invention involves the generation of new ideas, innovation concerns the marketization of these ideas, and diffusion is the spread of new products and processes across the market (Mahdjoubi, 1997).

It can be suggested that innovation is indeed ongoing on manifold fronts in the energy sector, from novel technologies to new business models and industry structures. Innovation in the energy sector pertains to technology and infrastructure, as well as social behavior and institutions (Grubler et al., 2012). This has been set off due to pressures of GHG emissions reduction alongside a need to sustain energy affordability and security: the energy trilemma (Hansen et al., 2019; Morstyn et al., 2018; Kuzemko et al., 2016). Examples of energy innovation trends are the use of multiple primary energy sources, distributed energy, energy storage, energy service provision, and demand side management (Patwardan et al., 2012). It is when these trends are put together that the energy transition can be observed (Patwardan et al., 2012). The sustainable energy transition is being shaped by decarbonization, decentralization, and digitalization (Di Silvestre et al., 2018 a; Brilliantova and Thurner, 2018; Andoni et al., 2019).

1.2.1 Energy decarbonization

It is clear that decarbonization and the transition from fossil fuels to carbon-neutral energy mixes is high on policy agendas worldwide (Koirala et al., 2016). In this context, rapid technical advancements, increasing private investments, rising scalability, and skill developments are facilitating low emission technologies and systems (Arent et al., 2017). This points to rapidly transforming foundations for decarbonization (Arent et al., 2017). With the rise of new and clean energy technologies, average primary energy carbon intensities are indeed declining (Di Silvestre et al., 2018 a). For example, the global average carbon intensity of power generation is approximately 475 $gCO_2$/kWh: a 10% decrease from 2010 (IEA, 2018 b).

Distributed energy resources, such as renewable energy, storage and demand response (DR), are important elements in supporting decarbonization (Koirala et al., 2016). Distributed energy technology cost declines are projected to continue, thereby supporting a shift to distributed energy systems, such as microgrids (Morstyn et al., 2018; Saberi et al., 2018 a; Cohn et al., 2017; Abe et al., 2019; Yang et al., 2017; Cao, 2019). These shifts as well as electrification call for coordination and integration of local generation (Koirala et al., 2016). This is linked to rising trends and challenges of energy decentralization.

### 1.2.2 Energy decentralization

Historically, power grids were created based on Nikola Tesla's AC format in large, centralized power plants that deliver electricity over long distances via high voltage transmission lines (Valocchi et al., 2014). This led to path dependence towards vertically integrated, highly regulated models for large-scale and centralized power systems (Valocchi et al., 2014) that rely on economies of scale (Arent et al., 2017). However, recent trends towards decentralization have led to the emergence of new system models.

At present there are two key power system development frameworks: bulk and micro models (Di Silvestre et al., 2018 a). Bulk models involve large-scale transmission networks and interconnection among regions (Di Silvestre et al., 2018 a). In this context, large-scale energy systems, such as coal or nuclear base load power plants, are key factors. In addition, resilient and efficient power transmission grids are important to support and transport electricity (Arcia-Garibaldi et al., 2018). However, continuously expanding power infrastructure can be expensive and unsustainable, for example due to transmission grid losses (McKinsey & Company, 2013). Conversely, ongoing trends toward distributed generation has led to an era of energy decentralization (Alanne and Saari, 2006; Arent et al., 2017), which is related the micro model. Micro models incorporate clusters of small-scale distribution networks, integrating distributed renewable energy resources (Di Silvestre et al., 2018 a).

Decentralized energy is indeed widely and increasingly discussed in academia (Hirsch et al., 2018; Di Silvestre et al., 2018 a; Soares et al., 2018). Decentralization concerns the generation and management of electricity near loads, by leveraging distributed generation (Di Silvestre et al., 2018 a). Distributed generation can be defined as “electric power generation within distribution networks or on the customer side of the network” (Ackermann et al., 2001). Pepermans et al. (2003) similarly discussed that distributed generation is connected to the grid directly on the customer side of the meter. Alanne and Saari (2006) explained that distributed generation comprises of energy conversion units placed close to energy consumers. However, it can be argued that the roles of “customers” and “consumers” are changing in the current energy landscape, with the rise of the “prosumer”.

Distributed generation in households, storage, and energy exchange technologies are likely to expand in future energy systems (Koirala et al., 2016). With such trends, there is a rise of new actors and roles in the energy sector and an ongoing shift from passive consumers to active prosumers (Koirala et al., 2016). Prosumers are agents that consume as well as produce energy, which may be small- or medium-sized, utilizing solar PV, vehicle-to-grid (V2G), electric vehicles (EVs), home storage, and other distributed energy resources (Parag and Sovacool, 2016). This means that electricity would need to flow bi-directionally as opposed to uni-directionally in the grid among producers, prosumers, and consumers. Figure 2 illustrates a simplified example of a shift from centralized to decentralized electricity systems leveraging microgrids. As a result of decentralization trends, traditional electricity sectors are likely to significantly change (Parag and Sovacool, 2016). There are indeed several pressures on utility business models arising with technological, economic, social, and institutional changes (Valocchi et al., 2014). Changing roles in the energy sector present social and political challenges as well as opportunities (Patwardan et al., 2012). For example, utilities may shift towards service-based business models, and increase digital engagement strategies (Koirala et al., 2016).

Decentralization is also enabling citizen inclusion for more context-based systems (Anthopoulos, 2015; Huber and Mayer, 2012; Komninos et al., 2013). When prosumers are interconnected in microgrids, local energy markets with unique pricing mechanisms can be supported (Mengelkamp et al., 2018 a). Microgrids incorporate local distributed energy supplies and demands in integrated systems (Wouters, 2015; Morris et al., 2012) that may function on-grid or off-grid in islanding mode (Noor et al., 2018). Such setups may facilitate high shares of local renewable energy, internal prosumer-trading, and community resilience (Mengelkamp et al., 2018 a; Di Silvestre et al., 2018 a). Di Silvestre et al. (2018 a) also discussed that low- to medium-voltage microgrids

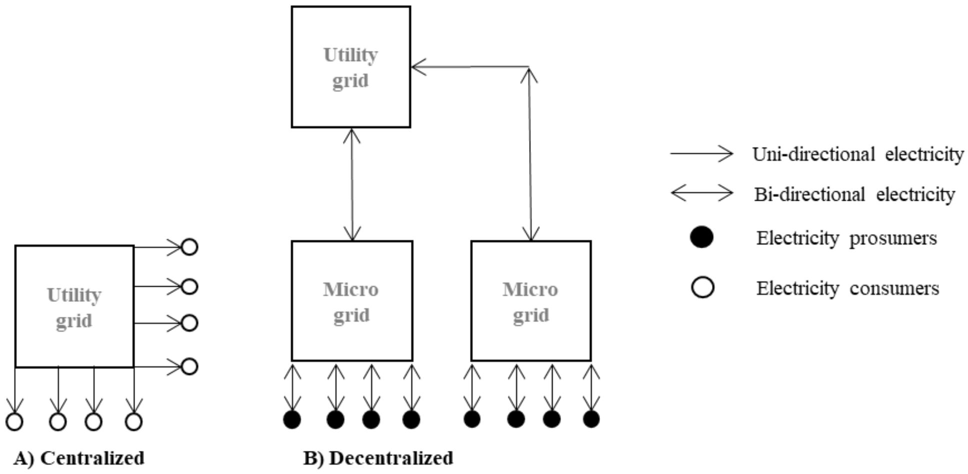


**Figure 2** Simplified overview of potential transition from A) Centralized, to B) Decentralized power system (Adapted from Ahl et al., 2019 a)

are a key potential pathway for distributed energy interconnection.

From the technical perspective, key enablers of energy decentralization include microgrids, low- to medium-voltage renewable energy generation (e.g. solar rooftop), EVs, EV-charging, behind-the-meter storage (Di Silvestre et al., 2018 a; IRENA, 2019 a), V2G, grid-scale storage, DR, energy efficiency advancements (Di Silvestre et al., 2018 a), and virtual power plants (VPPs) (Koirala et al., 2016). A diverse toolbox of potential technologies and systems indicate that there are several prospective decentralization approaches. Such approaches will also continue to develop via technological advances (Calvillo et al., 2016; EPA, 2018), increasing cost-effectiveness and reliability (EPA, 2018).

In addition to physical grid infrastructure, developments in exchange mechanisms, market access and grid stability are needed to support an increasing number of actors, such as prosumers (Brilliantova and Thurner, 2018). Integrating energy flows in collective energy systems largely involves identifying regional synergies (Johansen and Røyrvik (2014). As discussed by Hartmann (2014), several actors from one or more organizations are involved in innovation, whether related to technology, processes or organizational structure. Innovation in integrated energy systems necessitates stakeholder coordination and supply chain design based on local conditions and actors (Johansen and Røyrvik, 2014).

There is a need to further explore value and value capture, in addition to a focus on resource supplies commonly seen in the literature (Bowman and Ambrosini, 2000). While investments tend to go to large-scale supply technologies, demand-side technology and energy efficiency are also important in the energy transition (Grubler et al., 2012). It can be suggested that a full value chain perspective would be important in order to incorporate not only physical supplies and more technical opportunities, but also the social and economic dynamics of energy. With this perspective, silos and sub-optimizations across processes and actors may be more effectively avoided. Value may be economic or social, such as a preference to purchase locally produced energy (Mengelkamp et al. 2018 b). It is suggested that a holistic approach is needed in energy innovation, with technological, economic, social, environmental, and institutional factors across a networked value chain.

**Innovation and the value chain**

With an increasing number of agents and transactions, markets at large are increasingly decentralized (Bheemiah, 2017). Enabling technologies as well as business model innovation, market design, and system operations are shaping the energy innovation landscape (IRENA, 2019 a). Several authors have highlighted that future distributed energy systems cannot be effectively managed via the centralized energy markets of the present (Pop et al., 2018; Hirsch et al., 2018; Cruz et al., 2018). This is because the increase in variable data in distributed systems leaves centralized approaches inefficient (Andoni et al., 2019), calling for improved digital infrastructures, data management, and data quality (Camarinha-Matos, 2016). As highlighted by Schumpeter (1934), innovation concerns new products and technologies, as well as markets and industry structures. It can be argued that in order to support and diffuse technological innovation, innovation on multiple fronts would be needed in parallel, such via new market designs and business models. With this background, the energy value chain is an important point in discussions of decarbonization and decentralization.

The conventional concept of value chains involves a linkage of activities in an integrated company, especially in manufacturing (Peppard and Rylander, 2006). However, as value chains are digitalized, a linear focus in one company is no longer sufficient in uncovering value (Peppard and Rylander, 2006). Digitalization is also enabling reduced transaction costs, leading to shifts from vertically integrated firms to expanded market relationships (Peppard and Rylander, 2006). Weiner et al. (1997) similarly discussed the emergence of virtual value networks as opposed to integrated providers in the energy sector. With this, in this thesis the energy value chain is considered as a networked ecosystem of players that create and deliver value, as opposed to a single company. When the term supply chain is used in this thesis, it refers to a network of interconnected actors which support physical resource flows, such as woody biomass. It is suggested that the supply chain is a fluid and integrated element in the value chain and value creation among stakeholders, similarly discussed by Oliveria and Gimeno (2014).

Cooperation and co-creation is indeed increasingly important for strategic performance, via interlinked value creation among players in network economies (Peppard and Rylander, 2006). Innovation involves the integration of business models and flexibility across the value chain, as opposed to solely optimizing throughput efficiency, as specified in conventional supply chain theory (Hugos et al., 2011). As put by Hugos et al. (2011), "coordination is more powerful than control." The energy value chain involves several sub-systems and associated activities that need to be coordinated, as any changes incur both upstream and downstream impacts (Lund, 2009). It would therefore be vital to form energy policies based on the energy value chain in its entirety, by identifying opportunities and challenges therein (Lund, 2009).

Figure 3 illustrates the traditional electricity value chain, based on centralized power plants and uni-directional flows. This involves power generation, transmission, distribution, retail, and end-use (Valocchi et al., 2014). However, following the rise of distributed resources (Valocchi et al., 2014) alongside electricity sector liberalization, there are several new potential value chain pathways and industry structures (Eiid et al., 2017). An example of an emerging electricity value chain is shown in Figure 4. Emerging electricity value chains integrate end-users, such as via distributed energy resources including renewable energy, batteries, and EVs (Valocchi et al., 2014). New value chain pathways may involve a shift from the vertically integrated utility model to new market structures such as single buyer, wholesale competition, or retail competition, as illustrated in Figure 5 (Eiid et al., 2017).

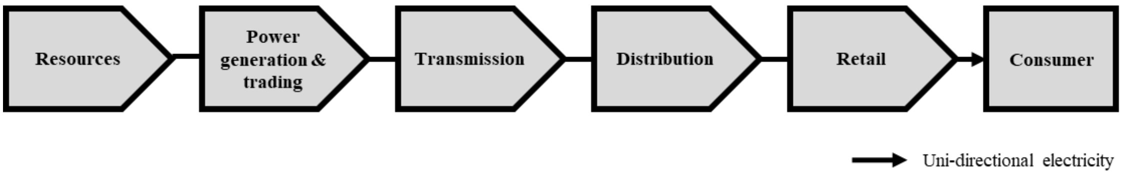


**Figure 3** Traditional electricity value chain (Adapted from Valocchi et al., 2014)

In emerging value chains, as exemplified in Figure 4, consumers and prosumers will become empowered participants as opposed to passives consumers (Valocchi et al., 2014). In this context, utilities as well as policy-makers need to explore how prosumers can be efficiently integrated into competitive markets (Parag and Sovacool, 2016). Parag (2015) discussed innovative platform markets through which prosumers can trade and actively participate in energy systems. A platform

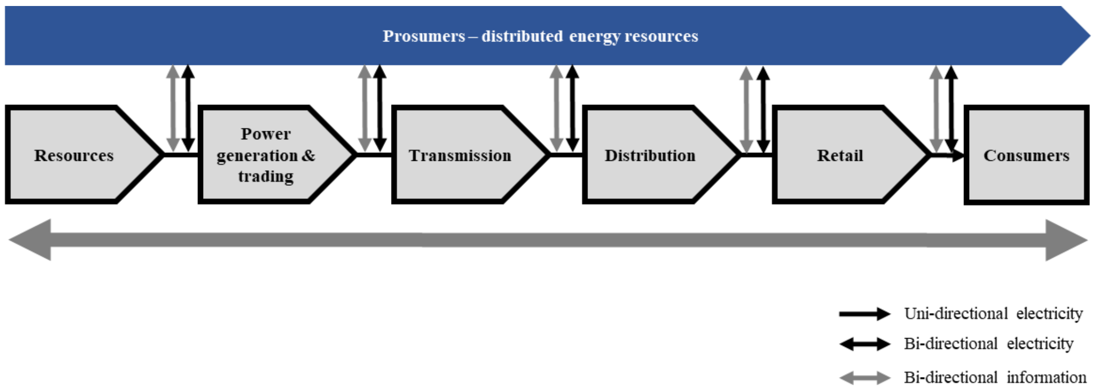


**Figure 4** Potential emerging electricity value chain (Adapted from Valocchi et al., 2014)

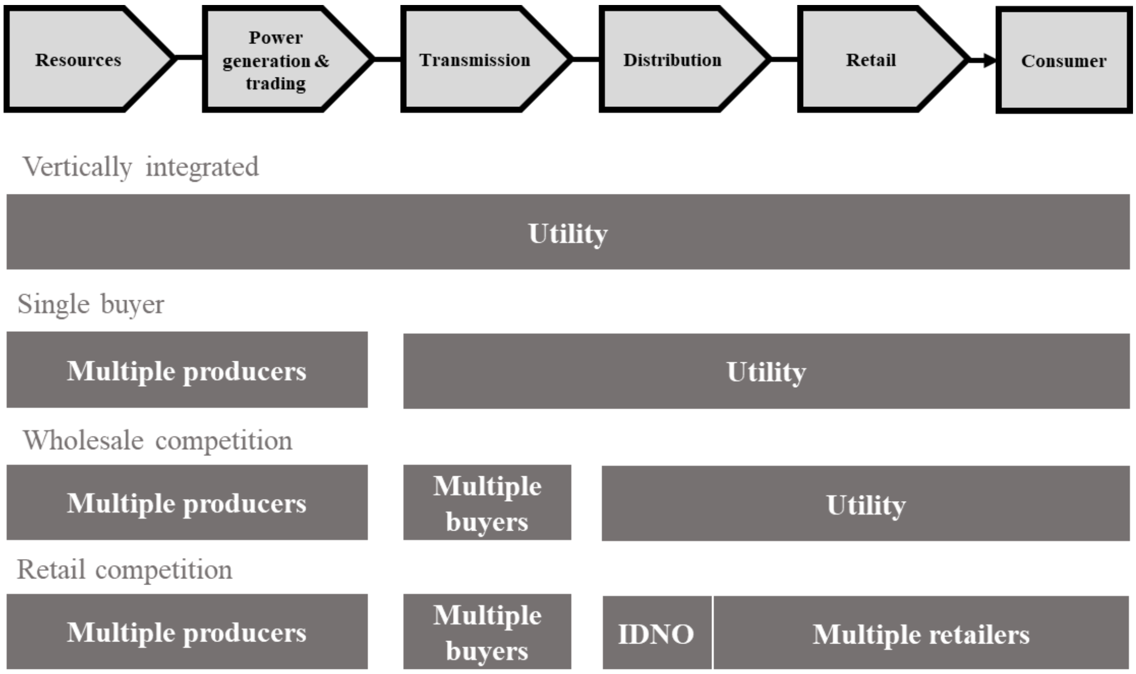


**Figure 5** Potential electricity market models due to liberalization. (IDNO: Independent Distribution Network Operator) (Adapted from Eiid et al., 2017)

market involves fee-based business models, as opposed to current transaction-based, marginal cost-based markets (Weiller and Pollit, 2016). It is a multi-sided market in which an intermediary captures value in transactions among users (Weiller and Pollit, 2016; OECD, 2018; Hagiu and Wright, 2015). Weiller and Pollit (2016) similarly discussed a shift to a two-sided platform market for electricity retail, supported by ICT. A platform market could support volatile renewable energy, facilitate new roles, as well as stimulate competition and innovation (Weiller and Pollitt, 2016).

New roles involve both prosumers and other actors, such as independent aggregators (Lind et al., 2019).

New value-added services can be introduced on such platforms, for example balancing services for home energy management (Weiller and Pollitt, 2016). Additionally, with the increasing electrification of mobility, clearly indicated by EV trends (Di Silvestre et al., 2018 a), platform markets may also incorporate services for EV charging management and storage (Willer and Pollitt, 2016). Furthermore, EV batteries may be used as distributed storage systems and to offer ancillary services in competitive electricity markets (Debbarma and Dutta, 2016). In V2G setups, meaning EV-grid connections for bi-directional power flows, EV batteries can become an integral part of the power network (Steitz, 2018). Thereby, for example, EVs can offer new products and services for grid management (Debbarma and Dutta, 2016). Several automakers, such as Nissan, are in the process of developing such systems (Steitz, 2018).

However, there are several challenges of decentralized energy and prosumer integration. Examples of such issues include poor market structure, grid reliability, and the management of increasing flows of information (Parag and Sovacool, 2016). Distributed generation, bi-directional flows of power and information, and new actors are increasing complexity (Valocchi et al., 2014), leading to challenges in the integration of intermittent renewables on the grid as well as in energy markets (Dena, 2012; IRENA, 2018; Wee et al., 2012; Saveedra et al., 2018; Mengelkamp et al., 2018 b).

**Complexity in the decentralization era**

While decentralized systems can support decarbonization, they also require enhanced coordination for energy efficiency and security (Di Silvestre et al., 2018 a). Distributed energy requires information exchange among smart units in order to maintain system balance and efficiency (Alanne and Saari, 2006; Goldthau, 2014). This is because these systems are complex, with prosumers and smart devices feeding into the grid with a need to communicate in real time (Pop et al., 2018; Tanaka et al., 2017; Efanov and Roschin, 2018; Hirsch et al., 2018; Goldthau, 2014). Increasing electrification, distributed renewable energy, and new agents have indeed given rise to growing grid congestion and balancing issues (Koirala et al., 2016; Lind et al., 2019). In fact, there is often a misalignment of load and supplies in the renewable energy value chain (Goentzel, 2009), and without enhanced coordination strategies, grid issues are likely to intensify. This calls, for instance, for improved coordination schemes among distribution and transmission system operators (DSOs, TSOs) (Lind et al., 2019).

Integration of distributed generation is clearly a key challenge (Koirala et al., 2016). Tackling this challenge and supporting coordination necessitates digital technologies such as smart meters (Parag and Sovacool, 2016) for bi-directional flows of electricity *and* information. As discussed by Lind et al. (2019), TSO-DSO coordination schemes can contribute to flexibility procurement, supported by smart meter data management and sharing models. Flexibility refers to capacity in power systems to manage renewable energy variability at various time scales, evade curtailment, and maintain electricity supply reliability (IRENA, 2019 a). Flexibility is important in grid congestion management (Di Silvestre et al., 2018 a; Arcia-Garibaldi et al., 2018), such as via ICT-based coordination in distribution and transmission systems (Arcia-Garibaldi et al., 2018). There are rising demands for flexibility, such as via distributed storage and new innovations to balance power grids, against a backdrop of renewable energy variability (Koirala et al., 2016; IRENA, 2019 a). For example, demand-side flexibility and ancillary services, including DR, micro-generation, and storage, can further contribute to grid management (Parag, 2015).

Furthermore, on the demand side, users are both seeking more control of energy consumption, and offering more to utilities, such as distributed energy, flexibility services, and new data streams (Valocchi et al., 2014). In fact, it can be suggested that prosumers are now becoming energy service providers (Parag, 2015). The ongoing increase in data presents significant opportunities for both flexibility and utility business model innovation, for example via new offerings for cost-savings, service personalization (Valocchi et al., 2014; Munoz et al., 2016), or service-bundling on new platforms (Midtun and Piccini, 2017). In conjunction, energy innovation is increasingly linked to emerging digital technologies such as Internet of Things (IoT), artificial intelligence (AI), big data, and blockchain (IRENA, 2019 a).

What is the next phase in the energy transition? To respond, it would be valuable to turn to digital technology trends. The rising significance of energy digitalization can undoubtedly create foundations for new opportunities, as well as raise several questions. For example, will software application developers become more active in energy systems or platforms? Will utility companies obtain new roles, such as service or platform providers? In future energy strategies, it is suggested that opportunities and challenges of digitalization would be vital. As emphasized by Weiner et al. (1997), “utilities must consider IT the single most important strategic asset.” As energy system data is both increasingly plentiful and fragmented, effective data-processing systems alongside common standards are required moving forward (Alanne and Saari, 2006). With this background, it can be suggested that the challenges of energy decentralization and decarbonization are closely linked to discussion on the third and final key trend: digitalization (Di Silvestre et al., 2018 a).

### 1.2.3 Energy digitalization

*"The world's most valuable resource is no longer oil, but data"*
(The Economist, 2017)

A rise in data and digitalization is a key trend which is rapidly shaping society. Gartner (2019) defined digitalization as "the use of digital technologies to change business models and provide new revenue and value-producing opportunities; it is the process of moving to a digital business." With changing business models, broader markets and industrial structures are also transforming. As highlighted by Bheemiah (2017), "the information revolution is reversing the industrial revolution and changing the structure of markets in this process." Digital technologies are altering entire industries and the inherent structure of payment and money. This is illustrated in the development of cashless societies, peer-to-peer (P2P) transactions, micro-payments in social networks (Bheemiah, 2017; Mancini-Griffoli et al., 2018), and digital currency deliberations in numerous central banks, such as in Sweden, Canada and China (Mancini-Griffoli et al., 2018).

Due to technologically as well as socioeconomically disruptive potential, digital technologies are likely to continue to strongly impact society. Figure 6 suggests key technology trends in the current era of digitalization, as well as social and managerial trends developing in parallel. *Present* trends in Figure 6 involve key technologies that are currently shaping the digital landscape, including cloud, analytics and digital experience technologies (Briggs et al., 2019). *Near future* trends in Figure 6 include digital technologies that are rapidly approaching scalability and commercialization for broader use in society. By leveraging such technologies, such as cognitive systems, machine learning (Barile et al.,2018), cloud computing, and IoT, complexity can be managed and responsiveness maintained in real-world, dynamic interfaces (Barile et al., 2018; Bifulco et al., 2018).

Managerial and social foundations would also require change in order to support digitalization. Such foundations may include abilities of companies to integrate digital technology, smoothly transition from legacy systems, develop cybersecurity procedures from the bottom-up (Briggs et al., 2019), as well as manage digital ethics and privacy (BBVA, 2019). As put by Briggs et al.

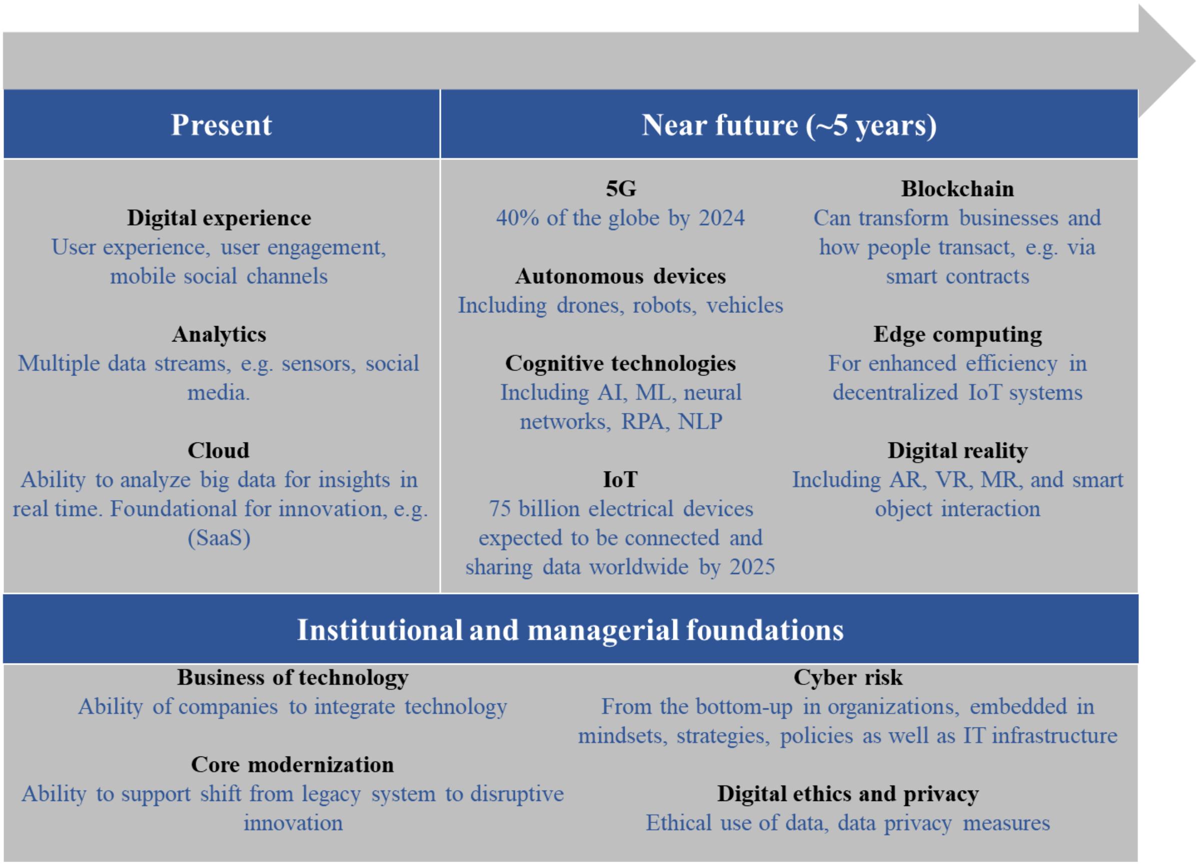


Figure 6 Key trends in the digital era. (SaaS: Software as a Service; AI: Artificial Intelligence; ML: Machine Learning; RPA: Robotic Process Automation; NLP: Natural Language Processing; IoT: Internet of Things; AR: Augmented Reality; VR: Virtual Reality; MR: Mixed Reality) (Based on BBVA, 2019; Briggs et al., 2019; Di Silvestre et al., 2018 a; IRENA, 2019 a).

(2019), "every company is now a tech company and every employee is a technologist."

### Why are digital trends important for energy?

Technological innovation is a vital force in energy transitions (IRENA, 2018; Hansen et al., 2019). Digital technologies, such as those shown in Figure 6, can increase efficiency in technical systems, as well as support stakeholder connectivity (Bifulco et al., 2018; Caputo et al., 2018), participatory systems (Bifulco et al., 2018; Khansari et al., 2013), and in so doing, innovation ecosystems (Bifulco et al., 2016). This can support activities throughout the energy value chain, and stakeholder management therein (Yarime and Karlsson, 2018; Camarinha-Matos, 2016).

For example, with the upsurge of smart phone ownership and mobile applications, strategies for customers' digital experience are increasingly seen among power utilities (Munoz et al., 2016;

Munoz et al., 2016). When coupled with smart grid and smart home setups, customer-centric business models can be improved, for example, by offering prompt billing, energy conservation measures, electricity cost-cutting (Midtun and Piccinni, 2017; Munoz et al., 2016), outage reporting, and energy visualization (Munoz et al., 2016). An additional case is the use of cloud and cognitive technologies for improved energy efficiency in Google's data centers (Briggs et al., 2019). By leveraging machine learning to manage and optimize cooling, cooling energy was reduced by 40% and overall energy consumption by 15% (Briggs et al., 2019). Other companies and startups, such as GridPoint and Shields Energy, have also adopted AI and cloud computing for automated energy efficiency measures in estates (Foot, 2018). This exemplifies the ongoing and increasing integration of emerging digital technologies in the energy sector.

Digital technologies are vital for efficiency efforts and automation in buildings, such as in the data center cooling case, and on the power grid (Di Silvestre et al., 2018 a). These technologies are indeed increasingly gaining attention for mediation of sustainable development (Bifulco et al., 2016; Bifulco et al., 2018; Lombardi et al., 2012; Barile et al., 2018) and support of distributed energy (Mengelkamp et al., 2018 a; Green and Newman, 2017; Caputo et al., 2018), such as through innovative energy management systems (Bifulco et al., 2018; Paredes-Sanchez et al., 2013). Digitalization at large involves the same enabling technologies as energy decentralization (Di Silvestre et al., 2018 a). This is linkable to the connectivity and communication required between distributed resources and demands (Di Silvestre et al., 2018 a). In this context, smart hardware and intelligent algorithms can support decentralization and new channels for value creation with distributed and renewable energy (Kloppenburg and Boeckelo, 2019).

Digitalization can be described in terms of "converting data into value for the power sector" (IRENA, 2019 a). This is growing in relevance, as connectivity, data collection, data analysis, communications and system control are vital in facing growing energy complexity (DOE, 2015). However, at present energy data and digital technologies are not fully taken advantage of. For example, only 10% of power distribution data is used for analytical purposes worldwide (IRENA, 2019 a). Essentially, energy data is of minor monetary or operational value because its scope and frequency are still limited (Valocchi et al., 2014). However, the quantity and quality of energy data is expected to grow exponentially with the expansion of smart grid infrastructure (Valocchi et al., 2014) electrical devices connected in IoT systems (IRENA, 2019 a), and other rapidly approaching advancements. Moving forward, foundational investments in data as well as data tools/platforms can enhance value creation and sustainability in the sector (Arent et al., 2017). This is important because there is a pressing need to ensure data input quality and effectively analyze this data in order to enable informed decision-making (Arent et al., 2017; Briggs et al., 2019). This background surfaces two key questions. What is the current state of energy digitalization? And how might future digital systems develop in the energy sector?

**Current state of energy digitalization**

There is a far-reaching consensus that smart grids are vital for energy decarbonization and decentralization (Eiid et al., 2017). Such systems can support renewable energy integration in power networks while maintaining efficiency and flexibility across the energy chain (ECRO, 2012). Before further discussing the smart grid, it would be important to define a smart technology per se, which can be based on its ability to utilize "sensors, databases, and wireless access to collaboratively sense, adapt, and provide for users within the environment" (Elwood, 2008). In the energy value chain, the adoption of smart technologies has at large centered on the smart grid.

There are several definitions of the smart grid, and it can be suggested that the concept is likely to continue evolving along with the rapid rate of digital technology development. A smart grid can be described it as an electricity network that supports bi-directional information, financial, and physical flows among interconnected consumers and producers (Eiid et al., 2017; Wee et al., 2012; Camarinha-Matos, 2016). Simply put, this is done by coupling the electricity network with an ICT network (ECRO, 2012; Caputo et al., 2018; Calvillo et al., 2016; Yarime and Karlsson, 2018; Basden and Cottrel, 2017; Wu and Tran, 2018). Smart meters are the basis of smart grid infrastructure, enabling real-time and remote readings as opposed to classic meter functionalities (ECRO, 2012).

Smart grids support the uptake of distributed and renewable energy, coordinate supplies and loads, as well as ensure secure and efficient generation, transmission, and distribution (Eiid et al., 2017; Cecati et al., 2011; Caputo et al., 2018; Lund et al., 2017; Mohammadi et al., 2018; Carvalho, 2012). It can therefore be suggested that the smart grid influences the energy value chain in its entirety. With a basis in smart meters and ICT, smart grids can operate in real-time, scheduling supplies and loads based on generation, market prices, contracts, and overall system requirements (Calvillo et al., 2016). Distributed energy resources can be balanced holistically (Park and Young, 2017), with excess generation stored or sold based on pre-established business models (Zhang et al., 2017 a).

Smart grid infrastructure can enable holistic management of energy flows by providing a platform for producers, consumers, distributers (Midtun and Piccini, 2017), and prosumers. Here platform refers to a common architecture for products or services, and rules such as protocols and pricing (Valocchi et al., 2014). This enables a standardized foundation for transactions among multiple, diverse participants, thereby stimulating competition and new value creation (Valocchi et al., 2014). Smart grid platforms can act as an interface between the grid and distributed energy resources, such as prosumer distributed generation, storage, DR, and EVs (Midtun and Piccini, 2017).

It can be suggested that smart grids can be utilized throughout the energy value chain. In this chain, electricity flows can be automated based on several parameters, such as market prices and contracts, by leveraging energy management systems (Cecati et al., 2011). With the smart grid in place, there are several such systems that can be built on top of its infrastructure in order to improve efficiency across the energy chain (ECRO, 2012). Distributed resource management systems (DERMS) as well as VPPs are examples that are being expanded worldwide (IRENA, 2019 a).

Energy management systems: DERMS and VPPs

DERMS are software platforms that coordinate operations of distributed energy resources on the distribution grid level (Next Kraftwerke, 2019). This is done by collecting information on demand and supply through smart meters, connected devices, and other grid distribution sensors in a smart grid (Enbala, 2018). For integration with the utility, a supervisory control and data acquisition (SCADA) system (or similar) is usually needed (Next Kraftwerke, 2019).

An additional and important example is the VPP, which involves the aggregation and interconnection of numerous distributed energy units within a large geographical area (Alanne and Saari, 2006; Cecati et al., 2011). While DERMS provides power control and grid services dependent on asset location, such as voltage management, VPPs provide such services irrespective of location, such as peak management or energy-trading (Next Kraftwerke, 2019). VPPs are reliant on software and smart grid infrastructure, to automatically dispatch and optimize distributed energy resources (IRENA, 2019 a; ECRO, 2012). Simply put, multiple resources are aggregated to operate as one larger (virtual) power plant. When aggregated, the units form a portfolio of generation which can facilitate a more stable power supply, which is at present preferable on power markets. VPPs allow small-scale distributed energy players to access electricity markets, based on this aggregation as well as bi-directional electricity and information flows (Alanne and Saari, 2006; Sprick et al., 2013; Cecati et al., 2011).

Both large companies, such as Siemens, General Electric, and ABB (John, 2017), and startups, such as VPP company Limejump (Foot, 2018) are leading innovation in VPPs, DERMS, and new smart energy systems. However, current systems are at large based on centralized management in virtual control centers where transactions are overseen (Alanne and Saari, 2006; Wu and Tran, 2018). In addition, profit distribution is not wholly transparent due to information asymmetries between prosumers and aggregators (Wu and Tran, 2018). With increasing distributed generation, it can be a suggested that a shift from centralized to distributed systems would benefit efficiency both of technical structures and energy markets. A distributed system can be defined as "a software system in which components located on networked computers (nodes) communicate and coordinate their actions by passing messages" (Vaos, 2016). Such systems can support communication protocols for distributed control and continuous response in future smart grids (Cao and Yang, 2013). This leads to the question: How may future energy digitalization develop?

**Future development pathways for energy digitalization**

With the rise in data and connectivity, the future of energy is likely to comprise of a "system of systems:" a heterogeneous network of smart, distributed, connected systems (Arent et al., 2017). Smart grid networks will increasingly be enabled by emerging digital technologies, such as AI and robotics, for grid automation and control (IRENA, 2019 a). In a survey of smart grid trends, Camarinha-Matos (2016) discussed IoT, sensor networks, big-data, AI, and cloud-computing as key technologies in future innovation. Strother and Lawrence (2016) discussed a future "energy cloud" paradigm in which devices are connected and managed across the electricity value chain, via smart sensors, ICT, machine-learning, and forthcoming 5G networks. It is clear that there is an increasing amount of technologies supporting energy system innovation. At large, end-to-end digitalization will considerably impact the energy value chain, for example due to automated analytical capabilities and enhanced flexibility (Booth et al., 216).

Kloppenburg and Boekelo (2019) discussed potential "platformization" of energy supplies and demands via digital exchange platforms. Platform energy markets, as already introduced in section 1.1.2, have been discussed by several authors in both academia (Parag, 2015; Weiller and Pollitt, 2016) and industry (Valocchi et al, 2014; Marubeni, 2019). Multi-sided smart grid platforms can incorporate consumers, prosumers, application developers, producers, service providers, and a multitude of other potential players (Valocchi et al., 2014). The rapid developments of digital technologies, such as AI and blockchain, can contribute to the advancement of such platforms (Kloppenburg and Boekelo, 2019). New business models will increasingly leverage the integration of digital and energy technologies, and companies will offer new energy services at this intersection (Camarina-Matos, 2016).

There is undoubtedly a large number and diversity of technologies that may contribute to digitalization in the energy sector. It can also be suggested that digitalization will occur based on a continuously growing toolbox of technologies that work in parallel, and that are selected based on multiple factors, such as local conditions and markets. Key examples of potential technologies in this toolbox that have gained attention in both academia and industry are introduced as follows.

Distributed computing for distributed energy systems: Blockchain potential

The Bitcoin cryptocurrency gained strong interest following its release in 2008 (Nakamoto, 2008), thereby also bringing attention to its underlying infrastructure: blockchain. Blockchain is a distributed ledger which enables transactions based on cryptography as opposed to a trusted intermediary, such as a financial institution. A block is essentially a time-stamped list of transactions and, as illustrated in Figure 7, each new block has an encryption or a hash value which is dependent on all previous blocks in the chain, thereby supporting traceability and security (Nakamoto, 2008).

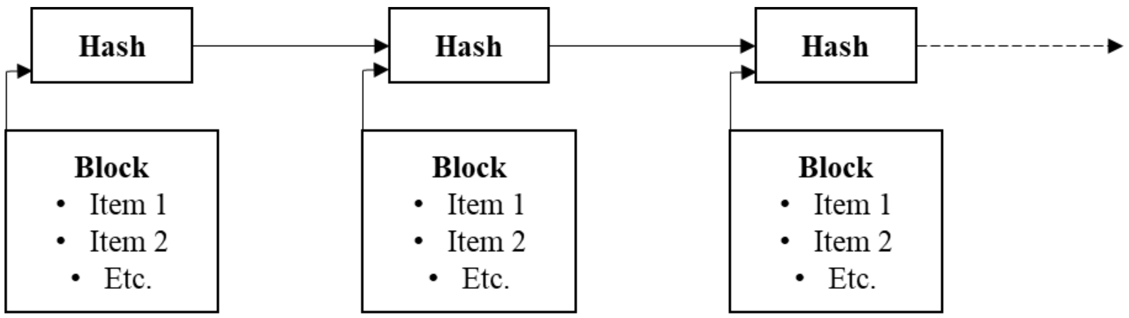


**Figure 7** Simplified overview of blockchain process (Based on Nakamoto, 2008).

In fact, attention is shifting from Bitcoin to blockchain (Buterin, 2014), including in the energy sector, due to its ability to support new business models on decentralized markets (Di Silvestre et al., 2018 a). Essentially, the technology can enable transparent, disintermediated, and distributed energy platforms (Cao, 2019; Wu and Tran, 2018; Casino et al., 2019). Blockchain can both contribute to existing systems, such as VPPs (Wu and Tran, 2018), and enable new pathways of energy exchange, such as P2P transactions among consumers, prosumers, and producers (Di Silvestre et al., 2018 b; Mengelkamp et al., 2018 a; Mengelkamp et al., 2018 b; Pop et al., 2018; Hirsch et al., 2018).

If the technology is expanded further in the energy sector, prosumers may conduct local P2P-trading within microgrids, alongside trading on the broader grid level via physical or virtual grid connections (Hwang et al., 2017; Mengelkamp et al., 2018 b). This potential development towards distributed P2P networks in microgrids is illustrated in Figure 8. It can be suggested that when applications are developed, blockchain platforms may enable open energy markets and support renewable energy uptake. It is a potential tool to create a distributed platform for energy flows that can maintain security, accountability, transparency, and efficiency in both electricity and financial transactions (Wu and Tran 2018).

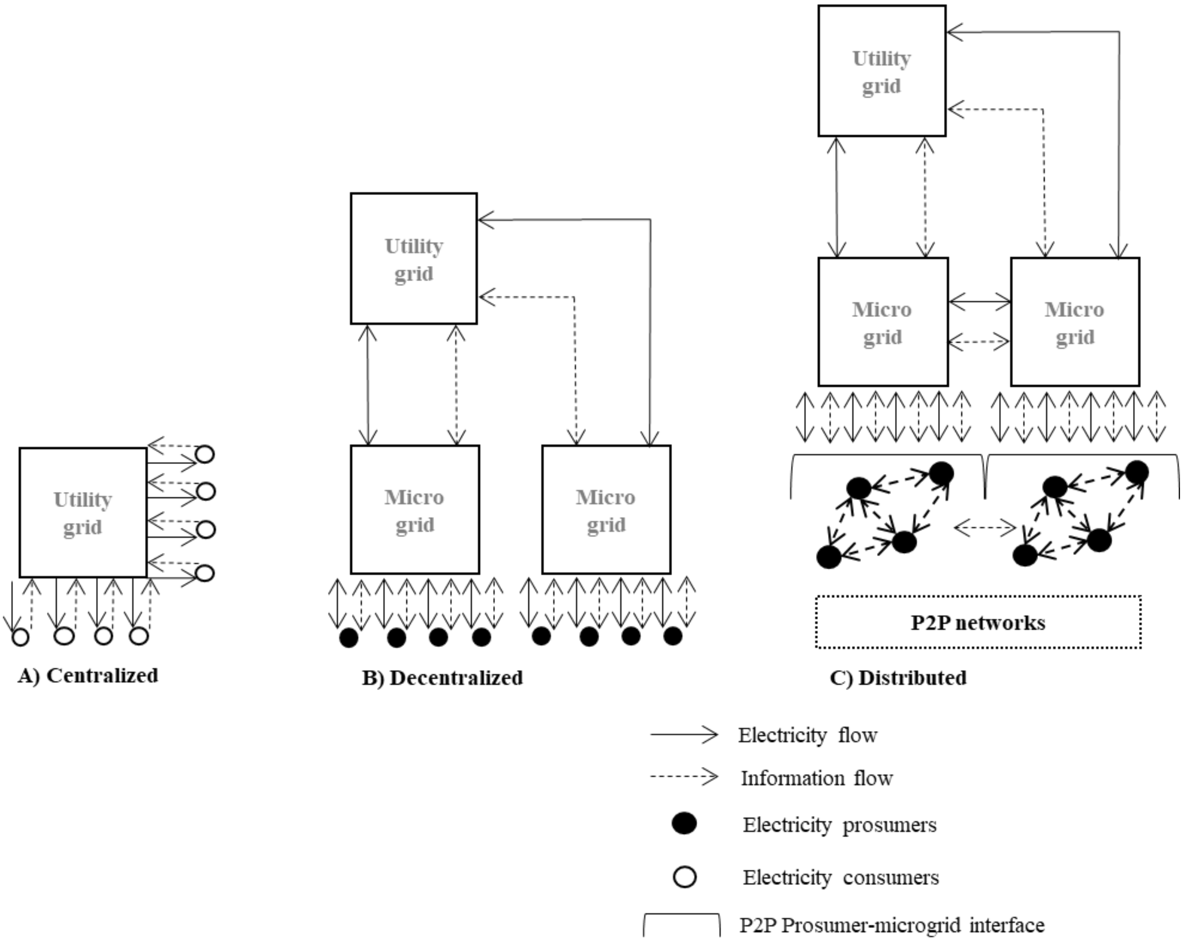


**Figure 8** Simplified overview of potential transition from A) Centralized, to B) Decentralized, to C) Distributed energy systems with microgrids and P2P networks (Ahl et al., 2019 a)

Blockchain technology's decentralized foundation lies in distributed computing. There are numerous advantages that can come with such decentralization, such as fault tolerance, attack resistance, price collusion evasion (Buterin, Unpublished results), transparency, security, and reduced transaction costs (Wu and Tran, 2018). Indeed, distributed computing may be an important element in increasingly networked and complex energy systems (Strother and Lawrence, 2016). With this increasing complexity, smart grid infrastructures would require development. Blockchain has been linked to the next generation of the smart grid, the "Energy Internet", by several authors (Park and Yong, 2017; Wu and Tran, 2018; Abe et al., 2019; Yang et al., 2017; Cao, 2019).

The Energy Internet takes advantage of digital technologies such as blockchain, big-data and cloud-computing, for multi-energy coupling and interconnection in smart grids (IRENA, 2018; Yang et al., 2017; Cao, 2019; Wu and Tran, 2018). Multi-energy coupling is related to the integrated coordination of electricity, transportation, thermal, and natural gas systems (Yang et al., 2017). The Energy Internet may facilitate trading among a diversity of distributed energy

resources (Hwang et al., 2017), such as EVs or power prosumers. One innovative example is V2G, which interlinks electricity and transport systems (IRENA, 2018; Andoni et al., 2019), as illustrated in Figure 8 and discussed earlier in section 1.2.2. The Energy Internet may contribute to a shared energy economy (Park and Yong, 2017; Potts et al., 2017) based on an open platform for the production, selling, and buying of energy (Hwang et al., 2017). Blockchain may be important in the infrastructure of such platforms, due to its ability to disintermediate and decentralize transactions in a secure manner. However, it can also be suggested that blockchain will not be a panacea, but interlaced with other digital technologies in distributed systems. It can be suggested that future smart grids, and the "Energy Internet," can be advanced via blockchain and other emerging digital technologies as exemplified in Figure 9, such as cognitive technologies and IoT.

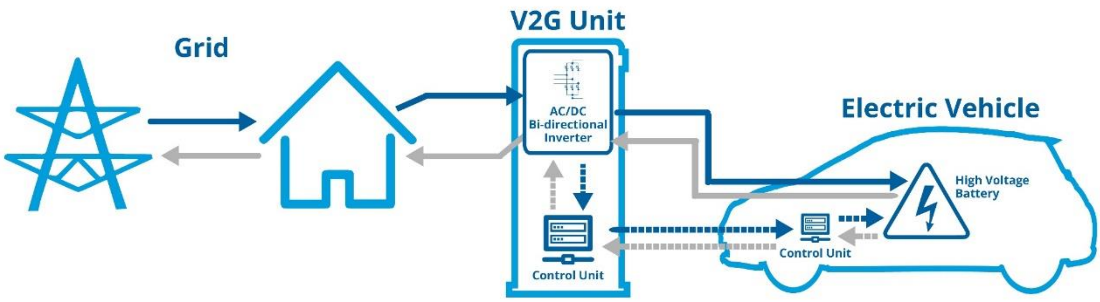


**Figure 9** Overview of potential Vehicle-to-Grid (V2G) setup (Fleetcarma, 2017)

IoT and the smart grid

An upsurge of distributed systems is especially important considering that billions of connected devices are expected on future IoT platforms, such as sensors, sub-meters, and communication gateways (Strother and Lawrence, 2016). As such devices increase, they would need to be coordinated accurately and at timescales of a second (or less). Worldwide, approximately 127 new devices are connected to the Internet each second (Patel et al., 2017). In fact, IRENA (2019 a) predicted 75 billion electrical devices to be connected in IoT systems by 2025, in turn indicating that a large number of IT companies are also likely to enter the energy sector.

The increase of connected devices is already being recognized as an opportunity among energy players. For example, in Japan large utilities are turning to IoT solutions to enhance power efficiency and reliability, analyze the grid on granular levels, and enable real-time or near real-time reactions (Storther and Lawrence, 2016). Utilities will need to operate grid networks with a rapidly increasing number of connected devices and distributed energy resources (Strother and Lawrence, 2016). How this will be managed may take several pathways. Two examples that be introduced at the intersection of IoT and energy are edge-computing and energy-harvesting.

Edge-computing involves computation closer to devices, for more frequent and efficient communication in IoT systems (Mocnej et al., 2018). This can provide several benefits, such as managing the energy consumption of IoT devices (Mocnej et al., 2018). Energy-harvesting involves the wireless capture and storage of energy from external sources for use in connected devices (Patel et al., 2017). This may be done, for example, through solar or wind power, as well as thermal or kinetic energy from a device's motion (Patel et al., 2017). Such processes can contribute to energy conservation under resource constraints of wireless devices in IoT-enabled smart grids (Ozger et al., 2018). IoT-related developments, such edge-computing, and energy-harvesting, may be especially relevant with the growth of the smart home market, driven by IoT and smart grid expansions. This market is expected to become more open and major worldwide, with players ranging from utilities to telecoms, retailers, and insurance companies (Munoz et al., 2016).

"Near future" digital technologies, shown in Figure 6, are already spreading rapidly in several sectors. There are also numerous potential pathways to leverage such technologies. However, their adoption is slower in more highly regulated energy sectors, in which they are only expected to begin to scale in at least five years (Briggs et al., 2019). In addition, several promising technical concepts are in theoretical or pilot stages, meaning that there is still a lacking understanding of economic, social, and institutional aspects. For example, the Energy Internet is mainly in theoretical development stages, with few systems running in practice (Wu and Tran, 2018).

Despite the many opportunities of digital technologies, their integration in the energy sector is certainly not without challenges. This is discussed further as follows.

**Challenges of digitalization in the energy sector**

The challenges of energy digitalization are multifaceted, calling for a holistic approach to tackling. It is suggested that challenges are in 1) technological as well as 2) economic, 3) social, and 4) institutional dimensions. *First*, while digital technologies have shown rapid advancements and significant impacts in society, they are not without technological challenges. Scalability in real-life applications is a key issue for new digital technologies, such as those exemplified in Figure 6 (Briggs et al., 2019). Scaling is also inhibited by challenges related to interoperability and integration of various applications and domains (Munoz et al., 2016). However, ongoing progress in digital gateways, integration layers and standardization is facilitating scalability (Briggs et al., 2019) and interoperability among services and applications (Munoz et al., 2016; WEForum, 2017).

*Secondly*, there is also a complicated interplay between technological challenges and economic dynamics (Midtun and Piccini, 2017). New digital technologies are continuously challenging conventional business models, including incumbent power utilities (Midtun and Piccini, 2017). In fact, the capacity to develop business models that can take advantage of rapidly advancing digital technologies is lacking in the energy sector (Arent et al., 2017). This means that there is a significant risk of value destruction, meaning failure to capture the value of distributed energy resources, thereby rendering them as stranded assets (WEForum, 2017). Therefore, the increasing intersection of the energy sector with the information-based digital economy is an important focal point for progress (Booth et al., 2016). Social as well as regulatory challenges are also central influences in business model innovation among energy players (WEForum, 2017).

*Thirdly*, the social dynamics of energy are being affected by decentralization and digitalization. While smart technologies benefit energy decentralization, the resulting transformation and increase of roles in the energy sector is both an opportunity and a challenge (Goldthau, 2014). It is suggested that this changing dynamic of roles and social structure is likely to take place on manifold fronts and in multiple scales along the energy value chain. On the one hand, industry structure and roles are expected to undergo modifications, such as changing utility, DSO and TSO activities (Eid et al., 2017). As illustrated in Figure 6, managerial foundations are important considerations in energy digitalization. On the utility side, digitalization calls for a shift in culture, organizational dynamics, and willingness to adopt new technologies and processes, such as automation (Briggs et al., 2019). This shift includes the development of new skills, knowledge, and approaches. There is a need of new skills for digital information-driven industry, and expanded knowledge on the network of new players, such as app developers (Valocchi et al., 2014). New approaches may include rapid innovation processes as opposed to the mid- to long-term business horizons of the present (Booth et al., 2016).

On the other hand, new players, from prosumers (Goldthau, 2014) to IT companies, are likely to rise. The shift of the energy sector to incorporate information-driven industry has led to a rise in new actors. Munoz et al. (2016) highlighted that incumbent utilities may either expand internal efforts to digitalize, or establish stronger external partnerships. Such external partnerships may include IT corporations, digital technology startups, and other players which can contribute to the knowledge, skills, and new approaches needed in energy digitalization. Based on these arguments, future utilities and energy companies are likely to increasingly comprise of digital business, through internal shifts, external partnerships, or a combination of both.

In addition to a rise in new companies, energy consumers and prosumers are likely to take an increasingly active role. It would be important to understand these new roles, the behavior of prosumers, and socioeconomic incentives that influence them. It can be suggested that new roles may be leveraged to contribute to energy sustainability from the bottom-up. In order to support bottom-up initiatives and coherent action in energy initiatives, Arent et al. (2017) discussed the potential to take advantage of social networks and communication technologies. This may be especially important in the event of energy platforms, as the success of platforms depend on network effects and reaching a critical mass of actors (Midtun and Piccini, 2017).

*Finally*, challenges of digitalization in the institutional landscape of energy are an essential discussion point. The scaling of technological innovation necessitates institutional change (Patwardan et al., 2012). Institutions can be defined as “systems of established and prevalent social rules that structure social interactions” (Hodgson, 2006). These may include language, laws, and regulations (Hodgson, 2006). While digital technologies are rapidly advancing, regulations to support their adoption and scalability are lagging behind (Arent et al., 2017; Munoz et al., 2016). This is especially pertinent in highly regulated energy sectors, in which institutions develop slowly and with little flexibility (Munoz et al., 2016). Generally, where regulations are less confining, the impacts of digitalization on energy systems can be greater (Di Silvestre et al., 2018 a). There is a need of clearer and more holistic energy policies (Eid et al., 2017) in order to ensure effectual outcomes in the long term. This is because energy innovation is part of a complex institutional picture, involving multi-stakeholder interactions and changing roles (Kuzemko et al., 2016).

There is a growing body of literature pertaining to the institutional aspect of energy innovation, and how energy decarbonization, decentralization and digitalization can be supported. For example, Midtun and Piccini (2017) discussed the need to develop competition policies by shifting from a focus on scale to a focus on energy network and platform regulation. Furthermore, WEForum (2017) discussed dynamic or time-of-use (ToU) price signals to stimulate competition and renewable energy on the market. It can be argued that there is a need for new economic signals, targeting both producers and consumers (Cecati et al., 2011). Coupled with market policies, balancing, storage, and grid policies would also require development, to support the integration of renewable energy and rise in prosumers (Midtun and Piccini (2017). In parallel, laws pertaining to the sharing of data among market players, as well as standards for smart devices, require improvement (WEForum, 2017).

Due to historical regulatory and market structure developments, the energy sector of today is stable, both in terms of technology and markets (Midtun and Piccini, 2017). As a result, it is suggested that introducing disruptive forms of innovation is a challenge. However, innovation processes are at large becoming more unpredictable and fast-paced, linked to entrepreneurialism, low-risk aversion and IT efficiency (Soete et al.,2010). Incumbent energy companies may be facing significant transformations, relatable to the leap from fixed to wireless internet networks in the telecom sector (Midtun and Piccini, 2017). Accordingly, innovation policy would be an important foundation in building a more iterative approach in energy innovation processes (Midtun and Piccini, 2017). This may, for example, involve the balancing of public and private sector interests (Midtun and Piccini, 2017), and investment incentives for renewable energy and smart grids (Eid et al., 2017).

Fundamentally, as underlined by Nam and Pardo (2011), digital and smart technologies can be drivers of sustainability and innovation when coupled with institutional change. As discussed earlier, it is also suggested that there is no panacea for energy digitalization, calling for a toolbox from which to select technologies based on social, economic and institutional backdrops. With this background, it can be suggested that the integration of digital technologies in the energy value chain offers several opportunities, as well as a raises a diversity of challenges. These opportunities and challenges are focal points in discussions on energy innovation in this thesis. The following section discusses the shortcomings and most interesting research gaps in the field of digital innovation across the energy value chain.

## 1.3 Research overview

### 1.3.1 Research gap

It can be suggested that digitalization will likely be a key competitive differentiator in the energy sector. This can be linked to the significant potential of digital technologies, such as blockchain and cognitive systems, to contribute to energy decarbonization and decentralization. However, cost-effective development of sustainable energy solutions remains far more complex in practice than in theory (Arent et al., 2017). Energy systems can be referred to as sociotechnical systems that involve complex social and institutional processes in addition to technological change (Bolton and Foxon, 2015, Kuzemko et al., 2016).

Sociotechnical shifts involve several interrelated factors, including skills, infrastructure, industry structure, products, regulatory frameworks, user preferences, and behavior (Schot and Steinmueller, 2018). Sustainable energy innovation indeed involves manifold dimensions of which governance through innovative government-society interactions is crucial (Kuzemko et al., 2016, Loorbach, 2010). Energy policies call for further incorporation of social, economic, and technical perspectives in order to more effectively integrate distributed energy resources and prosumers (Parag, 2015).

Despite the multifaceted nature of energy innovation, energy-related research has often focused on individual technologies and technical issues (Koirala et al., 2016). There is a need for further integration of socioeconomic, environmental, and institutional factors, in addition technological aspects (Koirala et al., 2016). Sociotechnical shifts, such as ongoing energy transitions, render new scope for academic research due to their multifaceted and complex nature (Bolton and Foxon, 2015). Such shifts involve transformative change, of which developments in innovation policy (Schot and Steinmueller, 2018) and transition management (Loorbach, 2010), are needed moving forward.

The approach taken in innovation policy development is important as it affects practices, conditions, and mindsets that influence innovation landscapes (Schot and Steinmueller, 2018). Such approaches have changed significantly over time, described by Schot and Steinmueller (2018) based on three frames:

1. **Government support for R&D** (1960s-1980s): governments increasingly funded inventions and scientific discovery to later be commercialized, in post-WWII directions

characterized by Taylorism (or Scientific Management) and Fordism. An example is the computer, originally used for defense and later commercialized.

2. **National innovation systems** (1980s-present): governments increasingly focused on knowledge creation, clusters, competitiveness, and entrepreneurialism in national ecosystems.
3. **Transformative change** (emerging): linked to current challenges, such as climate change, which call for multi-stakeholder involvement, interdisciplinary networks, and experimentation for system innovation to alter sociotechnical directions.

With the sociotechnical shifts underway today in the energy sector, there is a clear need for more holistic approaches to transformative change (Schot and Steinmueller, 2018), and transition management (Loorbach, 2010). A transition is a process of structural system change, such as in the energy system at large, as well as of sub-systems, such as specific energy resources (Loorbach, 2010). In transition management, governance relates to the practice of governments to support policy development based on multi-stakeholder involvement (Loorbach, 2010). A broad approach to governance, including multiple factors from regulation to behavior, is important in order to understand and incorporate changed practices among stakeholders (Kuzemko et al., 2016). Loorbach (2010) described transition management involving four key governance activities:

**1. Strategic:** vision and long-term goal creation for system.
**2. Tactical:** steering activities linked to sub-systems, such as regulations and infrastructure, based on multi-stakeholder interests.
**3. Operational:** short-term practices to establish new structures, routines, and players.
**4. Reflexive:** monitoring, assessments, and evaluation procedures.

It can be suggested that both short- and long-term strategies are needed in sustainable energy transitions, from strategic management to operational activities. Transitions take place in innovation systems that involve business, academia, government, and civil society (Loorbach, 2010, Schot and Steinmueller, 2018). The connections of these stakeholders across the process of invention-innovation-diffusion would be important in innovation policy (Schot and Steinmueller, 2018). While top-down planning and market dynamics is important, an inclusive process of learning and experimentation is needed as all stakeholders may influence change (Loorbach, 2010; Schot and Steinmueller, 2018).

For sociotechnical system change, policies and strategies for transformative innovation should be a priority (Schot and Steinmueller, 2018). It is suggested that this is lacking in the energy sector. For example, existing energy policies are largely focused on the supply side (Parag, 2015), lacking deliberation of the complete energy value chain. There is a need for more purposeful and comprehensive action, particularly in the public sector, to develop and deploy energy innovation backed by institutional arrangements (Arent et al., 2017). Digital strategies are also needed to a greater extent in energy-related policy (Arent et al., 2017). However, innovation policies are generally limited in scope with a need for more interdisciplinarity (Schot and Steinmueller, 2018).

A key question in energy research, which is clearly and broadly advocated by several authors, is how to mold holistic approaches to energy innovation, including technology, economic models, social networks, environmental impacts, and institutions (Araújo, 2014; Arent et al., 2017; Koirala et al., 2016, Loorbach, 2010, Parag, 2015). This is important as obstacles can include regulatory, economic, and social factors, technical infrastructure or specific technology lock-ins (Loorbach, 2010). In this thesis, it is suggested that key dimensions in energy innovation can be encapsulated as technological, economic, social, environmental, and institutional. It is further suggested that analysis pertaining to opportunities and challenges of digital innovation in the energy value chain would benefit from this multi-dimensional approach, as opposed to the wide-ranging technology focus adopted in the literature thus far. This is important because by discussing multiple dimensions, valuable insights on interrelatedness among them may be identifiable. It is suggested that with such insights, new lines for further research as well as practical implications for effectual energy innovation strategies may be formulated.

### 1.3.2 Research scope and motivation

The scope of this thesis centers on emerging transformative change in the energy sector, as described by Schot and Steinmueller (2018). Furthermore, focus is on strategic and tactical approaches to facilitating this change, as described by Loorbach (2010) in relation to transition management. For a basis in real-life cases and to substantiate concrete implications for digital innovation, this thesis is based on the context of Japan.

This thesis intends to explore the energy value chain, from upstream resources to downstream power-trading, and provide indications of how digital technologies may contribute therein in Japan. Focus is specifically on digital innovation for woody biomass and energy distribution, in order to provide foundations for discussion for the energy value chain. With regard to power distribution, a key emerging technology is blockchain. Woody biomass and blockchain-enabled distributed energy have both been gaining attention in Japan, presenting several opportunities as well as facing multiple challenges. This scope of this study is elaborated on as follows.

**Why Japan?**

Before elaborating on the current state and future of the Japanese energy market, it would be important to briefly discuss its history. A simplified timeline of the developments in Japan's electricity landscape can be seen in Figure 10. Prior to the year 1995 there was no power market competition in the country (Nakajima, 2016). In 1995, the Electric Utilities Industry Law was revised (TEPCO, 2019) to permit bidding and independent power producer (IPPs) participation in vertically integrated systems (Shinkawa, 2018). This means that companies could procure power from IPPs in addition to the incumbent utilities (TEPCO, 2019). The Electric Utilities Industry Law was thereafter gradually revised (TEPCO, 2019) for further liberalization of the power market reaching a proportion of (Nakajima, 2016; Shinkawa, 2018; TEPCO, 2019):

- **26% in 2000:** retail for high voltage (HV) customers over 2 MW,
- **40% in 2004**: adding retail for HV customers over 0.5 MW added,
- **62% in 2005**: adding retail for HV customers over 50 kW,
- **100% in 2016:** full power retail competition.

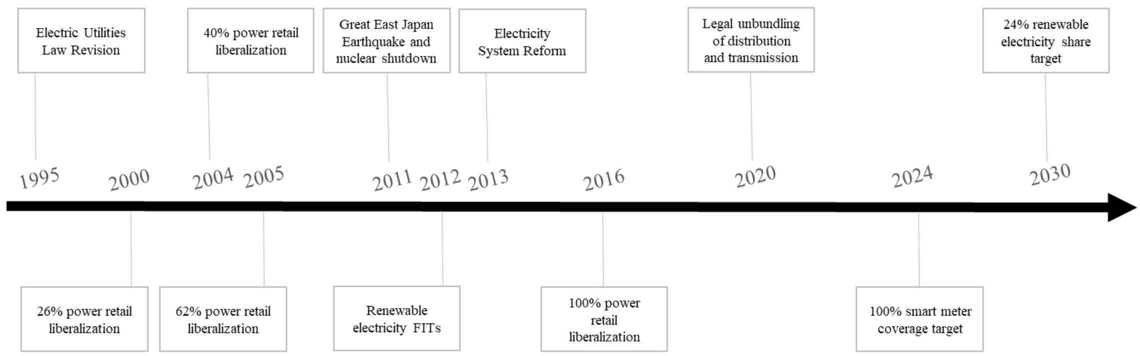


**Figure 10** Simplified timeline of power sector developments in Japan (Nakajima, 2016; Shinkawa, 2018; TEPCO, 2019; Toyoda, 2016; ISEP, 2019)

A key event in the history of Japan's energy sector is the 2011 Great East Japan Earthquake and Fukushima Daiichi nuclear power plant disaster, after which nuclear power was shut down and fossil fuel import dependence increased (Shinkawa, 2018). It can be suggested that as a result a shift in energy strategy focus towards self-sufficiency and domestic renewable energy took place in Japan, both in the private and public sectors. This can be seen for instance in the introduction of feed-in-tariffs (FITs) for renewable electricity in 2012 by METI (IEA, 2016; Shinkawa, 2018). The FIT scheme replaced the previous renewable portfolio standards and revised existing purchasing systems for solar power (IEA, 2016). Following the scheme's introduction, average annual renewable energy growth grew from 9% to 29%; mainly attributable to a sharp rise in solar power (Shinkawa, 2018). While power prices have indeed risen due to an increased fuel fee following the 2011 earthquake, surcharges for renewable energy are falling (Shinkawa, 2018).

Following the 2012 FIT introduction, in 2013 the Japanese Cabinet introduced an Electricity System Reform, focusing on 1) expanded wide-area power grids, 2) retail market and generation liberalization, and 3) legal unbundling of distribution and transmission (TEPCO, 2019). Following the full liberalization of power retail in 2016, a diversity of new players has entered the market (Toyoda, 2016). Examples include telecommunications and trading companies, such as Mitsubishi Corporation, KDDI, Marubeni, and Rakuten (Toyoda, 2016). However, there are still challenges in competition stimulation and power grid interconnection, with a national power system based on ten vertically integrated utilities and two frequencies (Shinkawa, 2018). Nesheiwat and Cross (2013) discussed incumbent mindsets and culture as obstacles of change in the Japanese energy sector. Cultural factors include reluctance to question authority, conformity, and consensus decision-making (Nesheiwat and Cross, 2013). This risks slow decision-making, risk aversion, and bureaucracy that in turn may inhibit innovation. However, efforts by incumbent utilities to innovate are indeed on the rise, seen in initiatives such as TEPCO Ventures focusing on partnering and co-creating with tech startups (TEPCO Ventures, 2020).

One of the main difficulties in renewable energy integration in Japan has been regulation as well as processes for regulation development that supports incumbent power companies. (Dong and Shimada, 2017). Wüstenhagen et al. (2007) noted that a resistance to effective support systems for renewable energy in turn indicates lacking socio-political acceptance and "trust" in related investments. It can be suggested that energy market and institutional development is needed to further support increases in distributed, renewable energy. Currently, the Japan Electric Power Exchange (JEPX) has forward, day-ahead, intra-day, and balancing markets, with ongoing discussions to establish baseload, capacity, and non-fossil value trading markets (Shinkawa, 2018). This indicates potential opportunities for increased market participation moving forward. In 2020, regulated retail tariffs will be stopped and the legal unbundling of power transmission and distribution will take place (Nakajima, 2016; Toyoda, 2016). This may further contribute to increased competition and transform the Japanese energy landscape. As highlighted by Markard and Truffer (2006), market liberalization certainly tends to accelerate innovation and development. This may also be the case for the Japanese energy sector.

In its 2019 Energy White Paper, the Ministry of Economy, Trade and Industry (METI) emphasized 1) renewable energy, 2) business operations, and 3) power networks (METI, 2019 a) for the future. In terms of renewable energy, cost reduction and FIT independence was highlighted, such as via revised auction scopes to support smaller-scaled power generators (METI, 2019 a). In terms of power networks, METI (2019) expressed aims to support distributed renewables via grid developments, such as lower grid costs and consignment fees. In addition, the government maintains 100% smart meter coverage targets in the country by 2024, and in Tokyo already by 2020 (Nakajima, 2016). Coverage reached 35.3% nationwide and 39.3% in Tokyo in 2017 (Shinkawa, 2018). Improved smart meter infrastructure may transform the power network and enable several new services, such as home energy management systems (Nakajima, 2016).

It can be suggested that the Japanese energy sector is developing on multiple fronts, from renewable energy to power network advancements. This is an important issue because the nation is the globe's third largest economy (WEForum, 2018) and second largest power market among OECD countries (Plessis, 2015). However, Japan is also among the largest importers of fossil fuels, lacking conventional energy resources domestically. Japan is even facing pressure internationally for its continued investments in fossil fuels, such as coal-fired power, as well as carbon emission reductions goals that fall short of other developed countries (Mainichi, 2019). Part of the reason behind this is strong opposition in the country from industry circles (Mainichi, 2019), emphasizing once again the influence of large corporations and incumbent companies in Japan's energy sector. This situation could render a policy impasse in terms of energy and economic progress (Portugal-Pereira and Esteban, 2014).

Despite difficulties, the public and private sectors in Japan are indeed showing growing emphasis on energy innovation and sustainable development. There are ongoing institutional, social, and market changes with potential to contribute to sustainable energy if effectively coupled with technological innovation. With this background, it is suggested that the energy value chain in Japan is of interest for exploration in this thesis. The country is especially relevant for this thesis due to strong emphasis in the government and the Japan Smart Community Alliance (JSCA) on digital innovation to support renewable energy and distributed energy systems (JSCA, 2015).

**Why woody biomass?**

Approximately 70% of Japan's land area consists of forest (World Bank, 2015) and the highest FIT is for electricity generated with forest-based woody biomass. From 2015 and also following the FIT review of 2017, woody biomass was granted a FIT of 40 yen/kWh for power plants under

2 MW, and 32 yen/kWh for those at 2 MW or over (METI, 2017 a). This led to an increase in woody biomass power plant development. Currently renewable energy comprises approximately 17.4% of Japan's power mix, shown in Figure 11, with a target to reach 24% by 2030 (ISEP, 2019). The share of biomass is at approximately 2.2% (ISEP, 2019). Nevertheless, the current share and future targets are relatively low, for example as compared to renewable energy targets of 100% in Spain and Denmark (ISEP, 2019). METI (2019) stated that while Japan shows strengths on the demand side, such as household energy efficiency, there is a significant need for improvements on the supply side, such as the expansion of low-carbon resources. It is suggested that woody biomass may be an important driver in increasing the nation's renewable energy share.

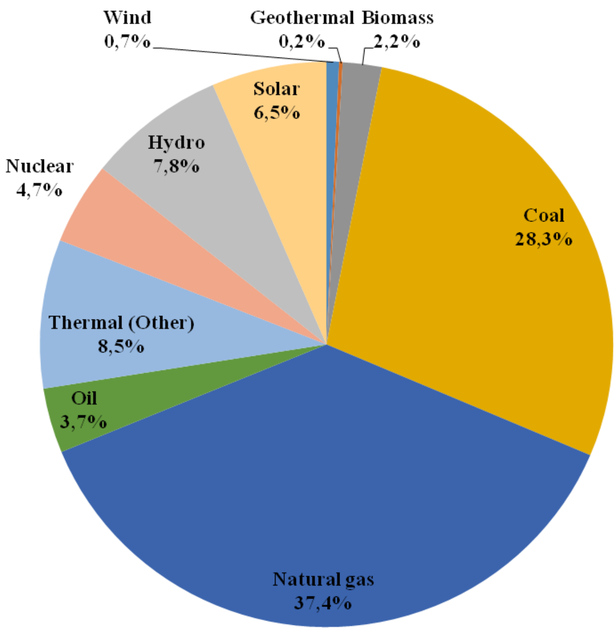


**Figure 11** Japan power mix in 2018 (ISEP, 2019)

The promotion of woody biomass for energy purposes in Japan is largely driven by METI, and by the FITs. The FITs focus on stimulating biomass-based power production, as opposed to productivity and stable supplies across the entire woody biomass supply chain. Considering the importance of sustainable and productive forestry in the bioenergy supply chain, METI, the Ministry of Agriculture, Forestry and Fisheries (MAFF), as well as the Ministry of Environment (MoE) would need to work in closer coordination (Aikawa, 2018). Other nations have taken different approaches in bioenergy promotion. For example, the introduction of the carbon tax by the Swedish parliament in 1990 has been the key driver of woody biomass because it enabled competitiveness with fossil fuels (IRENA, 2019 b). This was coupled with effective forest governance on the national level, alongside municipal governments receiving support in the form of grants, investment, and assistance in local energy planning (IRENA, 2019 b). This means that the Swedish Energy Agency as well as Forest Agency and Environmental Protection Agency are all actively involved in bioenergy development, decision-making, and regulation (IRENA, 2019 b). At present, bioenergy accounts for one third of Sweden's energy needs, including both power and heat (IRENA, 2019 b).

While there are incentives and policies promoting woody biomass, there have been multifaceted challenges across the supply chain in Japan (Ahl et al., 2018). There is a large body of research that explores individual technologies and elements in the supply chain, such as upstream sustainable forest management in Japan (Faburoso et al., 2014) and downstream biomass boiler technologies (Verma, 2014). However, despite the availability of research, technological development, and incentives in Japan, higher levels of woody biomass are yet to be reached. Supply chain innovation is vital, because woody biomass energy is dependent on logistics and stable flows from the upstream to downstream chain (Aguilar, 2014; Keefe et al., 2014). Most research of bioenergy systems has indeed been concentrated on single sections in the supply chain, rather than adopting a holistic approach (BR&D, 2014). This thesis contributes to filling this gap by exploring sociotechnical challenges and opportunities across the woody biomass supply chain and stakeholder management therein.

Stakeholder management is complex and central in woody biomass supply chains (Whalley et al., 2017; Welfe et al., 2014). Digital technologies are increasingly used in managing flows and complexity in supply chains. Such technologies can act as mediators in sustainability strategies (Caputo et al., 2018), including in the context of supply chain management (Kache and Seuring, 2017). Data and knowledge flows are growing, and reshaping socioeconomic interactions in new "sociotechnical configurations" (Del Giudice et al. 2016). Technologies, such as cloud computing, and resultant applications are valuable in supply chains, for knowledge-sharing, buyer-supplier relations, and market platforms (Scuotto et al., 2017). ICT is supporting a shift from linear to networked supply chains (Kache and Suring, 2017), that take advantage of real-time data to link stakeholders and coordinate resources (Bifulco et al., 2016).

There is abundant literature on digital technologies and on woody biomass, but a lack of research combining the two perspectives. This thesis contributes to filling this gap. It is of interest to understand how digital technologies can be leveraged for more sustainable, renewable energy value chains in Japan. It is suggested woody biomass value chains can be supported via digitalization, which in turn may contribute to the overall renewable share in Japan's energy mix. This is investigated via case studies, exploring potential strategic and tactical approaches to enabling woody biomass via digital innovation. The focus here is on woody biomass resource supply systems, energy generation and trading.

**Why blockchain?**

In addition, electricity generation and supply systems will be increasingly distributed with higher shares of renewable energy, in Japan and worldwide. It would be essential to manage increasing levels of complexity in distributed energy systems in multiple dimensions, from technical infrastructure to economic models. For example, FITs can support low-risk developments of renewable energy such as woody biomass, followed by further incorporation in liberalized markets (Couture and Gagnon, 2010). However, even in liberalized markets, small-scale trading is restrained due to regulatory requirements and transaction costs (Cao, 2019; Morstyn et al., 2018). For example, while Holland's energy market was liberalized in 1998 (Fraser et al., 1998), license requirements are still a barrier for small-scale prosumers to participate actively (Butenko, 2016). In Japan, following power retail liberalization of 2017, 9% of the market comprised of new entrants (Asano, 2017), with large incumbents dominating the JEPX (Maekawa et al., 2018).

An increase in new entrants, renewable shares, and resource transparency is needed (Maekawa et al., 2018). Wee et al. (2012) similarly discussed deficient transparency of renewable energy and trading data as a market barrier. METI (2019) has indeed discussed the incentivization and market integration of individual renewable power supplies. In addition, the government has drawn attention to reducing location and grid constraints for renewable energy distribution (METI, 2019 a). It is suggested that digital platforms may be of interest for transparency, security, reduced transaction costs, and further integration of distributed energy in Japan. It is further proposed that such platforms may be more effectual in practice if holistic strategic and tactical approaches are taken, also incorporating economic, social, and institutional factors.

An emerging technology being discussed both in industry and academia with potential for such platforms is blockchain. The technology is already gaining traction for adoption in energy-trading platforms by Japanese companies such as Marubeni in collaboration with LO3 Energy (LO3 energy, 2019), and Rakuten (Rakuten, 2017). There is clear interest in both the public and private sectors in the potential of digital energy platforms, and increasing research on technical aspects of energy blockchain applications. The technology may have potential to support sustainable energy transitions. However, blockchain still faces multidimensional barriers in the energy sector, such as regulatory issues (Andoni et al., 2019; Saberi et al., 2018 a). These barriers are yet to be integratedly addressed and need to further researched, alongside any impacts on sustainable development that blockchain may incur (Li et al., 2019; Kouhizadeh and Sarkis, 2018).

There are a few valuable examples of research with more holistic approaches. For instance, Wu and Tran (2018) discussed the applications of blockchain in sustainable energy systems, and identified regulation and technical bottlenecks such as data storage, cybersecurity, and skill shortages, as key challenges. It is suggested that in addition to technical and regulatory factors, social, economic, and environmental issues would also be important. There is a lack of holistic conceptualization of blockchain-based energy distribution (Noor et al., 2018). With this background, the second key focus of this thesis is the potential of blockchain for distributed energy platforms. The thesis contributes by adopting a holistic approach in analyses of opportunities and challenges of blockchain in the energy sector, exemplified based on the Japanese context. Strategic and tactical approaches to supporting blockchain applications for energy trading and distribution are to be suggested.

### 1.3.3 Aim & Objectives

There are several synergies between the development of digital technologies and sustainable energy value chains, which lay at the intersection if distributed systems and renewable energy. With this background, this thesis explores synergies between digital technology and sustainable energy value chains in Japan, with a focus on renewable energy exemplified by woody biomass, and distributed systems based on blockchain. The overall goal is to develop a holistic framework for the assessment of potential digital technology applications in the renewable energy value chain, which may then be further built upon in academia as well as by industry and government. By investigating woody biomass and blockchain-based distributed energy systems, the thesis is meant to investigate aspects from the full value chain in Japan, from energy source to energy conversion to power-trading.

With this background, **the major research question** (RQ) of this thesis is:

1. *How can digitalization in the energy value chain facilitate renewable, distributed energy in Japan?*

This question is addressed via two sub-RQs:

1 *A. How can digital technologies facilitate woody biomass energy in Japan?*

1\. *B. How can blockchain technology facilitate distributed energy systems in Japan?*

In line with the RQ, the **main objective** of this thesis is *to create a framework for the assessment of digital technology applications in the energy value chain in Japan.*

This objective is addressed through **five sub-objectives**. These sub-objectives and their relations to the RQ or sub-RQs are noted as follows:

1. [Related to RQ] To describe the current status and future prospects of digitalization in the energy value chain.
2. [Related to RQ 1A] To identify key challenges in the woody biomass supply chain in Japan.
3. [Related to RQ 1A] To analyze how digital technologies can be used to overcome challenges in the woody biomass supply chain in Japan.
4. [Related to RQ 1B] To describe the opportunities and challenges of blockchain-based electricity systems.
5. [Related to RQ 1B] To analyze the opportunities and challenges of blockchain-based electricity distribution in Japan.

### 1.3.4 Research contribution

This thesis aims to indicate pathways for digital innovation in the energy value chain in Japan. On the one hand, this is limited to case study findings in the Japanese context, questioning research generalizability. This is important, as opportunities and challenges of woody biomass and blockchain will vary in different countries and even regions. At large, there is no panacea for sustainable energy (Brewer II et al., 2018; Arasto et al., 2017). It can be suggested that a toolbox of technologies and framework based on local social, economic, and institutional conditions would be important. On the other hand, it proposed that the findings and implications identified in this thesis can be valuable in exploring initial pathways in a framework for digital technologies based on concrete sociotechnical challenges, exemplified based on cases in Japan. The thesis aims to present exploratory evidence on such pathways, which may then be of interest for further studies.

There have been several studies on energy decision-making frameworks, mainly incorporating technological, social, environmental, and economic criteria (Pohekar and Ramachandran, 2004; Ozorhon et al., 2018; Afgan and Carvalho, 2002), but often without a clear incorporation of institutions. A few include this to an extent, such as the multi-tier decentralized renewable energy evaluation by Katre and Tozzi (2018), which also integrated factors of governance and community involvement. However, there is as of yet a lack of research on holistic frameworks for energy strategies, and especially on those that also incorporate digital innovation. It is suggested that this is an important line of research moving forward due to the rising significance of energy digitalization.

This thesis aims to further incorporate the multi-dimensionality of energy value chains in a holistic framework focusing on digital innovation. This would be valuable in exploring how technological innovation can be developed towards institutional readiness, by also integrating economic, social and environmental dimensions. Each dimension as well as their inter-relatedness is needed in such analyses and in institutional development. This comprehensive overview is important, because there lies value in non-numerical information found in the relations among factors in energy system assessments (Afgan and Carvalho, 2002). While there is an abundance of research focusing on specific dimensions, such as economic models or energy technologies, this thesis contributes by taking a multi-dimensional approach.

With this approach throughout the thesis, contributions can be summarized as three-fold. First, the gap between digital technology and woody biomass research is addressed and strategic implications proposed. Second, a holistic conceptualization and analysis of the opportunities and challenges of blockchain energy-trading is carried out. Third, based on findings across the upstream to downstream energy value chain, a framework for digital innovation is proposed. Most previous research has centralized on siloed issues, such as on energy-trading or on specific generation technologies. This thesis contributes by attempting to reduce these silos by adopting a holistic approach to energy innovation, for a more practical overview of real-life development.

With a basis in academic research as well as an understanding of modern-day business developments, the thesis aims to maintain a foundation in real-world problems (and opportunities). The research in this thesis maintains a foundation in robust reviews of academic and non-academic literature, such as white papers and press releases, as well as in interviews with practitioners and academics. Thereby, the foundation upon which implications for digital innovation in the renewable energy value chain are created includes important insights and issues experienced among practitioners. This is important because practitioner and expert interviews are valuable for collecting data and understanding relatively unexplored areas (Bogner et al., 2009), such as blockchain energy applications and digitalization in the woody biomass supply chain. In qualitative research, the sufficiency of the number of interviews hinges on the research purpose, such as investigating convergences and/or contrasts (Baker and Edwards, 2012). It is suggested that the research foundation and number of interviews in this thesis contributes to the identification of initial practical implications for digital innovation in the energy sector. By unraveling the process of energy innovation in its multiple dimensions, it is suggested that the findings of this thesis may have important implications for government, businesses, as well as academia. Implications may be useful for policies designed for transformative energy innovation, improved energy business strategies, and for sculpting future research directions at the intersection of digital innovation and energy.

### 1.3.5 Thesis outline

**Chapter 1**, related to objective 1, provided an overview of energy and digital innovation developments, as a basis to identify key research gaps and formulate the aim of this thesis. In chapter 1, macro-trends and developments in energy innovation agendas were discussed. These developments were summarized as decarbonization, decentralization, and digitalization. The emergence of digital technologies and multifaceted implications for energy was elaborated on further. While digital innovation was identified as a key competitive differentiator in the energy value chain, it was also recognized that it faces several challenges.

Upon identifying a need for a more holistic approach to digital innovation in the energy value chain, the thesis aims to develop a multidimensional framework to contribute to lessening this gap. As illustrated in Figure 12, addressing the objectives of this thesis is rooted with a strong foundation in literature as well as concrete cases exemplified in Japan, seen in chapters 2 and 3. Based on this foundation, in chapter 4 the overall findings are discussed and the framework is developed, followed by key conclusions and implications for future work.

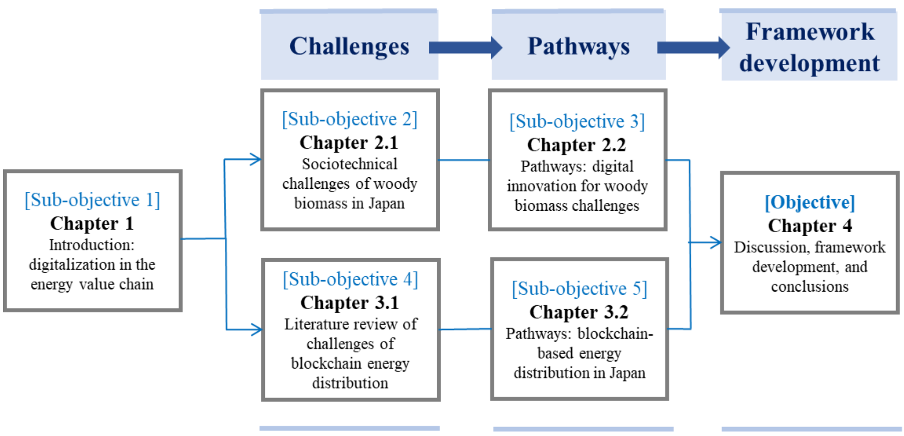


**Figure 12** Thesis outline

**In chapter 2**, objectives 2 and 3 are addressed. The sociotechnical challenges of the woody biomass supply chain in Japan are explored via case analysis and interviews with supply chain stakeholders. Based on identified challenges, opportunities for digital technologies to facilitate overcoming them are thereafter explored. This is done via interviews with biomass and digital technology experts. At large, chapter 2 aims to explore opportunities for digital innovation across the woody biomass value chain in Japan, from upstream forest management to downstream power-trading.

**In chapter 3**, objectives 4 and 5 are addressed. A comprehensive literature review on blockchain energy applications is carried out, focusing more specifically P2P distributed power-trading. Review findings are summarized in the form of an analytical framework for case studies on P2P blockchain-based electricity microgrids. This framework is used to analyze a P2P microgrid case in Japan. This is concluded with concrete indications on opportunities and challenges for blockchain-based distributed energy in the country. At large, chapter 3 aims to provide concrete, multidimensional implications for blockchain-based distributed systems in the Japanese energy sector. Chapter 2 and 3 integrate various research perspectives, combining comprehensive reviews and qualitative data discussed with a basis in both academic and grey literature.

**Chapter 4** directly addresses the main objective of this thesis by assimilating findings in a comprehensive discussion. Key indications are used to form and suggest a framework for digital innovation in the energy value chain. How these findings can relate to previous research as well as how they differ is discussed. Finally, potential pathways for future research and development in academia, as well as in industry and government are suggested. Chapter 4 ends with a conclusion based on an overview of 1) main findings, 2) how the research aims have been met and research gap lessened, 3) major contributions and implications for society, and 4) potential future directions for academia, industry, and government. At large, this thesis provides novel insights into digital innovation in the energy value chain by integrating various dimensions and combining theoretical and field studies. In doing so, the goal is to contribute to accelerated energy innovation and sustainable development in Japan, and worldwide.

# Chapter 2. How can digital technologies facilitate woody biomass energy in Japan?

In 2017 bioenergy accounted for approximately half of all renewable energy worldwide (IEA, 2018 c). This bioenergy was mainly utilized for heating, followed by transportation and electricity (IEA, 2018 c). Dispatchable bioenergy has gained attention, with an ability to contribute to energy security, economic efficiency, and energy diversification (IEA, 2018 a; Arasto et al., 2017; Jiang et al., 2017; Chuahan, 2014). Against the backdrop of rising intermittent renewable shares, such as solar and wind power, bioenergy can be valuable for grid-balancing, frequency control, back-up capacities, and other mechanisms that support energy system stability (Arasto et al., 2017).

Japan has the fifth largest biomass market potential (Plessis, 2015), but policy goals are low in contrast, with a 2030 biomass power share target of 3.7-4.6% (Kimura and Ninomiya, 2017). In Japan's biomass agenda, the government has also promoted local revitalization in aging rural societies (METI, 2014). In its 2006 Biomass Nippon Strategy, the government planned 300 Biomass Towns with domestic biomass projects for 2010 (Pambudi et al., 2018). Biomass Towns are defined as areas "…where a comprehensive biomass utilization system is established and operated through the cooperation of various stakeholders…" (MAFF, 2018). However, these initiatives have faced an array of challenges. Yoshida et al. (2014) discussed rural infrastructure and forest road networks as key issues in Biomass Town development.

The incorporation of woody biomass is low in Japan, despite public promotion and high FITs (IEEJ, 2014). These FITs were created based on potential power plant costs and revenue streams (Izumi et al., Personal communication). With a focus on incentives pertaining to power systems, the use of biomass heat in more efficient combined heat and power (CHP) systems has not expanded (Aikawa, 2018). It is suggested that emphasis mainly on renewable electricity, the downstream woody biomass supply chain, can cause imbalance across the chain. While bioenergy has potential to reduce lifecycle GHG emissions in energy systems, it requires sustainability frameworks focusing on environmental as well as social and economic aspects across the supply chain (IEA, 2018 c). In this picture, an understanding of upstream forestry and feedstock supply management is vital.

Expansive forests were planted in Japan after WWII, which thereafter led to the current abundance of mature trees and unmanaged forest areas (Yanagida, 2015). There are large amounts of unutilized forest biomass, with annual residues reaching up to 20 million $m^3$ (Yanagida, 2015).

This indicates a need for improved forestry for domestic woody biomass development. With low Japanese forestry productivity, feedstock accounts for approximately 77% of woody biomass electricity generation costs (Yanagida, 2015). There has been interest in the high FITs for electricity produced with biomass from domestic forest thinnings. However, difficulties in domestic feedstock supplies have affected the supply chains of several FIT-registered power plants. In 2015 the FIT-certified capacity of biomass was 2.7 GW, but the running capacity was 0.344 GW (Kuboyama and Yanagida, Personal communication).

Woody biomass development has faced inconsistencies between policy and infrastructure development in Japan (Pambudi et al., 2017). For example, an important reason why the FIT scheme has not been more successful in supporting woody biomass is the lack of an integrated policy for biomass heat use in Japan, such as district heating (Aikawa, 2018). Moreover, due to low forest productivity, domestic wood shares fell from 70% in 1964 to 20% in 2000, as supplies and prices could not maintain competitiveness with foreign wood imports (Fujiwara, 2003). Despite Japan's FITs and abundance of forest (MAFF, 2016), biomass plants have mainly utilized imported feedstock (Obayashi, 2017). In 2016 the FIT-certified capacity rose to 3.76 GW, of which 0.436 GW accounted for domestic woody biomass and 3.32 GW for "ordinary wood," a category that also allows for imported feedstock (Takanobu, 2016). The share of wood imports is expected to rise further (Kimura and Ninomiya, 2017).

Despite a seemingly favorable policy landscape and abundance of forest in Japan, there are challenges of domestic woody biomass energy systems that call for further exploration. At large, the gaps between certified and running capacity as well as feedstock costs and supply difficulties indicate an imbalance between woody biomass supplies and demands in the country. This suggests a need to develop a holistic understanding of challenges across the woody biomass supply chain.

The woody biomass supply chain is complex, involving a diversity of stakeholders and business models (Whalley et al., 2017; Welfe et al., 2014). In the upstream, forest and agriculture management as well as sustainability compliance affect capacities to maintain stable biomass supplies (Gold and Seuring, 2011). Moving downstream, biomass will be used in various business models with diverse feedstock quality needs and processes. This leads to complexity in the management of woody biomass supply chains, in terms of material flows as well as environmental and socioeconomic impacts (Soares et al., 2018). However, it is suggested that a diversity of stakeholders and potential business models in the supply chain can be leveraged for innovation.

It is further suggested that a multi-stakeholder approach would be beneficial in identifying challenges and opportunities for innovation as perceived by the range of supply chain players. With this, the objective of section 2.1 is to identify key challenges in the domestic woody biomass supply chain in Japan. These challenges are investigated based on interviews with stakeholders from organizations active across the supply chain.

The complex and multi-faceted nature of woody biomass supply chain management suggests a need for newfangled, innovative strategies. It is proposed that digital technologies can be valuable in such strategies. With this background, section 2.2 explores the gap between digital technology and bioenergy literature, and presents initial theoretical assumptions of pathways through which such technologies can contribute to regional woody biomass in Japan. The objective of section 2.2 is to analyze how digital technologies can be used to overcome challenges in the woody biomass supply chain in Japan. Based on an exploratory research approach, this is exemplified by referring to woody biomass and challenges in Japan, as identified in section 2.1. This analysis aims to support both academics and practitioners by indicating new approaches for digital innovation in woody biomass supply chains.

## 2.1 Sociotechnical challenges of woody biomass in Japan

Emissions reduction and local economic growth can be strengthened with bioenergy systems (Suntana et al., 2012; DeWit, 2015). At the same time, innovation is vital for growth and competitiveness (Weiss et al., 2011). It is suggested that innovation in regional woody biomass supply chains can benefit strategies for local economic growth in Japan, if integrated with domestic supplies and demands. Local integration of biomass systems is indeed crucial for balance between biomass demands and supplies (Hisashi et al., Personal communication). Woody biomass value chains have several potential pathways, from construction timber to renewable energy purposes. It is suggested that this creates innovation capacities and new business model opportunities.

On the one hand, biomass systems can increase local competitiveness and support new business prospects, such as for biofuel production (Yagi and Nakata, 2011). On the other hand, it is also suggested that innovation of woody biomass can contribute to the tackling of broader national issues, such as aging societies and climate change. Woody biomass systems can lead to several benefits besides economic growth, such as emissions reduction and energy security (Kishita et al., 2017). Malico et al. (2016) highlighted potential social benefits of forest ecosystem management, including socioeconomic progress, reduced forest fire risks, biodiversity preservation, and biomass for local heating/electricity security. Effective ecosystem management is needed to sustainably obtain such benefits. Leban et al. (2016) emphasized forest multi-functionality in modern forest management, meaning an integrative approach based on which woody biomass is a by-product of other forest products and services.

This suggests that environmental and socioeconomic sustainability calls for holistic woody biomass supply chain management. Furthermore, this suggests that value creation can be expanded through the production of diverse forest products and services. In the downstream woody biomass supply chain, such value can be in electricity and heating services. In Japan's 4th Strategic Energy Plan, emphasis is placed on both biomass electricity and heat utilization based on economic efficiency and regional integration (METI, 2014). This may be a measure to revitalize local communities and enable sustainable development therein. While renewable heating is mentioned in this agenda, it receives no financial incentives in Japan (METI, 2014). For small-scale energy systems, CHP setups are important as they can support higher system efficiencies of 80-90% (CHP) in contrast to 40% (power only) (Beith, 2011). Integration with local heat demands and heat distribution networks are key success factors for biomass heat utilization (Hisashi et al., Personal communication). Such distribution networks, such as district heating, have limited development in Japan thus far (Takanobu, 2016). Overall, it can be suggested that there is a series of challenges across the woody biomass supply chain, and in connecting downstream and upstream players.

### 2.1.1 Innovation across the woody biomass supply chain

There are several challenges unique to Japanese forestry, such as mountainous terrain, fragmented forest ownership, and ineffective forest documentation (Gain and Watanabe, 2014). This has amplified forest management and productivity issues (Gain and Watanabe, 2014), damaging the cost competitiveness of Japanese forest products as compared to imports (Ooba et al., 2015). Financial difficulties in managing and maintaining forests have led to their degradation in Japan (Nakano et al., 2015). Low domestic woody biomass utilization rates may also be due to irregular biomass quality in local supply chains, indicating a need for more effective supply chain management (Ooba et al., 2015). It is suggested that a focus on imports augments shortcomings in domestic forestry and biomass supply chains. This advocates a need for improved management and development processes across the woody biomass supply chain in Japan.

The woody biomass supply chain is rooted in a diverse, cross-sectoral stakeholder network. While this diversity can catalyze innovation, its complexity can lead to challenges. It is of interest to investigate such possible challenges further. Woody biomass energy is dependent on logistics, especially when considering high harvesting, collection, processing, storage and transport costs (Keefe et al., 2014). Supply chain design as well as forestry skills are important for woody biomass success (Aguilar, 2014). de la Fuente et al. (2017) further highlighted the importance of supply chain design by discussing how shifting the processing of forest biomass upstream can support emissions reduction and productivity. For example, removing stem residue (tops, branches and non-merchantable logs) earlier on in the supply chain may enable more effective separation from merchantable stems used for downstream timber and pulp production. This suggests that with improved supply chain planning and management, higher quantities of woody biomass could be obtained and value creation across the supply chain enhanced.

It is suggested that supply chain management involves technological, environmental, economic, as well as social factors. There is a lack of literature on the social complexities of wood supplies, or "social availability", which concerns raw material, harvesting, market competition, and stakeholder objectives (Aguilar, 2014). There is a need of further incorporation of management science in policy-making, and the integration of stakeholder values in new solutions (White and Bourne, 2007). A "mindful approach" can benefit supply chain management (Hugo, 2011). As discussed by Hugos (2011), this involves mindfulness at the individual stakeholder level in order to support openness, attentiveness to change, and an understanding of diverse contexts and perspectives. Mindfulness can contribute to innovation by supporting multifaceted problem-solving, adaptivity, and value creation (Hugo, 2011). Furthermore, inter-dependent relationships can influence attitudes as well as support co-innovation among stakeholders (Yeniyurt et al., 2014).

It is suggested that the involvement and coordination of upstream to downstream stakeholders can benefit holistic supply chain performance, and thereby support the performance of the companies and organizations therein. Energy is strongly intertwined with society, and can be discussed as a sociotechnical system (Bolton and Foxon, 2015, Kuzemko et al., 2016). Through this lens, interactions between social and technical systems can be explored in order to establish a stronger understanding of the supply chain.

**Supply chain innovation and stakeholder management**

The integration of social factors in analyses of technical systems paves way for new academic discourse related to sociotechnical systems (Bolton and Foxon, 2015). Sociotechnical transition management necessitates new methods of governance (Loorbach, 2007). As stakeholder consensus influences feasibility, it is imperative to identify diverse interests and challenges in stakeholder networks (Shiroyama et al., 2015). By adopting a multi-stakeholder approach, the current study intends to illuminate new angles for woody biomass strategy.

Multi-stakeholder systems can render challenges in grasping all viewpoints and the system's "problem structure" (Kato et al., 2013). Problem-structuring is especially important in systems with multiple actors, perspectives, and uncertainties (Kato et al., 2013). This structuring can be shaped to integrate all stakeholder perceptions, as well as convergences and divergences among them (Kato et al., 2013; Mingers and Rosenhead, 2004; Cronin et al., 2014). The term "wicked problem" describes a complex problem structure that arises with diverse stakeholder perceptions (Cronin et al., 2014). It is valuable to create an overview of individual stakeholder perceptions in order to understand the system holistically and to contribute in the management of wicked problems (Kato et al., 2013). An important factor in this overview is insight on divergences as well as convergences of perceptions among stakeholders (White and Bourne, 2007). Collective stakeholder engagement, from local communities to the central government, would be important for building such insight through a top-down as well as bottom-up approach (White and Bourne, 2007). By understanding the convergences and divergences among stakeholder perceptions, it is suggested that there is potential to more effectively manage conflicts, support relations, and clarify areas earlier obscured in stakeholder mental models. Improved understanding of and among stakeholders may increase collaboration and engagement, thereby potentially enabling innovation (White and Bourne, 2007).

Innovation is indeed strongly related to engagement, coordination, and stakeholder synergies in the supply chain (Hugos, 2011; Weiss et al., 2011; Loorbach, 2007). This is relevant in the context of collective energy systems (Johansen and Røyrvik, 2014), such as locally integrated woody biomass systems. Several authors have discussed the importance of managing perceptions across the woody biomass supply chain. Aguilar (2014) noted that issues often arise due to different world views among woody biomass stakeholders, and Gold (2011) especially emphasized impacts of citizen perceptions. Furthermore, Keefe et al. (2014) stated that supply chain stakeholder objectives vary considerably and need to be coordinated.

From a strategic viewpoint, information transparency and a common vision are vital in supply chains (Trapero et al., 2012; Badakhshan et al., 2015). Yoshida et al. (2014) emphasized transparency and a shared vision specifically for complex woody biomass stakeholder networks. This can be linked to the need for strategic vision and long-term goals in transition management, as described by Loorbach (2010). A multitude of factors discussed in previous research indicates the importance of stakeholder management in woody biomass supply chains. However, it is unclear which challenges are the most critical, and how to manage them.

**Informal and formal challenges in the supply chain**

Stakeholders in a social network have diverse mental "frames" and conceptual foundations (Bolman and Deal, 2008). It is suggested that without effective management, imbalance among these foundations can result in information asymmetries in the supply chain. A multi-frame approach is key in building an understanding of sub-elements in complex systems, and cumulatively of the holistic system (Thompson, 1967). This can be related to tactical sub-system activities, as emphasized by Loorbach (2010) for transition governance.

While energy governance and market developments have largely been directed by economic theory, this direction has created a foundation driven by technology and economics that is fragile for long-term, low-carbon investments (Bolton and Foxon, 2015). Rather than economic or technical emphasis, a holistic approach is needed for sociotechnical energy system innovation (Bolton and Foxon, 2015). It is suggested that by exploring woody biomass success from both formal and informal dimensions, a holistic understanding of the supply chain can be attained. Schiefloe (2016) described the formal dimension involving structure and technology. The informal dimension concerns social relations and networks, interaction, and culture (Schiefloe, 2016). Through these two dimensions, the supply chain can be holistically analyzed via social constructivism theory (Rolstadås et al., 2014), which states that interaction and social processes are influential in shaping individuals' world views and knowledge (Darby, 2006). Social aspects and social constructivism are valuable in analyses of sociotechnical shifts (Rolstadås et al., 2014).

There is an abundance of research related to the formal dimension of the woody biomass supply chain, such as of infrastructure, logistics, and technical processes. For example, several authors have discussed processes for biomass moisture control (Kishita et al., 2017; Greene et al., 2014; Malek et al., 2017). Kishita et al. (2017) noted that the moisture content of forest residue, at approximately 10.7%, is key for power production. Greene et al. (2014) discussed that concentrating on moisture content reduction can improve biomass logistics overall. Malek et al. (2017) noted a linear relationship between high moisture content and decreased lower heating values, which in turn reduces energy conversion efficiency and increases fuel costs. There is abundant literature on individual technical elements in the woody biomass supply chain. However, the majority of bioenergy research has focused on specific portions or components in the chain, rather than a holistic approach (BR&D, 2014).

A valuable example of a multi-perspective approach in academia is a study on biomass supply chains in Northeastern China by Wang and Watanabe (2016). The authors adopted a multi-dimensional model based on socio-demographics, policy, economics, and trust in exploring bioenergy risk perceptions among local farmers (Wang and Watanabe, 2016). The authors found that economic incentives are needed in the short term for cooperation with bioenergy businesses and intermediaries (Wang and Watanabe, 2016). For the long term, trust-building and education were emphasized for reduced risk perceptions in the supply chain (Wang and Watanabe, 2016). Due to a diversity of influencing factors, it is suggested that an integrated approach is needed in biomass research. It is further suggested that each supply chain stakeholder as well as their inter-relationships are important. Sarkis et al. (2011) similarly noted the importance of inter-organizational dynamics in sustainable supply chains. It is proposed that an integrated approach can support a holistic overview of the woody biomass supply chain and challenges therein, including both formal and informal dimensions.

### 2.1.2 Methodology

An exploratory approach was adopted based on four case studies in Japan. The aim of these case studies was to explore and illustrate formal and informal factors influencing the woody biomass supply chain. Case studies are valuable for analyses of contemporary phenomena and multi-variable contexts (Yin, 2009). Hence case studies were deemed suitable for analysis of the multi-stakeholder, complex supply chains of woody biomass. Case study-based theory induction is especially useful in new academic areas, because it can support insight creation by juxtapositioning possibly contradictory findings, and contributing with manifold perspectives (Eisenhardt, 1989). The general aim of a case study is to provide description, test theory, or generate theory (Eisenhardt, 1989). The aim of the current study is to provide description of the perceived challenges in the woody biomass supply chain in Japan, highlight convergences and divergences among such stakeholder perceptions, and discuss strategic implications for woody biomass.

Case studies were conducted via semi-structured, face-to-face interviews with four companies, noted for anonymity as Company A, B, C and D. Case selection should initially be based on a specified population in order to reduce extraneous variation and support the development of theoretically valuable concepts (Eisenhardt 1989; Eisenhardt and Graebner, 2007). The population of the Kyushu region was adopted for this study. This is because Kyushu has among the highest potential for woody biomass in Japan, both with existing harvesting technologies, and in scenarios considering technical advancements (Kamimura et al., 2012). It was of interest to explore key issues of woody biomass despite this potential. (For an additional example of a woody biomass case in Japan, please see Appendix A1). Companies A-D are active in rural areas, focus on domestic woody biomass, and together incorporate operations across the woody biomass supply chain. Regardless of the companies' relations, they were selected based on their role(s) in the supply chain, shown in Table 1. The purpose of this focus on specific roles is to build a full overview of upstream to downstream supply chain stakeholders. The supply chain and roles are further illustrated in Figure 13.

**Table 1** Roles of Companies A-D in woody biomass supply chain (X: Activity (X): Planned activity) (Ahl et al., 2018)

| | Forest-owner | Forest industry | Biofuel producer | Electricity/heat producer |
|---|---|---|---|---|
| Company A | X | X | (X) | |
| Company B | X | X | X | X |
| Company C | | | X | |
| Company D | | | X | X |

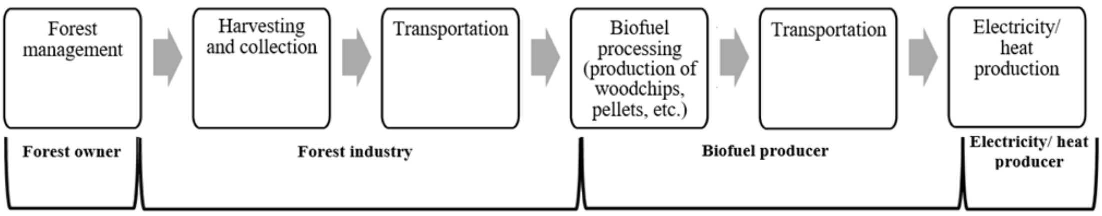


**Figure 13** Overview of woody biomass supply chain and roles (Ahl et al., 2018)

The company interviews were conducted through open-ended questions and semi-structured. The questions explored key factors and challenges of successful woody biomass supply chains, as perceived by company stakeholders. Follow-up questions such as "Could you please explain more about that?" gave interviewees chances to elaborate further. An overview of the interview outline can be seen in Appendix B1. A key aim of the interviews was to create an overview of the multiple stakeholder perceptions across the supply chain, and convergences and divergences among them.

One representative was interviewed in Companies A, C and D, and two in Company B. Interviews were conducted with translations from English (interviewers) to Japanese (interviewees), with the exception of Company A for which the interview was carried out in English. The translation procedures potentially inhibited discussion and/or incurred information loss. Interviewer bias was avoided with two investigators conducting the interviews and analyzing interview transcripts.

Through a thematic content analysis of the transcripts, themes were identified related to stakeholder perceptions of challenging factors in the supply chain. Emphasis given to each factor by each Company was ranked as strong, moderate or weak/none by the investigators. This ranking depended on a) the frequency a factor was mentioned, and b) the nature of the interviewee discussion of the factor. For example, if an issue was discussed as highly crucial for supply chain success it was ranked as strong. If a factor was deemed beneficial, it was ranked as moderate. If a factor was discussed as good but not necessary, it would be ranked with moderate/no emphasis. Theme identification and rankings were first created separately by two investigators, and discussed thereafter to avoid interviewer bias.

Based on the findings of the thematic content analysis, a comparative analysis was carried out in order to explore convergences and divergences of the stakeholder perceptions. This was explored in tabular form, which is useful for summarization, visualization, and testability of results (Eisenhardt, 1989), particularly with multiple cases (Eisenhardt and Graebner, 2007). This methodology draws from the stakeholder analysis and discussion carried out by Shiroyama et al. (2015) on issues and potential policy measures related to phosphorous recycling in Japan. Each company is explained further as follows.

**Company A**

Company A is a family-run business and the inherited owner of the largest forest area in Oita, a prefecture in Kyushu. The firm is active in the forest industry, selling products such as construction wood. The company created road networks across mountainous forest terrain in Oita to support wood harvesting and collection. In addition, Company A is exploring the feasibility of mobile wood-chippers on harvesting trucks, with considerations of woodchip market entry. Emphasis is placed on wood logistics innovation, especially due to the mountainous forest conditions.

**Company B**

Company B is a forest owner through inheritance in the Miyazaki prefecture, and also purchases wood from other owners. The firm sells multiple forest products, such as construction timber, chopsticks and biofuel. Company B emphasizes respecting the forest, conducting sustainable practices, and optimizing value creation from forest resources. Wood biofuel is given as the final step in the value chain, preferably by utilizing residues from manufacturing processes of other products. For example, chopstick manufacturing residues are used to produce briquettes. Company B uses self-produced woodchips for electricity and heat generation. This generation is at large purposed for the company's own operations, with excess electricity sold to the main utility grid.

**Company C**

Company C is a wood pellet producer in Miyazaki. The firm sources all timber from domestic forest players, and all pellets are sold to a single large utility in Japan for coal co-firing. The utility as well as a Miyazaki forest association are shareholders. With the association as a shareholder, a key purpose is to establish credibility and support among local forest industry actors. The firm noted the importance of such relationships for a stable wood supply.

**Company D**

Company D manages a 5.7 MW power plant, from which electricity is sold to the utility grid. To also incorporate local economic development in its business model, waste heat as well as land is shared at no cost with local farmers for greenhouse strawberry-farming. For its energy conversion processes, Company D maintains strict testing and control procedures for biomass moisture. Through woodchip-grouping based on moisture content, moisture levels are managed inside power plant boilers in real time. The owner of Company D is also the owner of a firm operating woodchip production and sales in Kyushu, further supporting woodchip supply and quality management.

### 2.1.3 Results and Discussion

Six key woody biomass supply chain factors were identified (in no specific order): 1) Respect of values and traditions, 2) Transportation infrastructure, 3) Business model integration, 4) Relationships and trust, 5) Local vitalization, and 6) Biomass quality control. Table 2 illustrates these factors and supply chain stakeholder perceptions, in order to clarify convergences and divergences among them. It can be seen that emphasis varies among the stakeholders, discussed as follows. Potential pathways for digital technologies to support these factors are thereafter explored in section 2.2.

**Table 2** Comparative analysis of stakeholder success factor perceptions. Emphasis - S: Strong, M: Moderate, W: Weak/None. (Ahl et al., 2018)

| | 1) Respect of values & traditions | 2) Transportation infrastructure | 3) Business model integration | 4) Relationships & trust | 5) Local vitalization | 6) Biomass quality control |
|---|---|---|---|---|---|---|
| Company A | S | S | M | M | M | W |
| Company B | S | M | S | M | S | W |
| Company C | W | S | W | S | W | S |
| Company D | W | M | M | S | S | S |

### Convergence of perceptions

As seen in Table 2, there is a convergence of stakeholder perceptions for several factors. It is suggested that this may be useful for strategic and collaborative advancements in the supply chain. While there is unison on factors, stakeholder views on approaches in developing these factors vary. It is suggested that a common understanding and vision, knowledge-sharing, and joint technology investment may contribute to efficient and mutually beneficial supply chain development.

Companies A, B and D emphasized 2) Transportation infrastructure, 3) Business model integration, 4) Relationships and trust, and 5) Local vitalization. An exception here is Company C, which did not accentuate 3) Business model integration and 5) Local vitalization. This may be due to Company C's business model, which centers on wood pellet supplies for one large-scale customer. Factors 2-5 were highlighted to a greater extent in the context of smaller woody biomass system scales. For example, Company D emphasized local community vitalization via agriculture support, by sharing land and waste heat. This may be due to business model benefits of integration with local community demands and supplies. In addition, corporate reputation and local credibility may be benefits of such local community focus. Perception convergences are elaborated on further as follows.

Transportation infrastructure

All companies discussed infrastructure for wood collection and transport as a key factor in the woody biomass supply chain. This was especially emphasized in parallel with discussions on the mountainous Japanese forest terrain. Also as discussed by Keefe et al. (2014), transport and other logistical costs of woody biomass are often high, and related business models are reliant on supply chain design and management. In Japan, there is a need for improved rural infrastructure to harvest and transport wood from the forest (Yoshida et al., 2014). There is a variation of approaches to this issue among the interviewed companies. Company A develops its own forest road networks, and noted deficient knowledge and skills for building such networks as a challenge in Japan. In contrast, Company B focuses on forward-thinking in terms of machinery for wood harvesting and collection, as opposed to investing in forest road networks.

Business model integration

Business model integration can be described as the incorporation of multiple value pathways in a business model. An example is the generation of power as well as heat in energy systems, to capture a broader spectrum of value. Business model integration was moderately emphasized by Company A, with plans to incorporate biofuel production and power generation in the future. Company B strongly emphasized value maximization from the forest via the combination of biofuel production in parallel with other forest products. The company discussed that biofuel should be created as a residual product; a final step in the wood value chain. Company B explained that in this way, additional and diverse streams of value can be leveraged. Leban et al. (2016) similarly discussed that for value maximization in contemporary forest management, multiple scopes of value are to be derived. Woody biomass should be a by-product of other forest products as well as services (Leban et al., 2016).

Company C's focus is on supplying pellets to one large-scale Japanese power utility, and there is no emphasis on business model integration. Company D provides waste heat captured in power generation processes to local farmers at no fee. Furthermore, Company D develops products from the ash that is produced during biomass combustion. It is suggested that these are valuable examples of value creation through business model integration, both on a company and local community level.

Relationships and trust

Considering the interdependencies among organizations in the supply chain, the development of relationships and trust was noted as a key factor by all companies. These interdependencies affect abilities to accomplish business model objectives. As discussed by Wang and Watanabe (2016), the development of trust is vital for cooperation among upstream and downstream biomass stakeholders, decreasing risk perceptions, and long-term collaboration. Companies C and D especially emphasized the building of relationships and trust. This may be due to that they are in the downstream supply chain, with a higher dependence on upstream relationships for a long-term and stable supply of wood.

Local vitalization

Companies A, B and D highlighted local vitalization. For example, Company D offers land and heating to local farmers, and emphasized “giving back to” local communities and industry. Companies B and D especially discussed leveraging forestry for the creation of new career opportunities in local areas facing decreasing populations and aging societies. The companies discussed a need to attract younger generations through opportunities in rural areas.

On the one hand, several authors (Yagi and Nakata, 2011; Kishita et al., 2017; Malico et al., 2016) have discussed the ability of local woody biomass supply chains to contribute to local industry competitiveness and socioeconomic progress. On the other hand, for long-term value creation, effective forest management (Malico et al., 2016) and rural infrastructure (Yoshida et al., 2014) are important foundations for such progress. Interviewed companies also highlighted a need to revitalize Japanese forestry. It can be suggested that considerations of socioeconomic progress alongside technology and infrastructure would be important in facilitating local woody biomass supply chains in Japan.

**Divergence of perceptions**

There is also a clear divergence in perceptions of 1) Respect of values and traditions, and 2) Biomass quality control, which suggests disparity between upstream and downstream stakeholders. This may affect abilities to conduct successful businesses in the short- and long-term. Long-term success can refer to multiple factors for individual companies, such as sales growth or business expansion. From the perspective of the supply chain, long-term success is related abilities to support stable resource flows (Wang and Watanabe, 2016) and profitability (Hugos, 2011). In building such abilities, the management of stakeholder relationships and coordination is important (Johansen and Røyrvik, 2014; Wang and Watanabe, 2016). It can be suggested that identifying and decreasing perception gaps, such as those identified in this study, may be important for long-term supply chain success.

Respect of values and traditions

Respect of values and traditions refers to awareness of the principles and customs among Japanese forest owners, and integration thereof in supply chain design. For example, Companies A and B (forest owners) emphasized Japanese forest culture and heritage, implying a strong social connection to the forest. These companies further noted that the heritage of the forest a key driver to maintain sustainable use of its resources and generation of several products/services as opposed to solely harvesting trees for biofuel purposes. This is also related to awareness and reflection of Japanese forestry culture and history. Upstream firms, which are forest-owners, strongly emphasized this factor while downstream stakeholders did not note it. Company B discussed supply chain design with a foundation in sustainable forestry, in order to show respect to forest-owners and the forest ecosystem.

Companies A and B also discussed lacking respect of values and traditions among downstream stakeholders, such as electricity producers. It can be suggested that if an understanding of stakeholder values and objectives were to be further developed among all stakeholders, a firmer basis may be built for communication and an integrated supply chain. It is suggested that collaboration can be enhanced by managing relationships based on mutual understanding and trust. In building such relationships, respect of values and traditions may be a key element. This indicates that social and managerial facets are important in the supply chain. Such aspects have been explored by a number of authors in the context of wood and forest products. For example, Aguilar (2014) discussed the "social availability" of wood, and that it is affected by various worldviews and values. Keefe et al. (2014) noted the importance of considering forest owner objectives in processes of woody biomass supply chain design. White and Bourne (2007) similarly emphasized the management of values of all supply chain stakeholders in order to set a foundation for long-term success.

Biomass quality and control

This factor refers to processes for the management of woody biomass quality. Woody biomass quality incorporates factors such as size, shape, density, ash, sugar, and moisture content (Kenney et al., 2013). This is strongly emphasized by Companies C and D, the downstream stakeholders: biofuel and electricity/heat producers. Biomass quality affects electricity generation efficiency, which is a key reason behind its stronger emphasis in the downstream supply chain. It is suggested that biomass quality management is an important point for improvement across the supply chain. Improved wood quality management, especially of moisture content, starting from the upstream can contribute to cost efficiency across the entire supply chain as well as energy conversion efficiency (Kishita et al., 2017; Greene et al., 2014; Malek et al., 2017).

It is suggested that awareness, co-planning, and knowledge-sharing could enable improved biomass quality management across the supply chain. Shifting biomass quality considerations and sharing related knowledge further upstream can support increased biomass quantities as well as quality (de la Fuente et al., 2017). It can be more economically as well as logistically efficient to move certain woody biomass drying procedures upstream. Knowledge-sharing of opportunities and procedures for quality control among supply chain stakeholders would be important in order to enable such advancements in the upstream. There are multiple pathways to develop woody biomass quality management. For example, forest residue-drying in the field prior to biomass transportation can improve feedstock flow quality and cost-efficiency across the supply chain (BR&D, 2014). This is for instance as drying wood in the forest can decrease its weight and enable more compact transport, thereby bringing down transport costs. This can also reduce drying requirements in the downstream supply chain, avoiding associated space and heating energy costs.

This is important, because as noted by Company B, space availability for woody biomass drying is a challenge for several firms. The company discussed that it could be more cost-efficient to store the timber for a longer period of time, and allow the wood to dry outdoors. While this would reduce or eliminate drying costs, land costs could be a problem for some companies. As forest owners already own land, an opportunity is to leave logs in the forest with branches and leaves on, which in turn supports water absorption from the wood and diffusion into the air (Kamijo et al., Personal communication). It is suggested that an open discussion and knowledge-sharing about such opportunities may support the development of wood quality for energy, and other purposes. This may enable new, efficient procedures for woody biomass quality management across the supply chain.

### 2.1.4 Summary

The objective of section 2.1 was to identify key challenges in the woody biomass supply chain in Japan. Based on interviews with stakeholders from across the supply chain, a series of issues were identified. These can be summarized as: transportation infrastructure; biomass quality monitoring and control; stakeholder respect, relationships and trust; local community revitalization and socioeconomic development. It is important to note that factors are likely to vary based on different local conditions and stakeholder synergies. Hence the factors found in this study may not be universally valid, which would require further research to show. However, it is suggested that the identified perception convergences and divergences among stakeholders are important to be bridged to support domestic woody biomass. Especially the presence of divergences indicates that it would be valuable to integrate a holistic supply chain perspective in woody biomass development. As the identified factors are in both formal and informal dimensions, it can be further suggested that this development would benefit from planning and management considering both dimensions. In section 2.2, potential pathways for digital technologies to be used in overcoming the identified issues and enabling woody biomass development in Japan are explored.

## 2.2 Pathways: Digital innovation for woody biomass

In section 2.2, strategies for digital technologies in overcoming challenges in the woody biomass supply chain in Japan are explored. There is a global need to couple the increase in bioenergy policies and incentives with improved biomass mobilization strategies (Welfe et al., 2014). Market- and policy-related drivers as well as technology and infrastructure influence biomass supply chains (Welfe et al., 2014). In addition, in Japan the financial costs of wood logistics alongside a dwindling forestry workforce are key present-day issues of woody biomass (Nishiguchi and Tabata, 2016). The challenges identified in section 2.1 points towards both technological and socioeconomic dimensions; in turn linkable to the context of sociotechnical systems (Camarinha-Matos, 2016; McCauley and Stephens, 2012; Lund et al., 2017; Barile et al. 2018). As follows, the technological and socioeconomic dimensions of the woody biomass supply chain is discussed, with a focus on opportunities for digital technologies. This overview is based on both academic and grey literature, such as news articles and company reports. Thereafter, digital innovation specifically for the challenges identified in section 2.1 is explored.

### 2.2.1 Technological dimension

Several authors have explored digital technology strategies and applications in supply chain discourse. For instance, Kache and Suring (2017) discussed the potential of big data analytics, stored communication records, GPS, and sensors to support predictive management, cost reduction, and risk analyses in supply chains. Furthermore, radio-frequency identification (RFID) tags (Guo et al., 2015; Tzoulis and Andreopoulou, 2013) and cloud technologies (Guo et al., 2015) can facilitate product-tracking, transparency, and data-driven management. Digital technologies may offer several mechanisms for the advancement of woody biomass supply chains. This is discussed as follows in the order of forest to biofuel production, and from biofuel to energy generation.

**Forest to biofuel production**

There is a need for improved decision-making tools to support sustainable bioenergy (Soares et al., 2018). High-quality data collection and analysis is essential in forest biomass approximations (Sinha et al., 2015), but data quality is as of yet insufficient and not fully reliable (Yarime, 2017). However, this is swiftly progressing through advancements in satellite systems, drones, and IoT (Yarime, 2017). Advancements in digital technologies enable several opportunities for forest management in the upstream supply chain, discussed further as follows.

Forest biomass estimation can be done via field measurement, geographic information systems (GIS), and remote-sensing (Sinha et al., 2015). While field measurement is useful for the collection of accurate data, it can be demanding in terms of time and capital in large areas (Lu et al., 2016; Sinha et al., 2015). GIS, which integrates databases and maps, can be leveraged to effectively identify natural resources (Calvillo et al., 2015). Remote-sensing can facilitate accurate large-scale aboveground forest biomass assessments (Lu et al., 2016), based on procedures for the retrieval of information via satellite or airborne vehicles. For example, airborne Light Detection and Ranging (Lidar), or laser-scanning through satellite systems, can be useful in forest biomass assessments (Koch, 2010). The adoption of multi-source (optical and radar) remote-sensing data collection processes is valuable for reduced data saturation and uncertainty in biomass estimations (Lu et al., 2016; Sinha et al., 2015). For instance, the collection of both synthetic aperture radar (SAR) and optical data can support estimation accuracy (Sinha et al., 2015).

Remote-sensing can be conducted with satellite systems, airplanes, as well as drones. Drones and image analytics can support geospatial surveys for investment planning, vegetation monitoring, and so on (PwC, 2017). It is suggested that drones could be a useful addition to a toolbox of digital technologies utilized in forest management. Zhang et al. (2016) emphasized prospects for drones to provide ultra-high spatial resolution data of forest stand characteristics in local or regional scales. Drones may also be integrated with other systems such as Lidar (Zhang et al. 2016). Commercial examples of this are California-based firm Velodyne Lidar (Velodyne Lidar, 2019) and French company YellowScan (YellowScan, 2019). AI can also be used to analyze forest biomass measurements collected by remote-sensing (Gingras and Charette, 2017). With aging populations in Japan, especially seen in rural areas, the labor force available for the forestry sector is likely to decline (Goh et al., 2019). Especially considering the aging population and declining workforce in rural Japan, digital technologies may be valuable in enabling more efficient forest management.

Image analytics, AI such as machine learning, and robotics can support automation, efficiency and human safety in woody biomass harvesting and transport (Gingras and Charette, 2017; Kies and von Lengelfeld, 2018). For example, in the “Smart Crane Control” project by the Cluster of Forest Technology of Sweden, an automatic harvesting crane is being developed (Skogstekniska Klustret, 2014). Another example is “Auto2”, a project co-developed by industry and research institutes in Sweden and Japan, focused on partially automated and partially remotely controlled forest machinery (Skogforsk, 2018). In Auto2, satellite imagery and laser-scanning will be utilized to collect the data that facilitates automation (Skogforsk, 2018). In addition to forest measurement and management in the upstream, biomass quality is an influential factor in the woody biomass supply chain.

Biomass quality varies across the supply chain, and benefits from improved management practices, rapid assessment, and pre-processing technologies (Kenney et al., 2013; Eisenbies et al., 2016). In the woody biomass supply chain, moisture content is one of the most complex and challenging factors (Kenney et al., 2013). Digital technologies may be valuable in supporting the management of moisture content as well as other quality parameters. For example, Inray Fuel Control is a European Union (EU)-funded firm that carries out X-ray analyses of biofuel moisture, foreign substances, and energy content (Inray, 2018). This data is shared in real-time and useful in fuel-pricing, optimization, emissions reduction, and cost-savings (Inray, 2018).

Literature related to digital technology opportunities in wood harvesting, transport, and quality management has been introduced. In addition, sustainable forest management (SFM) is a central concern in the woody biomass supply chain as there can be diverse sustainability issues (Soares et al., 2018). Such issues involve bio-diversity, air quality, soil quality, and so on (Soares et al., 2018). SFM is largely related to the proportion of wood that is harvested, and that which is left in the forest to maintain ecosystem health (Welfe et al., 2014). In this context, the availability of accurate data is valuable in environmental impact analyses (Nakagawa et al., 2018) and verification. Forest verification often adopts centralized tracking procedures which produces data that is insecure and mutable, such as paper-based Chain of Custody Systems (Dudder and Ross, 2017). Digital technologies can support SFM via transparency and wood origin traceability (Kies and von Lengefeld, 2018). For example, blockchain is a technology that could support traceability and the measurement of associated sustainability parameters across the wood supply chain (Clement, 2018; Dudder and Ross, 2017). Blockchain is a distributed ledger which can support transactions without an intermediary, instead leveraging digital consensus mechanisms. The technology can enable transparency, traceability, and stakeholder trust in biomass supply chains (Clement, 2018). Blockchain has gained significant attention in the finance sector. However, its potential in sustainable supply chains and in managing the distributed data therein is a key research gap (Dudder and Ross, 2017). A valuable example is a study on blockchain and certification schemes in the wood supply chain by Dudder and Ross (2017). It was found that a blockchain platform indeed can contribute to effective verification of legalities and SFM (Dudder and Ross, 2017).

**From biofuel to energy generation**

Digital technologies, such as ICT, are useful in the innovation of energy services (Mancarella, 2012; Calvillo et al., 2015; Kylili and Fokaides, 2015). By leveraging enhanced intelligence and communication (Calvillo et al., 2015), energy generation, storage, infrastructure, and mobility systems are increasingly integrated in distributed energy networks (Mancarella, 2012; Calvillo et al., 2015). This can be discussed as a paradigm shift, with a foundation in sub-sector synergies for integrated, "smart" energy services (Lund et al., 2017). Such synergies can refer to power, heating, cooling, and mobility (Calvillo et al., 2015; Kylili and Fokaides, 2015; Lund et al., 2017; Mancarella, 2012).

As discussed by several authors, biofuels such as woody biomass are valuable in the co-production of energy services, or polygeneration (Kylili and Fokaides, 2015; Proskurina et al., 2017; Jiang et al., 2017; IEA, 2018 c; Arasto et al., 2017; Mangoyana and Smith, 2011; Mancarella, 2012). For example, utilizing biomass heat in CHP systems can increase energy and cost efficiencies (Proskurina et al., 2017; Jiang et al., 2017; IEA, 2018 c). There are several potential CHP system designs. For instance, onsite biomass boilers can locally generate electricity and heat, and may be integrated into hybrid energy systems, such as with solar power (Kylili and Fokaides, 2015). This kind of polygeneration is relatable to multi-generation in smart energy systems, as discussed by Lund et al. (2017) and Mohammadi et al. (2018). Automated monitoring, optimization, communications and advanced applications can support such systems (Mohammadi et al., 2018). For example, CHP setups can be supported by smart grids, accumulators, district heating networks, thermal storage, and power/electricity from prosumers (Arasto et al., 2017). There is indeed an abundance of research on smart energy systems, but lacking literature that focuses on the intersection of digital technologies and the woody biomass supply chain.

### 2.2.2 Socioeconomic dimension

Technological advancements are foundational in decarbonization (Zhang et al., 2017 a). However, the implementation of new, smart technologies can face several challenges, such as issues of regulation, financial incentives (Mancarella, 2012; Calvillo et al., 2015; Mangoyana and Smith, 2011), and community management (Kylili and Fokaides, 2015). Smart technologies can be drivers of sustainability, when also coupled with governance and institutional readiness (Nam and Pardo, 2011). The smart city is one form of institutional innovation. In Japan, a key focus in the smart city concept is technological energy system innovation (Yarime and Karlsson, 2018).

The smart city is a development process (Huber and Mayer, 2012; Angelidou, 2015; Lombardi and Vanolo, 2015) through which smart technologies are used in developing services to tackle urban issues (Albino et al., 2015). It is suggested that this process can support innovation and regional development in both cities and rural communities. In its 2030 Agenda for Sustainable Development, the UN (2015) emphasized support of "economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning." This was related to SDG 11: "Make cities and human settlements inclusive, safe, resilient, and sustainable" (UN, 2015). Urban-rural linkages can indeed facilitate more symmetric economic relationships, knowledge-sharing, and sustainable regional development (Mayer et al., 2016). Such linkages refer to flows of people, capital, goods, information, waste, and services between urban and rural areas (IIED, 2019). This can further enable rural development and connect rural players to wider markets (Mayer et al., 2016). This can be valuable in discussions on local woody biomass supply chains.

Sustainable bioenergy systems benefit from design based on local conditions, supplies and demands (Mangoyana and Smith, 2011; He et al., 2013). The local context, referring to natural, economic and social conditions, would be a vital in supporting context-based investments in the woody biomass supply chain (He et al., 2013). For example, bioenergy systems can broaden market opportunities for local agriculture and forestry stakeholders (Malico et al., 2016). Indeed, this may lead to competition with food and timber industries, but it is suggested that bioenergy systems can be leveraged for the utilization of residues, such as forest resides. Thereby, value streams can be increased as opposed to replaced. Forest residues and waste should be used for bioenergy purposes following the creation of higher value products like furniture and pulp (Tiilikainen and Birol, 2018). This indicates the importance of business model integration in the woody supply chain. For example, in a study in Maine in the United States, it was found that harvesting and logging contractor profits rose by 34-70% and 3-7%, respectively, if roundwood and woodchip biomass businesses were integrated (Whalley et al., 2017). This implies that there are benefits achievable by leveraging stakeholder synergies in the woody supply chain, discussed further as follows.

**Stakeholder management and cascading**

Stakeholder synergies and cascading in the wood supply chain is often elaborated on in literature. However, cascading appears to have no universal definition. It can be explained as the diversified utilization of wood resources, which also incorporates residues and recycled wood (Mantau, 2012), in order to maximize value in the wood supply chain and life cycle (Odegard et al., 2012).

Cascading, local resource use, and logistics for sustainable woody biomass are important in coordination between the forest and bioenergy sectors (Proskurina et al., 2016).

Bioenergy systems are reliant on stakeholder coordination for feedstock supplies, finance, technological readiness and skill availability (Mangoyana and Smith, 2011). Cascading necessitates the effective sharing of information among supply chain stakeholders. Stakeholder synergies can be catalyzed via local energy clusters, with benefits such as reduced transportation costs, service specialization, and talent pools (McCauley and Stephens, 2012). In such clusters, it would also be crucial to consider social and cultural factors in order to avoid spatial or economic inequality (Mayer et al., 2018). Nishida et al. (2014) further discussed digital disparities between urban and rural Japan, which affect abilities to innovate and revitalize local communities. It can be suggested that technological, economic, as well as social factors are important in discussions on cascading and stakeholder coordination.

While digital technologies may benefit the information-sharing and coordination needed for cascading, such applications have not been explored to a great extent in academia. It would be important to discuss this from both socioeconomic and technical angles. There is deficient digital infrastructure in rural areas in Japan; often due to mountainous terrain and its escalation of telecommunication investment costs (Nishida et al., 2014). Low density rural areas in fact deter such investments, resulting in disparities of Next Generation Access (NGA) networks, mobile phone coverage, and broadband (Salemink et al., 2017). Indeed, lacking digital infrastructure and connectivity obstructs socioeconomic progress, because of the resulting deterrence of information-sharing and decreased innovation capacity (Salemink et al., 2017).

A community-based approach may contribute to bridging urban-rural digital disparities, with a focus both on expanding technical connectivity and on the inclusion of community members in the process (Salemink et al., 2017). Community engagement may be supported through outreach, training, extension programs, and courses (Nishida et al., 2014; Salemink et al., 2017). This kind of engagement can also be vital in creating stakeholder synergies to benefit bioenergy (Mangoyana and Smith, 2011).

Stakeholder management in the woody biomass supply chain is both vital and complex (Whalley et al., 2017; Welfe et al., 2014). There is an increasing data and knowledge flow, which is shaping socioeconomic relationships in new "sociotechnical configurations" (Del Giudice et al. 2016). It is suggested that digital technology applications are of interest for further exploration. From the technical perspective, capabilities such as ICT, cloud computing, and social media can contribute to supply chain advancements via knowledge-sharing, buyer-supplier relationship management, and digital market platforms (Scuotto et al., 2017). ICT can support a shift to networked as opposed to linear supply chains (Kache and Suring, 2017), via real-time data that can connect stakeholders and support integrated resource management (Bifulco et al., 2016). Despite this potential, there is a gap between woody biomass and digital technology literature.

### 2.2.3 Methodology

The objective in section 2.2 is to analyze how digital technologies can be used to overcome challenges in the woody biomass supply chain in Japan. Due to a lack of discourse in this arena, analysis was done through an exploratory approach. In this approach, expert interviews are valuable for data collection and familiarity in unmapped fields (Bogner et al., 2009). An expert can be described as an individual with technical achievements or professional know-how, that has an impact on contemporary material or social environments (Giddens, 1990). First, structured interviews were conducted with 20 experts from industry, government, and academia. The experts are active in the forestry, woody biomass, and/or digital technology fields. The experts and their affiliations can be seen in the Acknowledgments in Appendix B2. Dispersed internationally (Japan, Austria, Sweden, Germany, Italy, Denmark, Canada, Italy, and the United States), the experts were selected in order to collect various viewpoints. The initial selection was through the network of the authors as well as online searches of experts with demonstrated knowledge, such as publications or presentations in international conferences. Additional interviewee recommendations were also gathered from interviewed experts, via "snowball sampling," which is valuable for broadened access to experts (Littig, 2009).

There are nonetheless limitations in this methodology, including a low number of interviewees as well as the diversity of the expert network. For example, this network could be made more diverse by also incorporating experts from the African and South American continents where biomass opportunities are also prevalent. In the current study, the purpose of the interviews was to collect expert insights in order to formulate an overview of potential digital technology pathways for the woody biomass supply chain in Japan. The 20 interviewees were deemed adequate for assembling such initial insights.

The experts were requested to discuss how digital technologies may contribute to overcoming each of the five challenges of woody biomass identified in section 2.1. A structured interview framework with open-ended questions was used. This can be seen in Appendix B3. Open-ended questions are important as they allow interviewees to thoroughly share information, opinions, and experiences (Turner III, 2010). All correspondences were conducted in English. Six interviews were conducted face-to-face. Due to schedule-related and geographical limitations, nine experts were interviewed via conference call and five through email communication. Email-based correspondences potentially hindered in-depth discussion. Nonetheless, email interviews can be a good substitute when there are challenges of face-to-face or telephone interviews in qualitative investigations (Meho, 2006).

Moreover, risk of interviewer and confirmation bias is present in this study. To reduce this, interviews followed the same framework and adopted open-ended questions. The interview transcripts were analyzed through bottom-up, inductive coding. Qualitative data codes, derived from open-ended as opposed to pre-coded interviews, are valuable for the identification of multiple perspectives as well as the reduction of researcher bias (Turner III, 2010). The combination of qualitative and quantitative approaches can build a strong foundation for content analysis. This combination can be complementary. On the one hand, restriction to numerical, quantitative depictions of phenomena can be avoided (Krippendorf, 2004). On the other hand, bias can be evaded in impressionistic analyses, which is a usual source of criticism towards qualitative studies (Krippendorf, 2004).

Quantitative analysis of qualitative data can include the identification of concept and word frequencies (Krippendorf, 2004). In terms of the quantitative analysis, word frequencies were explored in the interview transcripts. This was done for discussions on each of the five identified challenges of woody biomass, and how digital technologies can be utilized in managing them. After removing stop words such as "a" or "the," words with frequencies above two were identified, as shown in Table 1 in Appendix B4.

In terms of qualitative analysis, collocation and concordance was adopted in this study. Collocation refers to the grouping of two or more words. Collocation of key words and associated words is valuable for creating "textual and cognitive bridges" between original statements and new theories or propositions (Mello, 2002). Mello (2002) also highlighted that collocation can support the upkeep of narrative integrity. Concordance analysis refers to the identification of key words in context (KYIC), and is useful in strengthening discussions on concepts and word senses (Krippendorf, 2004). In this study, the key words were identified based on the top five words in ranked frequency lists for expert discussions for each challenge. These key words were shown in collocation diagrams, with one diagram representing discussion for one challenge. In each diagram, black boxes were used to represent key words among the top five frequencies and white boxes showed associated words. In addition, connections among key words and among associated words were shown with thick and thin lines, respectively. The distance between the words has no significance.

Key words with connections in the interview transcripts were grouped in clusters, clarified by the thicker lines between them, to enable visualization of overarching concepts and messages from the transcripts. In addition, the relationships between these key words were illustrated through interlinkages with associated words, shown with thin lines and white boxes. This overview of key concepts, key words, and associated words enabled interview visualization, systemic analysis, and discussion of results. The open source text-analysis and data-mining platform, Voyant Tools (Sinclair and Rockwell, 2018), was used for word frequency, collocation, and concordance analysis. Comparable qualitative analysis and text-mining methods were adopted by authors Mårald et al. (2016) and Rasid et al. (2017). Moreover, the transcripts were thoroughly read in order to discuss key words in context (concordance analysis), identify convergences and divergences of expert opinions, as well as find any additional possible interpretations. Direct expert quotes were also used to further clarify concepts.

### 2.2.4 Results and discussion

As follows, the interview insights for each of the five challenges are presented and discussed with a basis in literature. Thereafter, an overview of the digital technologies and potential mechanisms by which they were suggested by experts to contribute to overcoming the challenges is presented.

#### Transportation infrastructure

Figure 14 illustrates the collocation diagram of expert discussions related to transportation challenges in the woody biomass supply chain. A need of accurate information is emphasized for forestry and digital services, such as via the use of drones and satellite imagery for route-mapping and optimization, or digital forest management leveraging virtual reality (VR). VR as well as augmented reality (AR) can support more effective and safe forest management and training (Gingras and Charette, 2017; Roßmann, 2011). With increased access to data and more accurate mapping, experts discussed the potential of partial or full automation in the supply chain. An example of this is autonomous vehicles or robotics for fertilization and harvesting.

While full automation may be a future advancement, a key current opportunity noted by experts is the use of digital technologies in transport route-related and logistical optimization. Experts

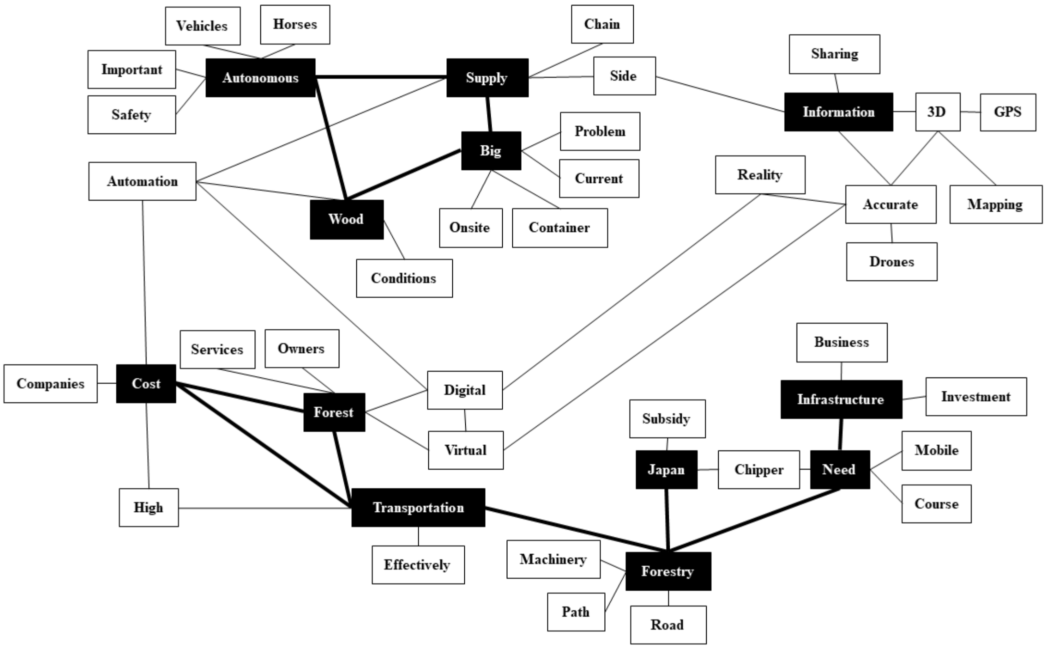


**Figure 14** Collocation diagram: digital technology and the transportation infrastructure challenge (Ahl et al., 2019 b) (Black boxes: key words among the top five frequencies. White boxes: words associated with key words. Think lines: connections between key words. Thin lines: connections to associated words).

explained that decision-making and the productivity of logistics can be improved through information-sharing across the supply chain. For example, accurate data on forest conditions, weather, and market demands is valuable in harvest decisions. In order to support more accurate forest data, drones and satellite imagery can enhance GIS and 3D-mapping. In Japan this is advancing in some regions. For instance, in the Gifu prefecture forest GIS data, such as tree species, is openly available (Gifu Prefecture, 2019). GIS system data necessitates processes of regular updates (FGIS, 2019), and remote-sensing developments may support these processes. Optical and radar data integration can further improve remote-sensing accuracy for forest-mapping (Lu et al., 2016; Singha et al., 2015) in this context.

Forest-mapping improvements can in turn support route-planning, harvesting and reforestation procedures. This is important in overcoming transportation infrastructure challenges, as associated costs are high and "…we need a planning system for that, for routing optimization." For example, "digital technology can enable utilizing more capacity of transport tracks." This is because transport plans can be improved and track-sharing among stakeholders coordinated. Forest digitalization, such as via remote-sensing, can also improve forest property identification.

Experts explained that via digital services, property identification and forest management would not only be on a broad forest level, but also with "fine-grained control on individual trees and their properties." Such advancements in data accuracy can contribute to the optimization of harvesting and transport processes, based on volume as well as each tree's quality.

Following improvements in data quality, information-sharing, mapping capabilities, and data analytics, experts noted that automation is a prospective next step for transport intelligence. "If robots can do it (bring timber from the forest) safely and at a low cost this can bring a lot of value to the supply chain." This would indicate that route-planning, harvesting optimization, transportation efficiency, as well as human safety can be supported by autonomous machinery and vehicles. In this context, accurate forest databases as well as connectivity would be vital. One expert noted that "the world of autonomous vehicles is important… Connected vehicles allow you to look at larger infrastructure on how to do routing."

Digital technologies may offer several mechanisms to improve harvesting and transportation processes, but socioeconomic obstacles may inhibit digital developments. As noted by an expert, in Japan there are numerous small-scale forest owners (2-5 ha = 0.02-0.05 $km^2$). These owners are not actively managing forests, and may not have financial or skill-related capacities to develop transport infrastructure. One solution may be forest associations, through which forest owners are coordinated for co-investment and collaborative learning. A number of authors have discussed that collaborative learning can contribute to knowledge transfer in multi-stakeholder contexts (McCauley and Stephens, 2012; Barile et al., 2018). It is suggested that educational communities can also support collaborative learning. For example, the Forest GIS Forum is a Japanese knowledge-sharing community focused on forest managers, forest researchers, and GIS specialists (FGIS, 2019). In the current study, one experts discussed that, "to get things going we need to convince people to invest in something new, to manage the forest in more effective ways, or even just to think about conducting forestry business in the first place."

**Biomass quality monitoring and control**

Expert discussions, as illustrated in Figure 15, focused on woody biomass quality management through assessment, tracking, and real-time information-sharing across the supply chain. The results further point to that digital technologies can support transparent information-sharing and accountability, in turn enabling effective control and management of quality parameters. Open data on such parameters can support knowledge-sharing and the management of quality inconsistencies. "Have them (parameter data) publicly available for knowledge-sharing of that

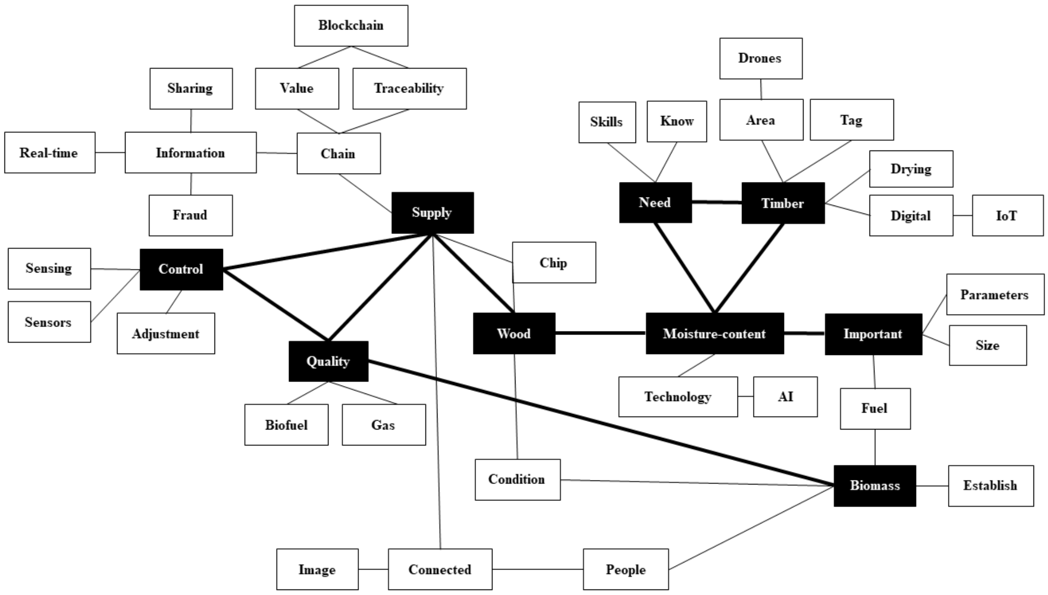


**Figure 15** Collocation diagram: digital technologies and the biomass quality challenge (Ahl et al., 2019 b) (Black boxes: key words among the top five frequencies. White boxes: words associated with key words. Think lines: connections between key words. Thin lines: connections to associated words).

variability... This comes back to communication and easily connecting." Real-time data related to moisture content of biomass earlier in the upstream supply chain would be particularly beneficial for downstream processes. As described by one expert, "drying is expensive. If we can monitor the moisture and quality of timber more effectively, we can optimize this process and make it more cost-efficient."

Digital technologies can support the evaluation of woody biomass quality from the upstream to downstream. Forest analyses can benefit from more accurate and diverse information, including tree ages, disease conditions, and other parameters. "Resource assessment technologies, such as laser-scanning, are useful to understand the forest resource conditions and terrain conditions." Experts noted that satellite imagery and/or drones coupled with image analytics can improve GIS systems, and support biomass quality monitoring in the upstream supply chain. Radar data, such as SAR, or laser-scanning would be especially imperative in moisture content measurements (Sinha et al., 2015). Multi-source remote-sensing, meaning the integration of both optical and radar data, can further facilitate accurate parameter measurement (Lu et al., 2016; Sinha et al., 2015). The measurement accuracy of chemical and structural properties of individual trees can also be improved with multispectral or hyperspectral drone image developments (Zhang et al., 2016).

Experts also discussed biomass size and volume measurement procedures. "Measurement of logs is manual and paper-based in Japan. If we digitalize this, we can improve efficiency. If we utilize photos, based on image data we can calculate the diameter or volume, and this would be very helpful for us." Imagery and other analytics can be enhanced via AI and IoT for decision-making guidance, digital tracking, and information-sharing throughout the supply chain. Sensors and timber-tagging schemes could be beneficial in such analytics. Sensor information was also discussed in the context of accountability. "To prevent fraud you can use different types of due diligence and traceability…by reading sensor information on quality control points in biomass products." With this, it is suggested that digital technologies have potential to contribute to quality control procedures as well as relationships and trust.

Value traceability and classification in each wood conversion step would be an important element in the supply chain, as noted by experts. "Having a classification system in place for biomass quality is necessary to properly assign a value to that biomass, establish the market structure, and reference values for different grades." Key potential drivers in woody biomass quality management include digital tracking and the sharing of standards, certification, and prices. An important factor here is traceability. For example, blockchain technology was a discussed by experts due to its potential to enhance traceability of supply chains, and the contracts and certifications therein. Market structure and price incentives would also influence and be influenced by tracking and information-sharing systems. "We need price incentives for upstream suppliers to manage moisture content. This would need information-sharing and supply chain transparency." This is important because "biofuel of varying quality can be sold at the same price on the market" in Japan.

While digital technologies enable numerous opportunities, education and skills related to biomass quality and power plants would also be imperative. Experts emphasized management and stakeholder skill development for digitalization efforts in the supply chain. "…There might be guidance from IoT for work flow… but we need skills and a shift in education for any digital transformation in an IoT realm." Scuotto et al. (2017) similarly highlighted skill development for the integration of digital technologies such as ICT in supply chain management, particularly among small and medium-sized enterprises. Digitalization and the introduction of new technologies would need to be integrated with community engagement, stakeholder collaboration, and the collection of feedback related to the new systems (Mirembe et al., 2018).

**Business model integration**

The results seen in Figure 16 centralize on ICT, remote-sensing, and real-time data-sharing to support business model integration and cascading. Experts noted that automation as well as traceability and trust can be supported via the sharing of material and price data among supply chain stakeholders. "ICT…Sensors, robotics. We can have an automation process based on algorithms… Optimizing systems like this would help to build trust as well." An example in this context is RFID tags, which can enable automatic tracking and wood supply chain management (Tzoulis and Andreopoulou, 2013). Sensors coupled with robotics can also be used for more accurate and rapid wood-, waste-, and residue-sorting, which in turn can support cascading in local or regional enterprise networks (Ciccarese et al., 2014).

Experts discussed that if the supply chain is more transparent, upstream suppliers can develop an improved understanding of downstream market prices and demands (and vice versa). This can facilitate informed planning and more effective operations among firms. Tzoulis and Andreopoulou (2013) similarly noted that wood supply chain production processes, partnerships, and communication can be enhanced with increased traceability (Tzoulis and Andreopoulou, 2013). Cyber-physical systems with technologies such as IoT and cloud-computing can support agility and responsiveness based on upstream supplies and downstream demands (Gingras and Charette, 2017; Kies and von Lengefeld, 2018). As put by experts, with "individualized production" and forest product value maximization, "high value components" can more efficiently be targeted to "high value markets." "Bioenergy is a part of bio-based economy…there will be more and more products, and then at the end it (biomass) is used for heat and power." As also discussed in literature, bio-economies based on cost-effective cascading in the wood market can support both economic progress and mitigation of climate change (Arasto et al., 2017; Brewer II et al., 2018).

Experts linked bioenergy to local policy, people, resources, and markets in discussions on a bio-based economy. Emphasis here was on "local." Experts noted that local policies can promote bioenergy in multiple ways, such as for domestic heating. In terms of local communities and people, as put by one expert, "positive value needs to be recognized by local people, such as the beauty of local resources." This value can be communicated in myriad ways, such as through visualization. In this context, pictures can be useful in order to engage emotional values that may be used to instigate change (Mayer et al., 2016). In terms of local forest resources, experts discussed a need for improved management of biomass quality, forest health, and reforestation procedures. This would require coordination among multiple stakeholders. "Management of

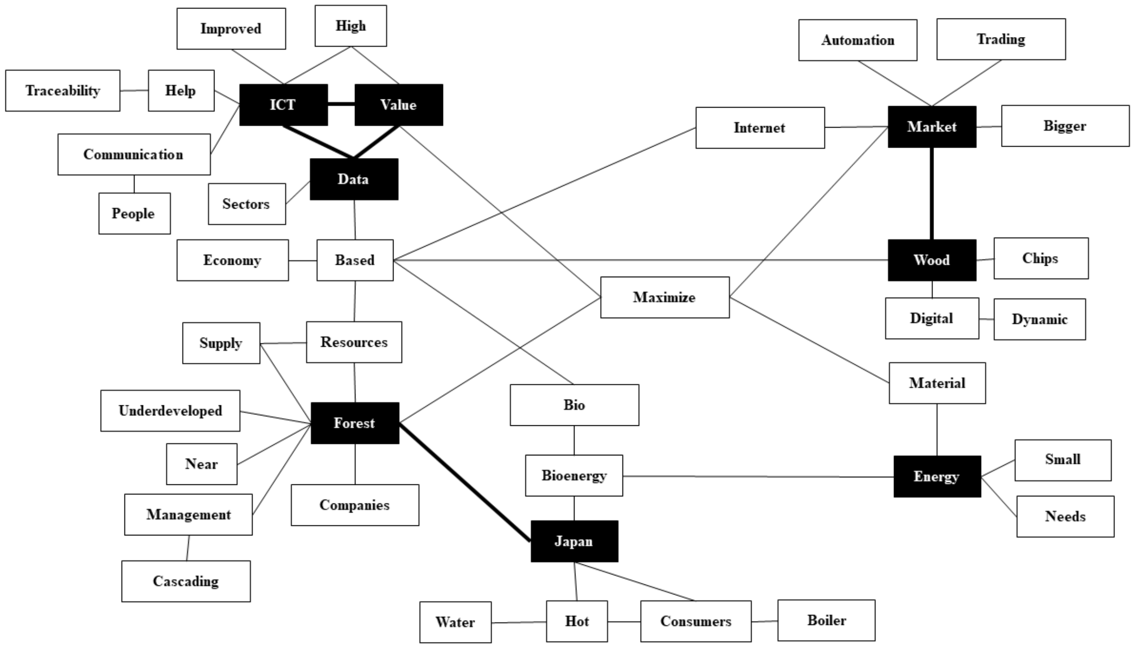


**Figure 16** Collocation diagram: digital technologies and the business model integration challenge (Ahl et al., 2019 b) (Black boxes: key words among the top five frequencies. White boxes: words associated with key words. Think lines: connections between key words. Thin lines: connections to associated words).

forest resources in Japan is still an underdeveloped area which would require further cooperation of forest owners, foresters, administrative agencies, and logistics companies." Stakeholder synergies are a key success factor for bioenergy (Mangoyana and Smith, 2011). Social networks and communication may support such synergies, and thereby catalyze change in incumbent systems (McCauley and Stephens, 2012). Experts discussed that ICT platforms could support collaboration among stakeholders through new channels for information-sharing, communication, and partnership-building.

For wood markets, experts discussed information transparency leveraging ICT for enhanced and even automated procedures for picking the "right biomass pieces for right markets." Access to accurate demand and price data can support informed forest management and planning processes. Experts suggested that such processes may also be gradually automated with enhanced data streams and analytical abilities. For example, in the downstream supply chain automated biomass dispatch can be coupled with other energy resources. Backup biomass dispatch capacities can contribute to energy-balancing in renewable energy systems (Jiang et al., 2017). As explained by one expert, “using digital technology you can store woody biomass and in real-time you can channel that energy...”

Experts also emphasized a need for digital skill and entrepreneurial ability development. Experts noted that bioenergy in Japan has not taken advantage of advancements in data analytics. “Data on bioenergy is not collective, and without this we cannot have metadata and understand general trends to enable innovation.” “Data and ICT can help bring up-to-date information to the market, and enable telling stories on what is happening.” It can be suggested that improved data collection, sharing, and analytics can support a stronger foundation for decision-making as well as innovation in the woody biomass supply chain. However, there may be several challenges in this context, such as a paper-dependency Japan. It is suggested rural entrepreneurs in local communities may be key players in overcoming such challenges, facilitating innovation, maintaining market knowledge, and assessing assets (Mayer et al., 2016). Rural entrepreneurship refers to the creation of a “new organization that introduces a new product, serves or creates a new market, or utilizes a new technology in a rural environment” (Wortman, 1990). Such entrepreneurs can also be key players to support knowledge-sharing and urban-rural linkages (Mayer et al., 2016).

**Stakeholder respect, relationships and trust**

The collocation of key words related to stakeholder respect, relationships and trust is shown in Figure 17. The most frequent key word is forest, with links to people, forest owners, and wood for energy purposes. Emphasis can also be seen on ICT services for supply chain communication and transparency. Transparency is related to information of resources and prices across the chain, which experts noted enables trust among upstream and downstream stakeholders. In this context, GIS, database development, and digital forest certification were given as potential enablers of accountable and transparent wood information-sharing. “Certification is traveling along the supply-chain. And bringing it digitally via ICT services, this could be very helpful for tracking services…”. Paper-based tracking has dominated the wood supply chain in Japan, which in turn increases faulty data or fraud risk. Experts noted that digitalization can support transparency, empower stakeholders, avoid fraud, aid in trust-building, and enable due diligence. For example, improved supply chain traceability can enable due diligence in terms of sustainability compliance. It is suggested that information-sharing can support compliance, management and transparency for supply chain interconnectivity. As described by one expert, “the more you move into an industrial environment, you need to communicate easily between groups and understand issues and each step of the process because they are so interconnected.”

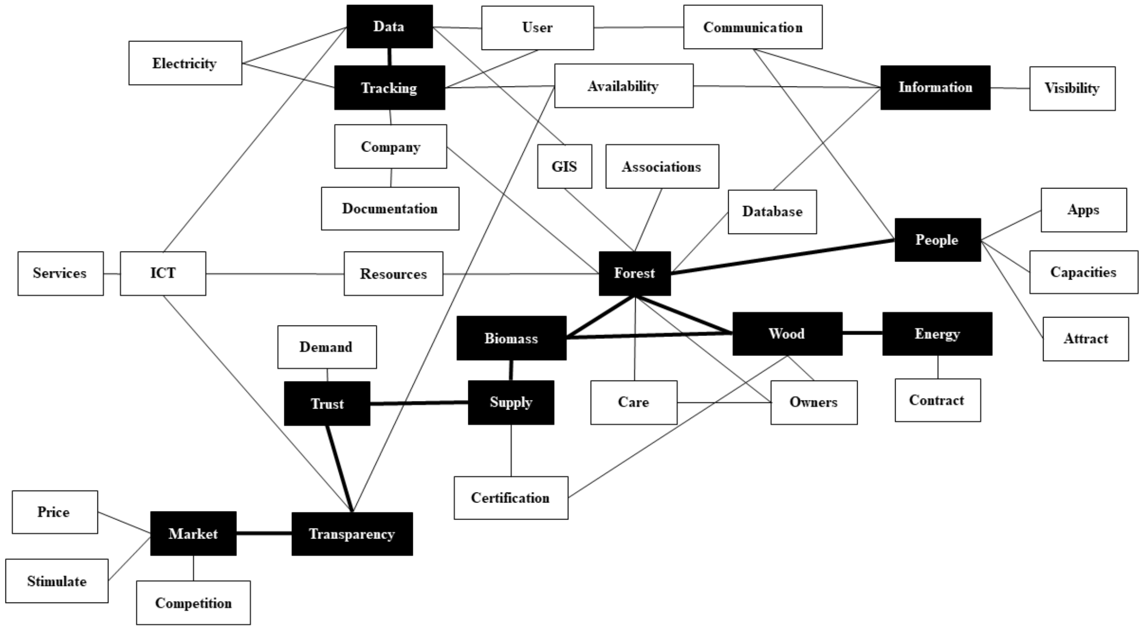


**Figure 17** Collocation diagram: digital technologies and the stakeholder relationships and trust challenge (Ahl et al., 2019 b) (Black boxes: key words among the top five frequencies. White boxes: words associated with key words. Think lines: connections between key words. Thin lines: connections to associated words).

In addition, improved tracking and sharing of data related to biofuel origins was emphasized by experts. "Tracking systems for electricity have become important… for a Guarantee of Origin (GoO)…". However, as noted by experts, tracking and sharing of wood data is lacking in Japan. Numerous digital technologies can be used to improve tracking systems, such as cryptographic GoOs on blockchain platforms (Castellanos et al., 2017). This can support fraud-resistant certification as well as the tracking of stakeholders and resources (Castellanos et al., 2017). To the authors' knowledge, while there have been no projects of blockchain platforms for wood supply chains in Japan, such platforms been investigated in other sectors. For example, the Japanese firm iSiD (2016) is exploring the use of blockchain for organic agricultural product traceability. This can in turn be used for customer reassurance of product origin and food safety (iSiD, 2016).

The experts further highlighted supply chain transparency and price visibility as an important catalyst for market competition. There is gap of awareness related to wood prices between the upstream forest owners and the downstream wood supply chain in Japan. "Forest owners do not have the means to track their timber after production and sales. Owners should learn how the wood is used in the downstream and the real value of the wood." Through transparent supply chain resource flows and prices, "forest owners may more easily find value on the market". A digital market platform may contribute to consistent access to price and resource information among all stakeholders.

Similarly discussed by Scuotto et al. (2017), digital platforms or "electronic markets" can facilitate communication, trust, coordination, and cost reduction among organizations (Scuotto et al., 2017). Thereby, stakeholder relationships, interaction, knowledge-sharing (Scuotto et al., 2017; Lopez-Nicolas and Soto Acosta, 2010), new entrants, and strategic partnerships (Scuotto et al., 2017) can be supported. Experts further noted that a digital platform could be used to more effectively integrate downstream demands into upstream harvesting decisions, as well as to incentivize biomass quality management to a greater degree. Experts also discussed that a digital market platform could especially empower upstream suppliers by reducing the wood price awareness gap in Japan. As discussed by Vinterbäck and Porsö (2011), market transparency and pricing mechanisms have been central in bioenergy advancements in Europe. This transparency has been supported by open data related to wood and biofuel prices (Vinterbäck and Porsö, 2011).

Digital technologies can increase transparency in the supply chain, but practical applications may encounter technical as well as social challenges. For example, one expert noted that "having a solid network in place to guarantee real-time communication between forest operations and market demand is key to success." Poor network coverage in remote forest ranges can inhibit the use of digital technologies (Gingras and Charette, 2017). Shared communication infrastructure, co-developed by telecommunication and energy companies, is one potential solution in this regard (Camarinha-Matos, 2016). From the technical perspective, low-orbit satellites can also be useful for network infrastructure expansion in remote areas (Briggs et al., 2019).

Social challenges may also arise, such as efforts to collaborate across the supply chain for ICT integration and data-tracking. As noted by experts, digital skills are not abundant in rural areas. Furthermore, trust-building cannot solely rely on digital solutions. "ICT can contribute and support this (trust) a lot but finally we cannot replace personal contact." Some experts emphasized that stakeholders may in fact favor direct communication for discussions and knowledge-sharing. Lopez-Nicolas and Soto Acosta (2010) discussed difficulties in communication for tacit knowledge formalization. The integration of face-to-face interaction and workflow-oriented digital platforms among stakeholders may be a solution in this context (Lopez-Nicolas and Soto

Acosta, 2010).

There is a multitude of potential social and institutional challenges in supply chain digitalization. For example, deficient trust among stakeholders can inhibit social practices for innovation (McCauley and Stephens, 2012). Kache and Suring (2017) emphasized trust, collaboration, governance, compliance, and information security as key issues. Traditional cultures and low ICT utilization rates are also challenges of digitalization in the forest sector, coupled with a lack of research and development on the topic (Kies and von Lengefeld, 2018). Cyber-physical developments among local companies are inhibited by lacking digital skills as well as risk aversion related to new technologies (Barile et al., 2018).

It is suggested that social challenges point towards a need for community engagement to manage risk perceptions and co-develop new systems. Community engagement was highlighted by several experts. "You need to build trust and a sense of connection… building better supply chains and show where they (community) impact the system." Awareness and institutions can be influenced via such engagement, in turn facilitating sociotechnical system change (McCauley and Stephens, 2012). "To really bring projects further and mobilize people we need meetings, workshops…. Get people involved with discussion." As discussed by McCauley and Stephens (2012), trust-building and risk perception management can be supported by co-learning based on impressions and recommendations, in a sustainable energy "buzz."

**Local community revitalization and socioeconomic development**

The results, as illustrated in Figure 18, are centered on rural socioeconomic progress, local supply chains, and local bioenergy. Local bioenergy is connected to people and rural economy vitalization. Experts discussed that the localization of woody biomass supply chains can reduce transport costs, support green energy, take advantage of stakeholder synergies, and expand local value creation. Community ownership and investment models can indeed strengthen synergies among local stakeholders (Mangoyana and Smith, 2011). For example, an expert noted that small-scale wood suppliers can be supported via collective collection and processing of wood. This may be through aggregated wood-chipping or coordinated mobile-chipping upon harvest. Furthermore, CHP integrated with local heat demands was discussed by experts, with potential to support local woody biomass suppliers as well as community energy security.

The effective management and value creation of local resources is a key issue. "Utilization of forest resources will lead to the promotion of autonomy by revitalizing regional economies. In

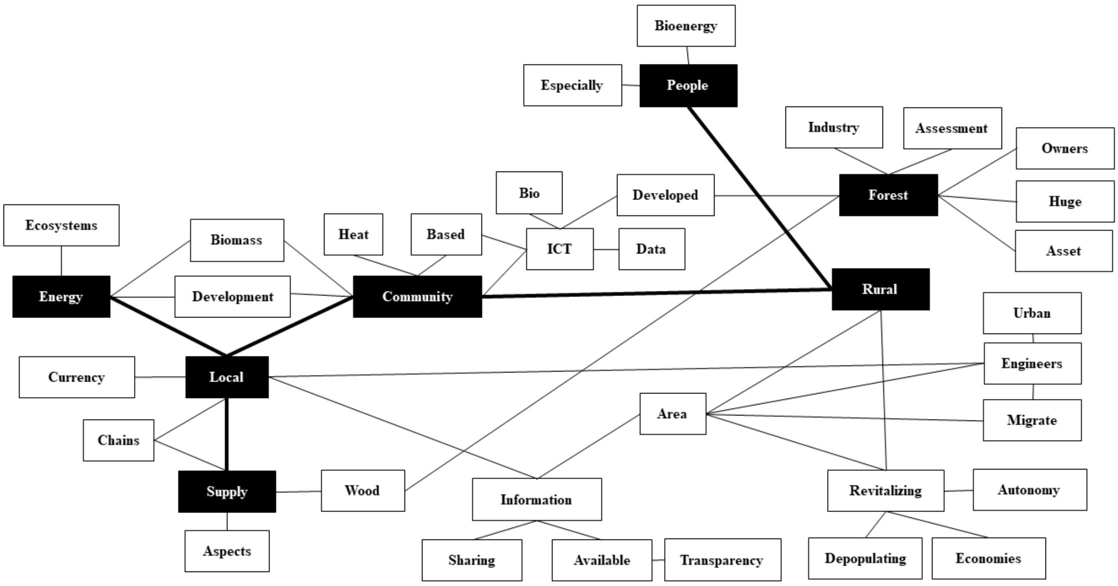


**Figure 18** Collocation diagram: digital technologies and the local socioeconomic development challenge (Ahl et al., 2019 b) (Black boxes: key words among the top five frequencies. White boxes: words associated with key words. Think lines: connections between key words. Thin lines: connections to associated words).

the strategy for resource utilization, it is necessary to position ICT." Experts noted that ICT can support optimization in supply chains and bioenergy business practices. This can be done, for example, though improved access to information on the species, distribution, and quality of trees. The integration of upstream forestry, biofuel production, and downstream energy system processes can be reinforced by ICT in decentralized market platforms. Such platforms can link multiple consumers and suppliers. "Local people (in Japan) do not have access to market tools, and can therefore not assess their value in their community". It is proposed that such market platforms would benefit local supply chains and connectivity among small-scale players. "Electronic markets" can decrease management costs and enable market entry, especially for small and medium-sized enterprises (Scuotto et al., 2017). Also noted by experts for other challenges, such as stakeholder respect, relationships and trust, digital market platforms may support innovation in Japanese woody biomass supply chains. An expert shared an example of an online platform called eTree: an open wood market for small-scale manufacturers in Japan (eTree, 2018).

While digital technologies have potential to contribute to innovation in the woody biomass supply chain in Japan, practical implementation may face a number of different issues. As put by one expert, "…Japanese startups or venture companies are not interested in the forestry sector…". There is an urban-rural digitalization and connectivity gap in Japan (Nishida et al., 2017), which may inhibit socioeconomic development (Salemink et al., 2017). Connectivity coupled with digital skill-building would be important in overcoming this gap in rural areas (Salemink et al., 2017). Improved connectivity may in turn attract talent and further contribute to local economic progress (Salemink et al., 2017). Experts also discussed prospects of urban-to-rural relocation of technical staff, such as software engineers.

"The future of work in urban and rural areas can be changed to a more dynamic city-rural interplay." Such urban-rural linkages, as argued by Mayer at al. (2016), can facilitate economic relations and sustainable growth. An important question is related to incentivization for migration. In a study on agriculture in China, Melo and Ames (2016) found that wage raises alongside technological progress can be key incentives for urban-to-rural migration. Furthermore, public-private biomass investment frameworks can support long-term talent- and capital-pooling (Mangoyana and Smith, 2011). Finally, as noted by an expert, it would be crucial to "work with the community and also with the local government for infrastructure development as this depends on local management."

### 2.2.5 Integrated overview

Based on expert insights, Table 3 presents an overview of digital technologies and mechanisms by which they can contribute to overcoming the explored challenges. It can be noted that the technologies and mechanisms often overlap across technical and social challenges. Concentration can be seen on the use of data, ICT, and information-sharing to support value creation in local supply chains. Furthermore, digital market platforms were discussed as a key mechanism for numerous challenges, such as business model integration and stakeholder relationship-building.

**Table 3** Digital technologies and mechanisms by which they may contribute to overcoming challenges in the woody biomass supply chain in Japan. (AI: Artificial intelligence; ICT: Information and communication technology; IoT: Internet of Things; GIS: Geographic Information System; VR: Virtual Reality) (Ahl et al., 2019 b)

| Challenge | Mechanisms | Technology |
|---|---|---|
| **Transportation infrastructure** | Transparency, information-sharing, communication, process efficiency | **ICT + sensors** |

| | | |
|---|---|---|
| | Value maximization, process efficiency (harvest and transport), safety, cost reduction | **Robotics, autonomous machines** |
| | Safety, efficiency, harvest planning, accurate assessment, 3D-mapping, route-planning and optimization, cost reduction | **GIS + remote sensing** (Optical data + laser scanning from drones/satellites) |
| | Safety, awareness, learning, training, forest management | **VR** |
| **Biomass quality monitoring and control** | Transparency, information-sharing, communication, accountability, fraud prevention, digital certification, material-tracking, market platform, accurate assessment, process efficiency | **ICT + sensors** |
| | Accurate assessment, process efficiency | **Image analytics** |
| | Accurate assessment, process efficiency, forest management | **GIS + remote-sensing** (Optical data + laser scanning from drones/satellites) |
| | Transparency, traceability, fraud prevention, material-tracking | **Blockchain** |
| | Material-tracking, accurate assessment, process efficiency | **IoT** |
| | Decision support, process efficiency | **AI** |
| **Business model integration (cascading)** | Transparency, information-sharing, communication, visibility, material-tracking, market platform, value maximization, traceability, collaboration, informed planning | **ICT + sensors** |
| | Accurate assessment, information-sharing, forest management, informed planning | **GIS + remote-sensing** (Optical data + laser scanning from drones/satellites) |
| | Automation, value chain optimization, process efficiency | **Robotics, autonomous machines** |
| | Process efficiency, awareness, learning | **Image analytics** |

| | | |
|---|---|---|
| | Material-tracking, collaboration, informed planning | **IoT** |
| **Building stakeholder respect, relationships and trust** | Transparency, information-sharing, communication, visibility, accountability, fraud prevention, digital certification, material-tracking, market platform | **ICT + sensors** |
| | Transparency, information-sharing, accurate assessment | **GIS + remote-sensing** (Optical data + laser scanning from drones/satellites) |
| | Transparency, traceability, accountability, fraud prevention, material-tracking | **Blockchain** |
| **Local community revitalization and socioeconomic development** | Transparency, information-sharing, communication, accurate assessment, material-tracking, value maximization, process efficiency, market platform, informed planning, knowledge-sharing | **ICT + sensors** |

The aim of this overview is to share initial prospective mechanisms through which digital technologies can contribute to woody biomass supply chain improvement. In reality, there will likely be numerous barriers to digitalization, and implementation would be dependent on local context. For example, while some of the technologies are relatively developed, such as GIS, others are emerging with technical, economic, and regulatory uncertainty. Examples include blockchain, VR, and autonomous machines. In addition, the financial and human capacities of companies to develop and implement digitalization strategies are uncertain. In Japan, several forest owners are small-scale and may not have the financial capacities to implement new digital solutions. There is also an urban-rural gap in digitalization and internet access in the country (Nishida et al., 2017). The existence of multi-faceted issues of digitalization in the woody biomass supply chain suggests a need for additional research, such as on technical, economic, and social feasibility. For example, the availability of talent to conduct development, implementation, and maintenance would be crucial. It is suggested that there is a need of a cohesive, multi-faceted approach in developing woody biomass supply chains and digitalization therein. What may such approaches be, and what are potential directions for change mediation? This is briefly discussed further as follows.

Experts emphasized a need to direct attention to stakeholders, objectives, and skills. Barile et al.

(2018) similarly highlighted that key drivers of sustainability sit in both technological and human dimensions. It is suggested that local context and capacities, such as physical infrastructure as well as social capital and talent, would be crucial in woody biomass supply chain digitalization strategies. Political and societal abilities of new technology adoption strongly influence renewable energy projects (Lund et al., 2017). While there are manifold prospects for digitalization in the woody biomass supply chain, local biomass innovation calls for stable (Proskurina et al., 2016; Jiang et al., 2017; Brewer II et al., 2018), targeted policies to leverage such prospects as well as manage challenges (Welfe et al., 2014).

"Japanese forestry is highly subsidy-dependent with forest management costing a lot." Experts discussed a need for market development and enhanced competition for progress in the forest sector in Japan. "We need to move away from subsidies and more to the private sector… The FITs are in the power market, and do not stimulate much market competition." Competition may strengthen innovation efforts among woody biomass supply chain stakeholders, including digital innovation. As discussed by Yarime and Karlsson (2018), market liberalization, subsidy-independent business models, capacity-building, and standard-setting for hardware and software may support entrepreneurship for energy innovation in Japan.

In addition, experts discussed change mediation and regional managers for the support of digital innovation. Mediation would depend on the local stakeholder network and relations therein. Change mediators may include rural entrepreneurs, local governments, co-working spaces, forest associations, and other local establishments. Public incentives, such as tax concessions or employment provisions, may be useful to initially boost entrepreneurship in rural areas in the short term (Johnsrud, 1991). This is important because rural change agents, such as entrepreneurs, can be key stakeholders in both rural activities and urban-rural interactions (Mayer et al., 2016). Such agents can integrate local knowledge, social capital, and market access (Mayer et al., 2016). It would be important for rural entrepreneurs to remain informed on industry developments and to maintain contact with urban as well as other rural areas, such as through networking events and study clubs (Mayer et al., 2016). It is suggested that such knowledge-sharing and networking efforts may be valuable in the context of woody biomass in Japan. As put by an expert, bioenergy stakeholders in Japan "cannot share information of their experiences, whether bad or good." The expert explained that knowledge-sharing platforms could be central for woody biomass development and integration of digital technologies.

It is further suggested that extension agents dispatched from universities can support community development and change mediation. Agents with expertise in both digital technology and woody biomass would be advantageous in the context of this study. Agent activities may comprise of knowledge-sharing, facilitating the establishment of local organizations, and enabling community-government communication (Oakley and Garforth, 1985). METI (2019) has also emphasized a need to improve business environments for renewable energy, such as via information liaisons for "regional symbiosis." For example, advanced use cases among local governments may be incorporated into such information (METI, 2019 a). Bottom-up approaches through participatory planning with local communities and organizations such as forest cooperatives, as well as workforce management, are key in forestry extension programs (Clark, 1982).

On the one hand, experts noted that renewable energy ecosystems and bottom-up approaches can contribute to local socioeconomic development and energy security. On the other hand, experts emphasized issues in grid access, distribution, and transmission capacities. With such issues at hand, woody biomass supply chain development would require "local efforts but also top-down regulation and support". The combination of a bottom-up, community-based approach and top-down, regulatory support may contribute to regional woody biomass developments and digital innovation. As discussed by Esparcia (2014), public actor involvement and funding can be fundamental in rural energy and environmental innovation (Esparcia, 2014). For example, in Europe such projects usually depend on governmental institutions, external experts, and public funding at the onset to thereafter gradually develop economic independence (Esparcia, 2014). While incentives are useful to stimulate entrepreneurship and innovation in the short-term, for long-term competitiveness subsidy-independence would be important (Yarime and Karlsson, 2018). Bio-based economies supported by digital technology and public-private frameworks may present new prospects to revitalize local economies, which may be of interest for Japan when considering the nation's rural depopulation.

While this study indicates initial prospects for digital technologies in the woody biomass supply chain in Japan, its exploratory approach is limited to findings in a Japanese region and to the expert interviews. There is no "one-size-fits-all" solution for sustainable energy (Brewer et al., 2018; Arasto et al., 2017). It is suggested that it would be important to consider a toolbox of technologies based on local conditions. While energy systems need to be tailored to local context, knowledge can indeed be garnered from learning curves in other regions (Goldthau, 2014). This study may be valuable as an initial exploration of pathways for digital technologies in the woody biomass supply chain, based on practical sociotechnical issues. Exploratory evidence was presented for such pathways, with a need for broader investigation in future studies. There is a need for further research on the economic, social, and regulatory feasibility and approaches for digitalization in the woody biomass supply chain in Japan.

### 2.2.6 Summary

The objective of section 2.2 was to analyze how digital technologies can be used to overcome challenges in the woody biomass supply chain in Japan. One the one hand, the adoption of digital technologies in supply chain and stakeholder management has been extensively explored by scholars. On the other hand, there is a lack of research on the integration of such technologies in woody biomass supply chains. Section 2.2 explored this gap and created initial implications on how digital technologies may contribute to woody biomass supply chains, exemplified based on a case in Japan.

Data collection, management, and analytics can be supported by digital technologies across the supply chain. Such technologies facilitate several mechanisms, such as information-sharing, transparency, interconnectivity, value maximization, and automation. It is suggested that such mechanisms can contribute to alleviating both technical and social challenges in the woody biomass supply chain, including transportation infrastructure, biomass quality management, business model integration, relationship management, and local socioeconomic development.

Conversely, a number of digital technologies are new and still developing, suggesting technical, social, financial, and policy uncertainties. Considering the rapid digital developments of today, the gradual and flexible development of a toolbox of technologies is proposed. Furthermore, with a focus on local sociotechnical context, this toolbox can be designed for an integrated, cohesive approach to digital innovation in the woody biomass supply chain. This focus may be facilitated by local community engagement, co-development, skill-building, as well as supportive institutions. In terms of institutions, digital innovation in the woody biomass supply chain may be supported by participatory planning, change mediators, the inclusion of both external experts and local actors, incentives for rural entrepreneurship, initial public funding, and long-term financial self-sufficiency development. Section 2.2 presented exploratory results and initial implications. These implications suggest that further exploration on the nexus of woody biomass and digital innovation is of interest both in academia and among practitioners. This would benefit from the incorporation of multiple perspectives, such as social, economic and environmental sustainability.

# Chapter 3 How can blockchain technology facilitate distributed energy systems in Japan?

Energy generation and consumption produce the majority of global GHG emissions, and therefore need to be in core climate change mitigation efforts (IRENA, 2018). This calls for the expansion of renewable energy, such as woody biomass and other diverse resources. However, the distributed and intermittent nature of renewable energy increases uncertainty and coordination difficulties on the power grid (Arcia-Garibaldi et al., 2018). For example, as discussed by Parag and Sovacool (2016), the rapid diffusion of rooftop solar and increase in prosumers has led to operational complexity and power grid disruptions, such as voltage spikes. Alanne and Saari (2006) similarly emphasized flexibility, locality, and networking (interaction among network nodes) as key challenges of distributed energy.

To cope with these issues, smart grids are in need of further advances in communication, control, and dispatch protocols (Parag and Sovacool, 2016). At present, it is suggested that energy and smart grids are at large closed and centralized systems with little end-user involvement and information asymmetries that can be exploited by larger market players. It is further suggested that new technologies are necessary to advance renewable energy expansion, support grid integration, ensure energy balance, and manage energy markets. In this context, distributed digital systems can be an important counterpart for distributed energy. Blockchain has received significant attention as a digital distributed platform which could transform value chains.

Blockchain is essentially a distributed ledger that carries out transactions without a third party, instead based on validation and security through consensus mechanisms and cryptography (Killmeyer et al., 2017; Nakamoto, 2008; Yli-Hummo et al., 2016). Transactions are validated based on computation (Stack Exchange, 2019). Blockchain can support transaction cost reduction on multiple scales (Cohn et al., 2017) via this exclusion of intermediary financial institutions (Nakamoto, 2008). Blockchains record information in a decentralized way (Memoori, 2017; Raconteur, 2016), for both tangible and intangible assets (Killmeyer et al., 2017). Upon reaching consensus among all parties, transaction data is stored in a block linked to all preceding blocks in a chain, which is shared with the network, enabling transparency and accountability (Green and Newman, 2017; WU GTPC, 2017). Thereby, all network participants can have transparent access to information, and value exchange can be automated and disintermediated (Potts et al., 2017). Advancements in blockchain platforms may also enable real-time transactions (Raconteur, 2016) at dispersed, micro-scales (Mengelkamp et al., 2018 a).

The underlying technology is not new, but its recent surge of emerging applications is disruptive (Wong, Personal communication; Gabison, 2016) due to abilities of disintermediation, irreversibility, near-incorruptibility, and economic decentralization (Gabison, 2016). Blockchain received over 1.4 billion USD in commercial investment 2014-2017, and has also been increasingly adopted in new public service trials as well as rollouts (Killmeyer et al., 2017). For example, in 2018 the World Bank Innovation Lab and Commonwealth Bank of Australia released the world's first blockchain-based bond (Livemint, 2018). Central banks including in Sweden, Denmark, and the United Kingdom are also investigating prospects of national digital currencies (Carlström, 2016).

As discussed by Hurwicz (1969) decentralized information is an important catalyst for market competition, linkable to the debate of laissez-faire. By enabling transparent, decentralized information and transforming economic models, blockchain can encourage innovation and support small economic players (Casino et al., 2019; Rocamora and Amellina, 2018). It also allows for new forms of trading, such as P2P transactions among prosumers in the energy sector (Brilliantova and Thurner, 2018). As emphasized by Vainio et al. (2019), citizens can contribute to sustainable energy transitions when given possibilities to actively engage. The decentralization and empowerment of small economic actors made possible by blockchain may in turn support this engagement.

Also referred to as the "Internet of Value" (Tapscott and Tapscott, 2016), blockchain can indeed be used to tackle several challenges in the Energy Internet, such as consensus, flexibility and security (Yang et al., 2017). In terms of security, it is harder to hack a blockchain as opposed to a central server (Potts et al., 2017). Each block on the blockchain is coded with a hash function which affects the hashes of succeeding blocks, enabling exposure of tampering (Khaqqi et al., 2018). Such features can contribute to P2P models and distributed energy (Park and Yong, 2017; Potts et al., 2017; Raconteur, 2018; Romero, Personal communication).

Through the integration of blockchain platforms in smart grids, it is suggested that several windows of opportunity can be opened. These may include new business models, and more transparent and decentralized markets. In this way, the technology may support more efficient energy markets as well as consumer choice and empowerment. However, there is a lack of knowledge and research related to prospective prosumer markets for distributed energy and blockchain applications. As emphasized by Noor et al. (2018), there is a need of holistic conceptualization of blockchain-based energy distribution. Exploring this gap and providing insights may be valuable in the formation of digital energy strategies in Japan as well as globally.

With this, the objective of section 3.1 is to describe the opportunities and challenges of blockchain-based energy systems. First, a wide-ranging review of the opportunities and challenges of blockchain applications specifically for P2P electricity microgrids is conducted. Second, rooted in key findings of the aforementioned review, an analytical framework for blockchain-based microgrids is proposed. This framework includes technological, economic, social, environmental and institutional dimensions. Finally, the framework is discussed, concluding with implications for practical institutional development as well as academic research.

Based on the developed framework, the objective of section 3.2 is to analyze the opportunities and challenges of blockchain-based electricity distribution in Japan. It is suggested that the incorporation of blockchain and other digital strategies involves an energy transition. Transitions often lead to uncertainties related to technological and social change (Hughes et al., 2013). Indeed, energy transition analyses call for incorporation of technological, economic, social, environmental, and institutional dimensions (Hansen et al., 2019; Saveedra et al., 2018; Bale et al., 2015). It is suggested that the multi-dimensional framework developed in section 3.1 is useful in the analysis in section 3.2. Through an exploratory approach, a blockchain-based P2P microgrid case in Urawa Misono, in the Saitama prefecture of Japan, is analyzed. This case was selected because it is the first blockchain-based P2P power-trading microgrid project in Japan, and at the time of this study also the only project. (For an additional recent commercial project case in Japan, please see Appendix A2). Concrete challenges affecting the case are explored, alongside opportunities to overcome them. Finally, indications for practitioners as well as academia are proposed.

### 3.1 A review of the challenges and opportunities of blockchain-based electricity systems

Distributed energy has been expansively discussed in academia (Hirsch et al., 2018; Di Silvestre et al., 2018 a; Soares et al., 2018). The support of distributed systems that blockchain may facilitate can be an important addition to this discussion. A simplified diagram of this shift, including power and information flow changes, was shown in Figure 8 in section 1.2.3. Centralized energy systems were initially created for a flow of high voltage fossil fuel-based power to low voltage loads (Soares et al., 2018). Energy decentralization has grown with increasing residential, small- and medium-scale renewable energy generation. This is increasingly supported by smart grid systems and microgrid setups. Several authors have noted that blockchain may also support energy decentralization, by enabling power producers, prosumers, and consumers to trade electricity in distributed P2P networks in microgrids (Mengelkamp et al., 2018 a; Memoori, 2017; Pop et al., 2018; Hirsch et al., 2018; Mengelkamp et al., 2018 b), and even in multi-microgrid networks (Hirsch et al., 2018).

Blockchain can be used in the balancing of demands and prosumer supplies, which can be coordinated based on conditions in smart contracts (Pop et al., 2018). In this way, excess power can be traded at transparent prices (Campbell, 2017). A smart contract is programmed into the blockchain, and automatically conducts transactions based on pre-determined conditions (Tanaka et al., 2017; Efanov and Roschin, 2018; WU GTPC, 2017). Such conditions may include energy sources, price ceilings, and price floors (Mengelkamp et al., 2018 a; Mengelkamp et al., 2018 b; Tanaka et al., 2017). Control is thereby increasingly shifting to citizens and governance is becoming more decentralized (Potts et al., 2017). Green and Newman (2017) described this as the “democratization of electricity” via “citizen utility.” Users can be an integral part of a system as opposed to at its edge by leveraging involvement and data ownership on blockchain platforms (Potts et al., 2017).

### 3.1.1 Methodology

The research arena of energy blockchain applications is new and relatively unexplored (Tapscott and Tapscott, 2016; Cheng et al., 2017; Noor et al., 2018). When there is a lack of previous studies, an exploratory approach is beneficial for new insights and understanding (Streb, 2010). This is particularly valuable when exploring the boundaries of issues and opportunities, and identifying directions for further research (Van Wyk, 2012). An exploratory approach was adopted in order to support the conceptualization of blockchain-based P2P power microgrids and the development of a holistic analytical framework. This builds on the methodology of Mengelkamp et al. (2018 b), which incorporated a number of factors in a blockchain-based microgrid case analysis.

An analytical framework, TESEI, was developed including five main dimensions: 1) Technological, 2) Economic, 3) Social, 4) Environmental and 5) Institutional dimensions. Dimensions 1-4 were included in TESEI because technological, economic, social and environmental criteria are key components in energy decision-making (Pohekar and Ramachandran, 2004; Ozorhon et al., 2018; Afgan and Carvalho, 2002). The institutional dimension was added because related factors, such as regulation, also strongly influence the energy sector and innovation therein. Several other authors have noted the importance of institutions for energy innovation (Araújo, 2014; Arent et al., 2017; Koirala et al., 2016, Loorbach, 2010, Parag, 2015).

The factors included in each dimension of TESEI were based on an extensive review of academic as well as grey literature relevant to blockchain-based P2P microgrids. This review incorporated academic papers as well as news articles, reports, white papers, conference presentations, and press releases. The purpose of this was to capture the rapid progress of blockchain, multi-dimensional issues of blockchain-based P2P microgrids, as well as practical opportunities moving forward. The selected factors were based on the literature indications and conclusions of key issues and factors in this field. While some authors shared unique issues, the majority of the factors included in TESEI were emphasized by numerous authors. The factors in each dimension were organized into categories in order to clarify key concepts in each dimension and indicate practical areas of interest. These categories were created based on factor inter-relatedness and opportunity for mutual benefit. For example, the category of "institutional innovation mechanisms" included factors pertaining to community-building and co-development (among others) which can be mutually beneficial.

In addition to a literature review, complementary insights were garnered via interviews with five experts. An outline of the interview structure can be seen in Appendix C1. An expert was identified as an industrial or academic player with experience and/or actively working with blockchain and/or blockchain energy applications. Reference to the experts can be seen as 'Personal communication.' The experts and their affiliations can be seen in the Acknowledgements in Appendix C2. Three interviews were conducted face-to-face, and two through conference call. The experts were asked to discuss blockchain-based P2P microgrids challenges pertaining to each TESEI dimension. The purpose of these interviews was to identify current and practical issues of blockchain-based P2P microgrids which may not have been covered yet in the literature. Interviews were semi-structured and open-ended, with the same phrasing of questions among all interviewees, with follow-up questions as necessary. This enables interviewees to share comprehensive and thorough replies (Turner III, 2010).

### 3.1.2 Analytical framework development: TESEI

The foundation of TESEI aims to incorporate the multi-dimensional issues of blockchain-based P2P microgrids. It is suggested that TESEI may present useful insights and contribute in analyses of blockchain microgrid applications. It is further suggested that analysis of each dimension as well as their interrelatedness would be important in short- and long-term strategy developments. TESEI is proposed for use among practitioners as well as in academia. The framework itself may also be further developed in academia. As follows, each dimension is explored, and the overall framework as well as the interrelatedness of its dimensions is discussed.

**Technological dimension**

Technology is a key dimension in decision-making in energy system developments (Ozorhon et al., 2018). The technological foundation of blockchain applications in microgrids is relatively established, when put in contrast with its social and regulatory uncertainties (Mengelkamp et al., 2018 b). The technological dimension of blockchain-based energy distribution has gained attention in academia. For example, based on power-trading scenario data, Oh et al. (2018) modelled a multi-chain blockchain platform and found that concurrent electricity and financial transactions could be effectively carried out. Another example is the simulation-based research by Tanaka et al. (2017), exploring P2P power-trading on a private Ethereum blockchain. These simulation models assumed the use of bi-directional digital inverters and explored multiple solar generation levels, storage capacities, and demand profiles (Tanaka et al., 2017). Results indicated that local exchange could be carried out and energy waste reduced, even when omitting storage (Tanaka et al., 2017). An additional example of simulation-based research is the exploration of blockchain for DR by Pop et al. (2018). The authors found that energy loads and supplies could indeed be balanced based on an Ethereum blockchain and smart contracts (Pop et al., 2018). Hwang et al. (2017) studied prosumer business models also based on laboratory simulations, and proposed an efficient transaction model for virtual trading with a foundation in blockchain and IoT.

Technological issues of blockchain infrastructure

It would be valuable to initially encompass technical issues of blockchain and potential impacts such issues may have on P2P microgrids. Currently there is low throughput or transactions per second (tps) on platforms such as Bitcoin and Ethereum (EdChain, 2018), at 3-7 and 12-30 tps respectively (Prentiss, 2018). The computational intensity and costliness of consensus mechanisms has led to scalability challenges (Efanov and Roschin, 2018; Gabison, 2016; Wu and Tran, 2018; Mengelkamp et al., 2018 b; Bloomberg, 2018). The creation of each new block on the blockchain may require energy-intensive computation, which increases with larger quantities of data (Gabison, 2016; Mengelkamp et al., 2018 b). Proof of Work (PoW) is a one of the main consensus mechanisms used at present, which requires the solving of a complex mathematical problem for the validation of new blocks (Efanov and Roschin, 2018). This mechanism enables disintermediation, combats fraud, and avoids double-spending (Efanov and Roschin, 2018). However, PoW requires high levels of central processing unit (CPU) power and can therefore be energy-intensive, based on computational difficulty (Romero, Personal communication; Mishra, Personal communication), and have a high latency (Andoni et al., 2019). Graphics processing units (GPU) and Application Specific Integrated Circuits (ASIC) have been increasingly adopted to increase PoW and cryptocurrency mining efficiency (Seth, 2018). However, CPU, GPU and ASIC are all still highly energy-intensive (Li et al., 2019).

New consensus mechanisms are contributing to energy-intensity reduction and blockchain scalability. A key example is Proof-of-Stake (PoS), through which validation of transactions is based on assets or owned cryptocurrency units (stake) (Romero, Personal communication; Bergman, 2018; Bambrough, 2018). This means that neither particular hardware nor high energy consumption is needed for validation of new blocks (Romero, Personal communication; Bergman, 2018; Bambrough, 2018). Proof of Identity (PoI) is an additional example, grounded on hash-based user identification for validation as opposed to stake (Mengelkamp et al., 2018 b; Romero, Personal communication). PoI also requires lower CPU, energy consumption, and transaction costs as opposed to PoW (Mengelkamp et al., 2018 b; Romero, Personal communication). This mechanism may be apt for private (Mengelkamp et al., 2018 a) or semi-private (Romero, Personal communication) blockchains with selective access in local energy markets. A semi-private network means that a single unit permits access to eligible users (Mougayar, 2016). In a private blockchain, there are fewer members and the blockchain network is managed by those members (Mougayar, 2016). Rapid blockchain development is undoubtedly ongoing, and it would be of interest to explore how this progress and various blockchain typologies may be applied to energy use cases in future studies.

Issues of scalability and energy-intensive mechanisms may inhibit economic and environmental sustainability if blockchain is applied in distributed energy systems. However, developments for enhanced blockchain scalability, performance, and security are continuously being introduced (Buterin, Unpublished results). For example, sharding involves the creation of side-chains which are run in parallel. This increases scalability because it can lessen the quantity of data on each chain (Nafqvi, 2018), thereby increasing throughput and decreasing latency. Such advancements could contribute to scaling as well as business model innovation across sectors (Lee, 2018). Nafqvi (2018) noted that communication across sidechains is indeed in need of further progress. However, blockchain is still rapidly advancing and organizations are making progress in cross-chain communication and other measures for enhanced scalability. For example, Polkadot is a multi-chain platform which allows for integration and communication across chains in an ecosystem with standardized mechanisms (O'Neal, 2019). It is based on parallel blockchains (termed "parachains") that process transactions, and one relay chain which links parachains and validates transactions (O'Neal, 2019).

Energy management infrastructure

Both software and hardware components are key for quality, cost-effectiveness, and market support in microgrids (Basu et al., 2011; Long et al., 2018). Both are required for the coordination of bi-directional flows of electricity and information via smart meter infrastructure (Noor et al., 2018; Basu et al., 2011). The state of smart meter and smart grid expansion also affects the potential for coordination and reactive power via digital inverters (Cruz et al., 2018). This expansion can support congestion management, renewable energy interconnection, market efficiency, and new market entries (Cruz et al., 2018). This is important because energy autonomy in P2P networks can be facilitated by effective energy management and market mechanisms (Zhou et al., 2018). Especially when considering the complexity introduced in multi-prosumer P2P networks, coordination of the trading and dispatch of electricity and storage is vital (Mengelkamp et al., 2018 b; Zhou et al., 2018). Automated management based on bidding schemes, available supplies, and demands can enable energy-balancing in microgrids (Yarime and Karlsson, 2018; Mengelkamp et al., 2018 b; Zhou et al., 2018). This can also be leveraged in peak power management, to evade technical issues and avoid expensive network reinforcements (Zhou et al., 2018).

Energy management systems can maintain acceptable ranges of frequency and voltage, thereby also enabling the utility grid interconnection of distributed energy (Tanaka et al., 2017; Hirsch et al., 2018; Cruz et al., 2018). Tanaka et al. (2017) demonstrated that a back-to-back (B2B) setup, as shown in Figure 19, can be valuable in supporting grid interconnection through bi-directional conversion of voltage and frequency. Microgrid low voltage alternative current (AC) is first converted to direct current (DC), and thereafter to high voltage AC on the utility grid (and vice versa). With this isolation of microgrid frequency and voltage, issues that arise due to discrepancies between the utility grid and microgrid can be managed (Tanaka et al., 2017). This can in turn enable branched energy-balancing on multiple levels and microgrid-islanding, for enhanced energy security (Zhang et al., 2017 a). Such branched or meshed energy networks can alternate between closed and open branches for more dynamic and reliable distributed energy systems (Cruz et al., 2018). In addition, as discussed by Alladi et al. (2019), power metrics such as frequency, voltage and current can be recorded on blockchain blocks with timestamps. This can be leveraged to remotely monitor metrics and identify anomalies in remote terminal units (RTUs), which is important in the data transfer to and control of SCADA devices on the grid

(Alladi et al., 2019).

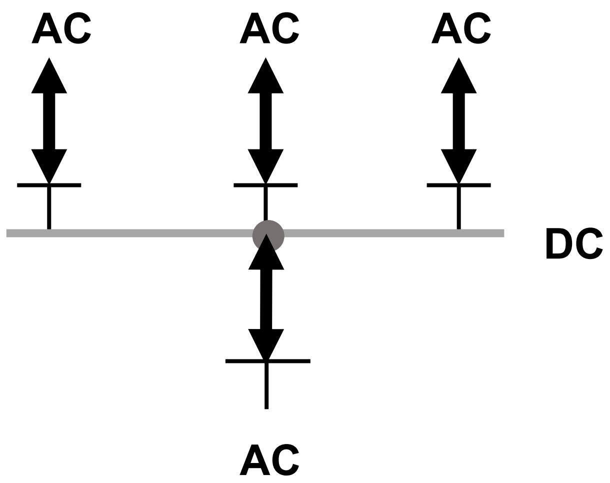


**Figure 19** Back-to-back (B2B) power conversion. Adapted from Tanaka et al. (2017)

Power grid infrastructure

On the one hand, microgrid-islanding is an important factor in system-planning (Mengelkamp et al., 2018 a; Hirsch et al., 2018; Cruz et al., 2018; Wouters, 2015; Basu et al., 2011), because it supports supply reliability (Cruz et al., 2018; Hanna et al., 2017) and may also be a regulatory requirement (Tsukamoto and Morozumi, 2014). On the other hand, microgrid interconnection with the utility grid can also be an important factor for energy security (Noor et al., 2018; Mengelkamp et al., 2018 b), such as for occasions when microgrids power supplies are insufficient. The integration of energy storage can also add to reliability, facilitate ancillary services, and support voltage management (Hirsch et al., 2018). It is suggested that storage is an important consideration in P2P microgrids, as it can be key enabler of power stability and quality (Cruz et al., 2018).

P2P energy-sharing mechanisms are increasing (Zhou et al., 2018), which in turn calls for several considerations in microgrid planning and management in the short- and long-term. An important issue is the interoperability between utility infrastructure and blockchain-based P2P microgrids (Killmeyer et al., 2017; Ogushi, Personal communication), which would also affect platform scalability (Killmeyer et al., 2017). With the rise in power exchange frequencies in P2P networks, the tracking and attribution of power loss would also be important in the evaluation and pricing of transactions (Di Silvestre et al., 2018 b). In addition, microgrid operations and maintenance (O&M) is needed in long-term planning (Hanna et al., 2017; Juan et al., 2017).

The P2P network

In addition to the physical utility grid and microgrid, the software layer is crucial in P2P power trading networks (Zhang et al., 2017 b). This is because it is essential for all nodes in the network to be reactive to grid conditions, market prices, and local supplies and demands (Park and Yong, 2017). The information system is key for microgrid responsiveness, market access, market-monitoring, and the coordination of prosumers and consumers (Mengelkamp et al., 2018 b). Blockchain is one platform to facilitate this information system and support the P2P network through simplified and decentralized metering and billing (Zhang et al., 2017 b). In this context, smart contacts can be used to automatically conduct bidding strategies and payments based on smart meter values.

Smart contracts register bidding strategies, notify the network on any changes thereof, and enable automated transactions (Noor et al., 2018; Mengelkamp et al., 2018 b). Effective consensus mechanisms as well as cryptography, data storage, and decentralized applications (dApps), such as virtual wallets, are needed in P2P networks (Noor et al., 2018). Each of these factors and their issues pose important directions for future research. For example, the storage of transaction records on a blockchain requires large data storage capacities across all nodes, and thereby higher energy consumption (Wu and Tran, 2018). In addition, there is a need to explore trade-offs between cybersecurity and consensus mechanism complexity, based on requirements in the energy sector (Mishra, Personal communication). It is suggested that these requirements depend on technology as well as economic, social, and environmental sustainability. As follows, the economic, social and environmental dimensions of TESEI are discussed. Insights on these dimensions will thereafter be leveraging in discussions on how institutions can be developed conjunctively with technological change.

**Economic dimension**

It is suggested that with the disintermediation made possible on blockchain platforms, the technology has potential to decentralize markets. This can open new windows of opportunity in the energy sector for business model innovation and new market entrants. As follows, energy market mechanisms, blockchain infrastructure, smart contracts, and prosumer business models are discussed.

Energy market mechanisms

Microgrids can support energy generation and demand diversity and connectivity (Hirsch et al., 2018). Technological innovation coupled with the liberalization of markets can in turn support microgrid energy-sharing, -trading, and -balancing (Wouters, 2015; Basu et al., 2011; Long et al., 2018). New markets mechanisms are also needed to support to expansion of technological innovation in P2P microgrids, with an example being local pricing (Zhou et al., 2018). There are numerous questions in the context of microgrids with P2P trading. For example, how would power-pricing be carried out? How would grid infrastructure be financed?

Parag and Sovacool (2016) discussed the currently sub-optimal mechanisms for energy-pricing, due to lacking representation of ToU and full costs in these prices. Clear, dynamic pricing mechanisms are needed for effective market competition and to support new market entrants. This may be facilitated through fixed infrastructure charges coupled with volumetric ToU or real-time pricing (Basu et al., 2011). McKenna (2018) similarly emphasized the macroeconomic net effects of decentralized energy and the importance of infrastructure charges. Infrastructure cost distribution among prosumers and consumers may be one pathway to ensure macroeconomic sustainability (McKenna, 2018). Grid ownership models and regulations would influence such infrastructure charges (Wouters, 2015; Juan et al., 2017). Fee-based pricing, used in platform markets, is an opportunity for energy service pricing (Weiller and Pollit, 2016). This would be in replacement of current transaction-based marginal cost pricing (Weiller and Pollit, 2016), which assumes energy as a commodity market.

Globally numerous energy markets are liberalized or in the process of liberalization, including Japan. This enables new markets, such as energy-balancing, ancillary, and retail markets. This is highly relevant for P2P microgrid business models. For example, prosumer supplies in P2P microgrids can be aggregated (Hwang et al., 2017; Mengelkamp et al., 2018 b) to provide ancillary services, such as balancing (Morris et al., 2012). An ancillary service market could incentivize support related to voltage, frequency, restoration, peak load, and balancing (Morris et al., 2012). This can be important for market competition, and a key opportunity for prosumers (Morris et al., 2012). The dynamics of P2P microgrids and energy market developments is of interest for further studies, especially as scenarios for prosumer markets are still uncertain.

Smart contracts and market interoperability

Blockchain can enable new mechanisms in decentralized energy markets, such as P2P trading, which would involve technological as well as business model change. The nature of this change will vary depending on market players, value propositions, and profit structures (Park and Yong, 2017; Zhou et al., 2018). Blockchain platforms can enable a number of new mechanisms, such as micropayments (Mengelkamp et al., 2018 a; Wong, Personal communication), load-scheduling based on internal as well as wholesale prices (Noor et al., 2018), and settlement time reductions (Wong, Personal communication; Noor et al., 2018; Romero, Personal communication). Real-time price settlements may be a key opportunity in managing and scaling complex blockchain-based P2P microgrids (Noor et al., 2018; Mengelkamp 2018 b). Through encrypted and automated business models for sales and purchases, smart contracts can facilitate transactions based on real-time energy loads and supplies (Noor et al., 2018).

This automation through smart contracts can incorporate system conditions and preferences, such as price ceilings and energy resources. Cruz et al. (2018) noted that shorter temporal resolutions can further facilitate energy pricing mechanisms that correspond to real system conditions. This may enable efficient billing and transaction clearance procedures. The use of smart contracts would influence P2P network efficiency, market mechanisms, and competition (Ogushi, Personal communication). P2P networks may involve both conventional utility contracts and smart contracts. A key uncertainty in this context is how such networks and smart contracts can be gradually integrated in the overall energy market (Ogushi, Personal communication).

In order to take advantage of the improvements of blockchain throughput and latency (Killmeyer et al., 2017; Potts et al., 2017), advancements are also needed in the interoperability of conventional and smart contracts (Ogushi, Personal communication). The effectiveness and transparency of distributed data-tracking enabled on blockchain platforms (Green and Newman, 2017; Gabison, 2016; WU GTPC, 2017) can contribute to energy source, contract, and financial traceability. This may be especially valuable if coupled with standardized data formats across organizations (Jackson, 2018). The relationship between smart and conventional contracts is of interest to be explored further, in order to understand a potential transition to prospective decentralized markets. More well-defined roles of prosumers and microgrids in the energy market are also proposed as an important area when exploring contract interoperability and prosumer business models.

Prosumer business models

If prosumers can participate both in wholesale markets and local P2P microgrids, their trading strategies may incorporate self-consumption, storage, and power purchases based on multiple market prices. Preferred renewable energy proportions (Mengelkamp et al., 2018 b) and even ancillary service provision may influence these strategies, which in turn can be encoded and automated in smart contracts (Noor et al., 2018). Zhou et al. (2018) emphasized value-tapping and participation willingness in analyses of prosumer business models. Value-tapping concerns the overall microgrid community's cost-saving potential in a P2P network, and participation willingness relates to this potential for each individual in that community (Zhou et al., 2018).

Selectivity and locality are additional concepts that can be used when discussing prosumer business models (Morris et al., 2012). Selectivity is related to taking advantage of wholesale price fluctuations, whereby prosumers can sell electricity when these prices are high and purchase when they are low (Morris et al., 2012). This ability to shift sales would also be reliant on storage (Cruz et al., 2018), which is a key factor in the economic as well as technological dimension. Locality concerns microgrid prosumer access to wholesale electricity purchases (Morris et al., 2012). This is beneficial because wholesale prices are lower than retail prices, as they do not incorporate additional tax, market, network, and service charges (Morris et al., 2012). The dynamics of selectivity, locality, value-tapping, participation willingness and other factors in prosumer business models are of interest for further research. It is suggested that this can be explored in the context of blockchain-based microgrids and in digital strategies at large in the energy sector.

While technological innovation is continuously creating opportunities for new energy business models, prospects of these business models are dependent on energy market liberalization and institutions (Park and Yong, 2017; Yarime and Karlsson, 2018). FITs, accelerated depreciation of assets, certificate-trading, and other incentives can promote technological progress, renewable energy, and environmental sustainability at large (Ozorhon et al., 2018). In the realm of financial incentivization, taxes and rebates may drive energy market competition and business model innovation to a greater extent than subsidies (Romero, Personal communication).

Blockchain is introducing new economic dynamics and opportunities, such as P2P-trading. It can facilitate economic benefits, entrepreneurship, and independence (Potts et al., 2017), among prosumers and other energy market players. Interrelatedness can also clearly be seen between the economic and institutional dimensions, indicating a need for institutional development in order to further take advantage of economic prospects. In addition, discussion on distributed energy also needs to encompass the rise of new behavior in decentralized markets, of which there is as of yet little research (Green and Newman, 2017). Skills in the realm of blockchain technology and dApps are also in need of expansion (Wu and Tran, 2018; Suzuki, Personal communication) for the development and maintenance of effectual technical energy systems as well as prosumer business models. This in turn indicates ties between the technological, economic, and social dimensions.

**Social dimension**

What may the roles of social and economic actors be in decarbonized, decentralized energy markets? A key question in the social dimension is that of user engagement and how this can facilitate social, economic, and environmental sustainability (Caputo et al., 2018). Behavioral change is an important element in regulatory and policy development (Wong, Personal communication), especially for blockchain, considering the impacts on values, social infrastructure, and business models that it will have (WU GTPC, 2017). For example, with increased involvement of prosumers, these individuals may feel more invested in the energy system and in its sustainability (Caputo et al., 2018; Green and Newman, 2017). With this in mind, socioeconomic incentives, stakeholder management, and community engagement in the context of blockchain-based P2P microgrids is explored further.

Socioeconomic incentives

There is a research gap pertaining to socioeconomic incentives in local energy market design (Mengelkamp et al., 2018 a; Mengelkamp et al., 2018 b; Green and Newman, 2017). Market designs that do not integrate prosumer behavior are inefficient for the long term (Parag, 2015). This is because prosumer interests, concerns (Long et al., 2018), and willingness to participate (Zhou et al., 2018) affect microgrids at large, including P2P networks. There is a need of expanded insight on incentives for prosumer participation and engagement (Parag, 2015). Through domestic resource use and profit creation, local economies can be strengthened (Zhang et al., 2017 a; Noor et al., 2018; Zhou et al., 2018). This can in turn lay a foundation to build public acceptance and engagement. However, income equality within the community would be an important consideration, as a lack thereof may inhibit acceptance and expansion of P2P energy-trading (Zhou et al., 2018). If there is a large income gap, some individuals may end up with an economic disadvantage in P2P networks and the gap may be widened.

Several authors have explored approaches to strengthening the socioeconomic foundation of microgrids, including those with P2P networks. For example, Mengelkamp et al. (2018 b) noted that the willingness to pay for renewable power in P2P microgrids is higher if community members attach importance to local and renewable resource utilization. Green and Newman (2017) found that ToU FITs for distributed storage can be effective for incentivizing peak power provision. This in turn reduces the need for expensive peak generation capacities (Green and Newman, 2017). Campbell (2017) discussed the use of blockchain coupled with AI to create reward mechanisms for energy efficient behavior. With a basis in game theory, Nicolson and Lotti

(2018) created simulations of potential prosumer behavior in P2P electricity markets, finding that cost-benefit analyses commonly carried out by policy-makers do not effectively embody real-life behavior. These analyses often lack incorporation of relationships, norms, and numerous other social factors that influence such behavior (Nicolson and Lotti, 2018). Social aspects are especially vital due to their stimulus on other dimensions. For example, social factors and behavior influence prosumer market pricing and allocation mechanisms (Mengelkamp et al., 2018 b) in the economic dimension.

In addition, abilities in the technological dimension can influence social factors. For example, P2P microgrids can contribute to energy autonomy and security by aggregating local renewable energy and storage (Hirsch et al., 2018; Wouters, 2015; Morris et al., 2012; Zhou et al., 2018). Energy security can be increased further through microgrid flexibility and islanding abilities for cases of utility grid outages (Hirsch et al., 2018). Low- or zero-carbon microgrids can also contribute to emissions and pollution reduction (Hirsch et al., 2018; Morris et al., 2012; Mengelkamp et al., 2018 b). This indicates that energy security, self-sufficiency, and pollution reduction can be key benefits and incentives for P2P microgrid development. Interplay can also be seen between the environmental and social dimensions. This may be of interest for policy-makers and the institutional dimension. It is also important to note that national contexts would affect the relevance and emphasis of such benefits. It would be key to understand what key stakeholders, such as prosumers and consumers, value and emphasize.

Due to its facilitation of polycentric governance, shared economies, and P2P-trading, blockchain can be used to enhance consumer choice (Potts et al., 2017) and economically empower users in energy markets (Memoori, 2017). Energy consumer and prosumer choice is expanding due to improved distributed data management arising with ICT and blockchain developments (Mengelkamp et al., 2018 a; Tanaka et al., 2017). As a result, user preferences can be incorporated more effectively and transparently than in centralized energy systems (Green and Newman, 2017). Transaction and origin traceability (Wong, Personal communication) as well as preferences for the timing, price ceilings, price floors, quantity, and origin of energy can be enabled through distributed computing (Green and Newman, 2017; Tanaka et al., 2017). In P2P energy markets, prosumers can create conditions for trading, such as opting to sell excess power or to store it until wholesale prices increase (Green and Newman, 2017), as discussed in the economic dimension. In this way, prosumers would gain more control and an ability to act strategically in energy markets (Potts et al., 2017). User empowerment and choice may offer important socioeconomic incentives for P2P microgrids as well as contribute to building sustainable energy behavior.

Development of market regulations and financial incentives would also be necessary, indicating a strong link between the social and institutional dimensions.

Effective mechanisms to encourage sustainable behavior encapsulate a key research gap (Caputo et al., 2018) which is highly relevant for the energy sector. It would be valuable to understand consumers, producers, and prosumers, as well as interactions among them. How may blockchain platforms be designed and managed in order to encourage sustainable energy behavior? Tokenization involves the conversion of assets to tokens on such platforms (Chu, Unpublished results). The use of tokenization is one example of a new opportunity to promote more sustainable behavior with blockchain, such as via reward or gaming systems (Chu, Unpublished results). In addition, the increased transaction settlement frequency on blockchain platforms may be more effective in encouraging sustainable choices as opposed to traditional pricing (Memoori, 2017).

User behavior and mechanisms to influence this behavior is not yet empirically explored in the context of blockchain-based P2P microgrids. Empirical contributions may be highly valuable in the social dimension of blockchain-based energy and for developing practical applications. This may be done via studies on opinions and behavioral change through surveys, interviews and observations. Insights on socioeconomic incentives can in turn contribute to institutional development. As emphasized by Axsen and Kurani (2012), understanding the multiple perspectives and behavior in new energy systems is important in policy developments driving low-carbon energy transitions. This further emphasizes interlinkage between the institutional and social dimensions.

Stakeholder interest management

In order to understand the multiple perspectives and behavior in new energy systems, it would be important to first identify stakeholders. In microgrids, stakeholders include government, national grid companies, microgrid owners, energy producers, equipment suppliers, and consumers (Long et al., 2018). In systems with P2P-trading, prosumers introduce diverse bidding strategies (Zhou et al., 2018) and would also be a key stakeholder. It would be valuable to understand and manage stakeholder interests when creating incentives that affect microgrid energy markets (Long et al., 2018; Morris et al., 2012; Zhang et al., 2017 b; Zhou et al., 2018). Exploring the perceptions and social acceptance of distributed power grids can be an important first step in building this understanding (Green and Newman, 2017). By understanding perceptions and behavior, appropriate information can in turn be shared with users to enhance the acceptance of new energy systems (Ozorhon et al., 2018).

Accenture (2017 a) surveyed 80,000 energy consumers globally, exploring opinions on digital utility services. Strategies centering on customized user experiences and individual levels of digital skills tended to be more successful, while technology-led strategies inclined to being less fruitful (Accenture, 2017 a). Advancements in information-sharing (Ozorhon et al., 2018) and digital engagement can be essential in the energy sector. For improved engagement in blockchain-based services at large, there is also a need to advance user-friendliness and user experience (Bhuptani, Unpublished results; Thorén, 2018).

There is an ongoing shift to distributed electricity, which poses an uncertain future and role for conventional utilities (Cruz et al., 2018). Utilities are being affected by digitalization through the introduction of new business models, market players, and roles on the grid (Hirsch et al., 2018; Green and Newman, 2017; Di Silvestre et al., 2018 a; Romero, Personal communication). For effective stakeholder interest management and socioeconomic sustainability in energy transitions, it is suggested that concerns related to changing roles and uncertainty would also be important. The "utility death spiral" refers to the phenomenon whereby self-generation and self–consumption in microgrids can lead to a fall in consumer power demands and rise in power prices (Hirsch et al., 2018). This price increase further leads to reduced demand, likened to a spiral (Hirsch et al., 2018). This possibility suggests a need to decouple revenue from power sales, and instead couple it with grid management or efficiency (Hirsch et al., 2018). Power utilities may take on different roles in the future, such as service or platform providers (Romero, Personal communication), and are key stakeholders to consider in distributed energy developments.

Future energy grids and markets will necessitate the coordination of diverse and competitive players (Soares et al., 2018). These players may include energy consumers, producers, prosumers, suppliers, service providers (Soares et al., 2018), and other potential new roles. Roles and stakeholder landscapes in distributed energy systems are changing. With this, it is suggested that effectively managing stakeholder interests and diverse stakeholder groups would be key in bridging between technological innovation and commercialization. In addition, it is proposed that stakeholder and project management is of interest for further research in the context of P2P microgrid networks.

Community engagement

As noted by Caputo et al. (2018), with the rise of prosumers, levels of involvement and engagement in the energy system are also likely to escalate. Public acceptance of P2P microgrids can be enhanced through the co-development of market objectives and operations, and effective management of public relations (Mengelkamp et al., 2018 b). As highlighted by Koirala et al. (2016), community engagement is essential in transitions from centralized to distributed energy systems. Opportunities, such as demand reduction, emissions reduction, flexibility and renewable energy, can be more effectively identified through such engagement (Koirala et al., 2016).

A key opportunity gained through digitalization is expanded user engagement (Hwang et al., 2017). Through mechanisms such as interaction and visualization on digital platforms, stakeholders can more easily follow energy production and consumption (Hwang et al., 2017). Through the integration of physical and virtual microgrids, stakeholders may be more involved and thereby more interested in energy (Hwang et al., 2017). Effective energy management systems can also automate and simplify P2P-trading processes among platform users, which may further support acceptance (Mengelkamp et al., 2018 b). Parag (2015) similarly discussed the potential of leveraging the increase in smart meters and appliances to further integrate demand-side management and automation. Such mechanisms would in turn also call for a change in regulatory frameworks (Parag, 2015), indicating a further link between the social and institutional dimension.

There are as of yet research gaps in the social dimension of blockchain-based P2P microgrids, of interest to explore further via empirical research, such as through user surveys and interviews. Potential direction of such research may be to explore pertinent user concerns, value propositions, and user experiences in P2P energy networks. Engaging a multi-stakeholder community, including prosumers and consumers, may provide a valuable platform for exploring stakeholder interests in P2P microgrid development. Managerial research on community management and engagement in P2P microgrids is an area for further exploration. Multi-stakeholder discussions on blockchain applications may contribute both to digital skill-building and the collection of social insights that can guide institutional development (Kurihara, Personal communication).

User involvement and communication strategies are vital in digital energy services (Accenture, 2017 a) and are of interest for further research. Community engagement and participatory planning can support stakeholder interest management (Long et al, 2018; Morris et al., 2012; Soares et al., 2018; Zhang et al., 2017 a; Zhou et al., 2018) and knowledge-sharing (Ogushi, Personal communication; Suzuki, Personal communication; Kurihara, Personal communication). Insight on the perspectives and behavior of users in new energy systems also contributes to institutional development (Axsen and Kurani, 2012). This reemphasizes the strong linkage between the social and institutional dimensions that has already been discussed. For instance, grid digitalization may escalate data privacy and security concerns (Cruz et al., 2018; Parag and Sovacool, 2016). How may such concerns be managed? What are other vital factors to be integrated in P2P microgrid user experiences? Based on user engagement and feedback, for example collected through surveys, insights on such questions would be important in constructing the social pillar of an institutional arch.

**Environmental dimension**

Microgrids can contribute to emissions reduction (Hirsch et al., 2018; Basu et al., 2011; Zhou et al., 2018; Hanna et al., 2017). This is particularly important in microgrid design when considering the need to limit global warming to 1.5 degrees above pre-industrial levels, as expressed by the IPCC (2018). In this context, blockchain can contribute to traceability and transparency, such as in GHG emission-tracking or carbon-trading schemes (UNFCCC, 2017). At large, the technology can be used to make data more visible and inhibit data manipulation (Khaqqi et al., 2018). This can be relevant and valuable for environmental data. The potential of blockchain-based P2P microgrids to contribute to environmental sustainability is discussed further as follows.

Energy management and self-sufficiency

Self-sufficiency in microgrids can be valuable for power line loss reduction and increased renewable energy shares, with ensuing environmental benefits such as emissions reduction (Hirsch et al., 2018; Zhou et al., 2018). Microgrid interconnection can support the expansion of distributed renewable energy and contribute to long-term emissions reduction strategies (Hirsch et al., 2018; Morris et al., 2012; Basu et al., 2011). With this potential, it is suggested that P2P microgrids may be an important element in policies for emissions reduction (Basu et al., 2011). Environmental regulations are vital factors in microgrid planning and management, especially regulations concerning targets for emissions reduction as well as renewable energy shares (Di Silvestre et al., 2018 a; Basu et al., 2011).

Pathways for environmental sustainability

Blockchain and smart devices can contribute to emissions reduction, such as through more effective emissions-trading platforms (Khaqqi et al., 2018). Blockchain can enhance platform transparency and thereby support identifying emissions information interference (Khaqqi et al., 2018). The United Nations Framework Convention on Climate Change (UNFCCC) has also discussed the potential of blockchain for climate action, to support "stakeholder involvement, transparency, and engagement" (UNFCCC, 2017). UNFCCC shared P2P energy-trading, emissions-trading, GHG-tracking, and crowd-funding as potential use cases (UNFCCC, 2017).

The business world is also increasingly turning attention to the opportunities of blockchain to support environmental sustainability. For example, in China IBM and the Energy Blockchain Lab are developing a blockchain platform for the trading of carbon assets (UNFCCC, 2017; IBM, 2018). It is suggested that emissions-tracking and reduction strategies may be a key opportunity in blockchain-based P2P microgrids. This would also depend on jurisdiction, regulations, and interests within the corresponding stakeholder network.

An environmental issue which is often overlooked is the resource depletion and toxicity of microgrid equipment, such as end-of-life batteries (Soares et al., 2018). Blockchain can facilitate transparent, accountable material-tracking in supply chains (Marr, 2018; Korpela et al., 2017). In this way, the technology can be useful in managing the full supply chain and life-cycle sustainability of microgrids. Blockchain can indeed contribute on multiple fronts to climate action, such as to financial instruments or in supply chain management. However, there is a need of regulatory and legal reforms to enable blockchain applications in this context (Zhang et al., 2017 b). Thus far, strong links have been seen between the technological, economic, social, as well as environmental dimensions with the institutional dimension. This indicates the significance of this dimension, which is discussed further as follows.

**Institutional dimension**

It has been clearly stressed the technological blockchain advancements are outpacing institutional development (Killmeyer et al., 2017; Cheng et al., 2017; Raconteur, 2016; Mengelkamp et al., 2018 a; Calvillo et al., 2016; Green and Newman, 2017; Gabison, 2016; Potts et al., 2017). Institutions related to blockchain applications is still a relatively unexplored area (Cheng et al., 2017; Mengelkamp et al., 2018 b; Tapscott and Tapscott, 2016). Regulations for blockchain energy applications are yet to be established while technical advancement proceeds rapidly, especially by startups (Wong, Personal communication; Cheng et al., 2017; Hsu, 2018). Such applications are entering arenas with no previous regulatory frameworks, such as P2P power-trading. The institutional dimension is among the most challenging and major when discussing blockchain-based P2P microgrids. This dimension is a key research gap in this discussion (Wouters, 2015), for example pertaining to standards for smart contracts (Cheng et al., 2017), and incentive structures (Noor et al., 2018; Green and Newman, 2017; Killmeyer et al., 2017).

Institutions include formal factors, such as standards and regulations (Nam and Pardo, 2011), as well as informal aspects, such as norms and customs (Berman, 2013). Examples of energy-related institutions include policy, dominant technologies, stakeholder relations, industry relations, and even social expectations (Koirala et al., 2016). A few authors have contributed to research on institutions related to blockchain energy applications. For example, Mengelkamp et al. (2018 b) developed seven components to analyze a blockchain-based microgrid case in Brooklyn (New York) which also incorporated regulation. In addition, the authors discussed economic (market, pricing) and technological aspects (setup, grid connection, information system, and energy management) (Mengelkamp et al., 2018 b). Readiness of the microgrid case was fulfilled to some extent for each of the seven components, except regulation (Mengelkamp et al., 2018 b). In fact, in this case, electricity cannot yet be legally traded and hence P2P-trading is based on renewable energy certificates (Romero, Personal communication; Cardwell, 2017). An additional example is the discussion by Potts et al. (2017) on the adoption of decentralized economic entities to provides urban series, such as energy, in blockchain-based "crypto cities." Furthermore, authors Green and Newman (2017) discussed the potential of blockchain for "citizen utilities" in Australia couple with the expansion of rooftop solar and power storage. New policies would need to incorporate shifting utility roles (Green and Newman, 2017). Blockchain applications and local energy markets are inhibited by current regulatory frameworks in most countries is regulation (Mengelkamp et al., 2018 b). This means that there is a need for further development of institutional arrangements. As follows, market policy, grid codes, microgrid policy, governance, and institutional development per se are discussed further.

Market policy and grid codes

There are numerous regulatory challenges of distributed energy, such as grid interconnection, pricing mechanisms, and market design (Koirala et al., 2016). Grid interconnection codes, islanding standards, smart metering procedures (Hirsch et al., 2018; Wouters, 2015; Mengelkamp et al., 2018 b; Basu et al., 2011) and other well-defined regulations for microgrids is key for success (Wouters, 2015; Mengelkamp et al., 2018 b; Basu et al., 2011). Market design is also an imperative facilitator of market competition and energy services such as capacity, balancing, and ancillary services (Koirala et al., 2016).

Clear pricing and market mechanisms can enhance market microgrid competition (Basu et al., 2011). Microgrids transcend generation, transmissions and distribution (Hirsch et al., 2018). Generation, transmission, distribution, and retail unbundling can further enhance market competition and support renewable energy (Long et al., 2018; Wouters, 2015). Some jurisdictions have institutions that support microgrids, such as New York State's "Reforming the Energy Vision"

(Hirsch et al., 2018; Hanna et al., 2017; NYS, 2018), targeting unbundling for market competition (Hirsch et al., 2018), and resilience based on distributed energy resources (NYS, 2018),

Microgrids face a number of other regulatory challenges, such as physical grid interconnection (Hirsch et al., 2018), connection fees, and waiting times (Hanna et al., 2017). Centralized governance and utility monopolies are also suggested as key challenges that prolong issues of interconnection and market design. Utility grid control and franchise exclusivity inhibits competition (Hirsch et al., 2018). Intermittency and grid capacity concerns expressed by incumbent utilities may prevent the interconnection of distributed energy (Hirsch et al., 2018; Yarime and Karlsson, 2018). Policies and market mechanisms that facilitate business model innovation can be vital in overcoming such challenges (Soares et al., 2018). Innovation agendas at the nexus of energy and digital technology are imperative for P2P energy networks. Entrepreneurial experimentation may contribute in such agendas (Yarime and Karlsson, 2018), both in the public and private sectors.

P2P microgrid policies and governance

Regulations specifically for blockchain-based energy applications is needed for any long-term development (Mengelkamp et al., 2018 b; Zhou et al., 2018). This may include laws and frameworks for P2P trading (Ogushi, Personal communication; Romero, Personal communication). Identities and roles of microgrid participants, such as prosumers, would require clarification when establishing such trading frameworks (Hirsch et al., 2018). For example, in Japan prosumers would theoretically require a license for wholesale market participation (Ogushi, Personal communication). This license requires that the entity can ensure continuous supplies and even customer support, which would be unrealistic for small-scale prosumers (Ogushi, Personal communication). Ownership and partnership models for energy generation and distribution infrastructure can contribute to role and responsibility establishment (Juan et al., 2017; Mishra, Personal communication; Wouters, 2015; Morris et al., 2012). Governance and regulation related to such roles would need to ensure accountability, energy security, and affordability (Parag and Sovacool, 2016). Ownership models, partnership frameworks, market roles, and prosumer licenses and requirements are in need of further research.

Microgrid models can support distributed energy in various ways. A microgrid can support distributed energy integration through aggregation, acting as a consuming or producing entity in relation to the utility grid (Hirsch et al., 2018; Hwang et al., 2017; Mengelkamp et al., 2018 b). With multiple microgrids acting as VPPs, bidding and ancillary services can be carried out in a broader network (Hirsch et al., 2018). Governance for various microgrid systems and associated blockchain trading platforms is an important factor in the coordination of such networks. Will such platforms be based on private, semi-private, consortium, or public infrastructure? How will smart contracts be managed? There are numerous questions in this context.

A private blockchain can be useful for auditing, dispute management (Wong, Personal communication), and internal transactions (Mengelkamp et al., 2018 b). When scaled up, private blockchains may become a semi-private platform in which a central entity decides on access to qualifying units (Mougayar, 2016). In consortium blockchains, a determined group of nodes carries out consensus mechanisms and information can be shared publicly (ILTA, 2018). Public blockchains are self-regulating, open, and consensus is reached based on all network nodes. Such setups would require a high degree of regulatory change as they would be the most decentralized (Wong, Personal communication). Therefore, energy applications based on public blockchains would likely be a latter step in use case development (Wong, Personal communication). The role of governments and other public entities may shift to platform providers (Potts et al., 2017). Hence, blockchain platform governance is potentially a critical factor to be explored further.

Pathways for institutional development

Knowledge-sharing, stakeholder participation, and skill-building can facilitate innovation in the energy sector (Yarime and Karlsson, 2018). Policy change and informed decision-making among private and public sector players can be supported by knowledge-sharing and community engagement (Ogushi, Personal communication; Suzuki, Personal communication; Kurihara, Personal communication). The involvement of multiple public sectors can enable silo reduction, the development of applications with societal impact (Kurihara, Personal communication), and cross-ministerial consistency (Suzuki, Personal communication). Technological, economic, social, and environmental dimensions all influence blockchain-based P2P microgrids, and are imperative considerations in institutional development.

Technological innovation is strongly influenced by institutional frameworks. Digitalization tends have stronger market impacts when regulatory frameworks are less limiting, support role shifts, and enable new pathways for development (Di Silvestre et al., 2018 a). Innovation at the nexus of energy and digital technologies can be catalyzed by entrepreneurial experimentation in both the private and public sectors (Yarime and Karlsson, 2018). On the one hand, governments have tended to be risk averse when facing blockchain applications and its security liabilities (Wong, Personal communication; Romero, Personal communication; Mishra, Personal communication).

On the other hand, governments can better steer the direction of rapid digitalization through pilot projects in partnership with relevant stakeholders (Cheng et al., 2017). Diverse social groups affect low-carbon system development (Axsen and Kurani, 2012). Multi-stakeholder collaboration can contribute to awareness-building and new policies related to blockchain innovation (Hsu, 2018). In such pro-active policy development and innovation management, regulatory sandboxes can be a valuable setup. Based on collaboration among public and private sector players as well as citizen involvement, products and services can be tested in in real-life situations (EY, 2017). This can empower citizens via participatory planning (Potts et al., 2017; Soares et al., 2018).

Strategic, gradual development approaches with a foundation in multi-stakeholder involvement can guide change (Cheng et al., 2017). It is suggested that involvement can support the incorporation of stakeholder interests as well as concerns, which in turn can inform institutional change. Flexibility and a basis in the viewpoints and behaviors of stakeholders is needed in new policies (Axsen and Kurani, 2012). The stepwise, multi-dimensional approach to institutional development suggested in this section may be based on multi-stakeholder regulatory sandboxes (Hsu, 2018). For example, blockchain governance, prosumer licenses, and microgrid ownership models are all areas that may be researched via regulatory sandboxes.

**Main takeaways: The multi-dimensionality of institutional development**

Technology, policy as well as economic markets are important factors in microgrid business models (Hanna et al., 2017). Table 4 shows key factors in each dimension of TESEI are shown in Table 4. An important observation is that the dimensions are inter-related, which means that developing from technological to institutional readiness also necessitates environmental, social, and economic considerations. For example, energy digitalization and market liberalization are global trends which can support microgrids (Basu et al., 2011; Long et al., 2018; Wouters, 2015).

In this context, trading mechanisms for zero- or low-carbon systems may be coupled with other environmental regulations (Basu et al., 2011). This illustrates how institutional change can take place at the juncture of the other dimensions. In fact, it can be argued that the technical energy decentralization also calls for the decentralization of markets as well as of social, environmental, and institutional structures. For example, from the social perspective, further research on community co-development, socioeconomic incentives, and acceptance of P2P microgrids is needed. Decentralization may need to be echoed in stakeholder management and social systems, in order to support the expansion of decentralized technical and economic systems.

**Table 4** TESEI framework (Ahl et al., 2019 a)

| Technological | Economic | Social | Environmental | Institutional |
|---|---|---|---|---|
| **- Energy management system:** automatic management of energy & bidding strategies, frequency and voltage control, reliability.<br>**- Power grid:** smart metering, energy storage, O&M of microgrid, virtual & physical grid connection, P2P microgrid-utility grid interoperability & islanding, microgrid power loss<br>**- P2P network system:** smart contracts & consensus mechanisms, cybersecurity, data storage | **- Energy market mechanisms:** competition, scheduling, real-time pricing for frequent power fee settlements, ancillary service participation<br>- **Prosumer business models:** selectivity & locality, value-tapping & participation willingness<br>- **Smart contracts:** business model support through automated purchase & selling strategies, smart-utility contract interoperability | - **Socioeconomic incentives:** local economy growth, income equality, reduced pollution, energy security, enhanced consumer/ prosumer choice, sustainable behavior.<br>**- Stakeholder interest management**: interests, concerns & acceptance, shifting roles, user friendliness<br>- **Community engagement:** communication, public acceptance, stakeholder skill development. | **- Emissions reduction:** energy management for emissions reduction, emission regulations in smart contracts<br>- **Self-sufficiency:** higher renewable share, lower line losses<br>- **Life-cycle impact:** tracking microgrid equipment end-of-life impact and recycling | - **Market policy:** liberalization, microgrid ancillary service market, emission regulations<br>**- Grid codes:** for microgrid interconnection, islanding, metering<br>- **P2P policy:** prosumer licenses, ownership & sharing models for infrastructure & energy, blockchain governance<br>- **Institutional innovation mechanisms:** community-building & reduced silos, co-development, regulatory sandbox |

Technology is rapidly advancing and barriers, such as scalability, are progressively being solved. How can institutions gradually transform in order to support this progress while maintaining energy security? The interoperability and integration of new P2P platform with conventional trading systems is essential in this regard. For long-term sustainability, a strategic and stepwise approach to institutional change is suggested.

Existing infrastructure, markets, and human resources would need to be included in this approach. "Creative syncretism" refers to the gradual transformation of stakeholder behavior and systems done in *relation* to preceding institutions, on a mutable foundation for new institutions (Berk and Galvan, 2009). It is suggested that a syncretic approach can support innovation in the energy sector based on interoperability between current and new systems. In this context, regulatory sandboxes can support community engagement and stakeholder involvement for informed decision-making. This may lessen silos between industry and government, and support the development of parallel pillars in multi-dimensional institutional development.

### 3.1.3 Summary

Section 3.1 set out to describe the opportunities and challenges of blockchain-based electricity systems. Both academic and grey literature was comprehensively reviewed, and an analytical framework for blockchain-based P2P microgrids was developed. This framework, shown in Table 4 and titled TESEI, includes 1) Technological, 2) Economic, 3) Social, 4) Environmental, and 5) Institutional dimensions.

On the one hand, each dimension would be dependent on local context, and hence the factors shown in the framework may not be universally applicable. However, it is suggested that the dimensions and the overall framework can be further developed in academia. In addition, the focus of TESEI is on areas where microgrid interconnection with the utility grid is a possibility. Microgrids in remote areas with poor electricity access can indeed be valuable for improved energy security via off-grid solutions (Hirsch et al., 2019), and may be of interest for future studies. In addition, while CHP systems can enhance energy system flexibility and efficiency (Cruz et al., 2018), TESEI is limited to power. Blockchain applications in off-grid as well as CHP-based microgrids may be two areas of interest for future research, but are outside the scope of this study.

On the other hand, it is suggested that TESEI can offer valuable insights on the multi-dimensionality of blockchain-based P2P microgrids. This can be vital in academia as well as in practical institutional development. There is a need to bridge the gap between technological and institutional readiness by also incorporating economic, social, and environmental dimensions. This is because lacking strategy in one dimension signifies a missing pillar in institutional development. Regulatory sandboxes and community engagement is one pathway by which substantiated institutional development can be supported, in parallel with development across all dimensions. This can be supported by the incorporation of multiple stakeholders, knowledge-sharing, and cross-sectoral integration. A multi-dimensional syncretic process may facilitate multi-stakeholder management as well as interoperability between current and future systems. Based on the described approach, institutional readiness may be achievable on a holistic level for blockchain-based energy systems.

### 3.2 Pathways: blockchain-based energy distribution in Japan

Electricity, information, and financial flows are increasingly distributed. This means that centralized energy structures may be inefficient in supporting these flows in the near future. However, the Japanese energy sector is yet to be fully liberalized and has historically been based on ten centralized power monopolies. Blockchain may be an important tool in energy decarbonization, decentralization, and digitalization. How may this be applied to Japan? Based on the TESEI framework, section 3.2 explores concrete challenges and opportunities of blockchain energy applications, substantiated based on an analysis of a blockchain-based microgrid case in Urawa Misono, Japan. The technical details of the case are shown in Table 5. Based on this study and extensive literature review, an overview of strategic indications for blockchain energy applications in Japan is proposed.

**Table 5** System details of case project (DGC: Digital grid controller; DGR: Digital grid router) (Ahl et al., 2020).

| | **10 Consumers** | **5 Prosumers** | **1 Mall** |
|---|---|---|---|
| *Equipment* | DGC, smart meter | 5kW solar PV, 12 kWh Li-ion battery, 10 kW sub-grids, DGC, DGR | 60kW solar PV, DGR, DGC, smart meter |
| | 200 V AC distribution line (connects prosumers, consumers, mall), 350 V DC sub-power line (prosumers only), 6600 V HV embedded distribution line (connects prosumers/consumers/mall & main utility grid) | | |

#### 3.2.1 Technological dimension

There are several technological blockchain challenges that affect the case scalability: throughput (tps), latency (seconds per transaction: spt), data storage, legacy system interoperability, high speed connectivity, and cybersecurity. These challenges have their roots in blockchain design and consensus mechanisms.

The system in the case adopts smart contracts, asynchronous grid connections, and digital grid routers (DGR) to conduct power and financial transactions (Abe et al., 2019). The case is based on a private Ethereum blockchain, and Proof-of-Authority (PoA) consensus mechanisms. PoA adopts a known validator, or authority node, to coordinate bids, transactions, and completion. PoA has a lower energy intensity and latency than PoW as it requires minor computational power. Energy efficient consensus mechanisms are increasing, such as PoA and PoS (Andoni et al., 2019), with plans to standardize PoS as the mechanism for the Ethereum blockchain (Poon and Buterin, 2017) as well as to integrate sharding (Bheemiah, 2017; Casino et al., 2019).

Sharding means to branch one large blockchain into numerous smaller chains, which can reduce latency and increase throughput. However, multi-chain interaction and communication is a key issue in need of further research (Poon and Buterin, 2017). There are ongoing efforts at Ethereum in this context, such as Plasma (Poon and Buterin, 2017). Plasma is a framework through which scalable, multi-chain, multi-party channels connect to the core blockchain root and can be used to autonomously execute smart contracts (Poon and Buterin, 2017).

Ethereum requires high-speed, large-scale databases such as solid state drives (SSDs) for node-syncing and data transmission (Danziger, 2017). Large-scale blockchain data storage is key blockchain scalability issue (Andoni et al., 2019; Saberi et al., 2018 a; Yang et al., 2017). It is suggested that if the case is to be scaled, this issue would be highly relevant. Cloud computing (Saberi et al., 2018 a), side-chains (Andoni et al., 2019), off-chain storage (Hepp et al., 2018), are examples of advancements that may be used in managing this challenge. Blockchains can also be made more scalable by shifting processes, including storage, off-chain via state channels (Horne, 2017).

Data security is a key advantage of the distributed structure of blockchain versus centralized data systems, as blockchain evades single points of failure (Kouhizadeh and Sarkis, 2018; Nakamoto, 2008; Cohn et al., 2017). There are nevertheless cybersecurity risks, including smart contract bugs (Orcutt, 2019), 51% attacks, double-spending, and ledger data falsification (Li et al., 2017; Park and Park, 2017). In the short term, consensus mechanism development and privacy measures such as pseudonymity and asymmetric encryption are important steps for fraud prevention and security (Li et al., 2017; Orcutt, 2019; Cohn et al., 2017; Cao, 2019). The blockchain topology is a central deliberation for security and privacy, as related threats are particularly pungent in public blockchains (EWF, 2018). While such risks are currently lower in the case as it is based on a private blockchain, the topology and thereby cybersecurity risk may change with scaling. In the long-term, it is important to note that quantum computers could hypothetically ‘break’ algorithms (Casino et al., 2019). However, lattice and new code-based cryptographies can be used to lower this risk (Casino et al., 2019).

Figure 20 shows potential topologies, including private, public, consortium (Cohn et al., 2017; Wu and Tran, 2018), and semi-private blockchains. Private, semi-private, and consortium blockchains have lower energy consumption than public topologies, because consensus mechanisms are conducted in a smaller number of nodes or by cloud solutions (BDEW and SAP, 2019). Semi-private structures are at the juncture of private and public blockchains, with a single authority node managing the blockchain and access to it. Consortium blockchain have pre-selected authority nodes that coordinate access and consensus, and may be suitable for P2P-trading in microgrids in the short term (Brilliantova and Thurner, 2018). Future energy blockchains may be public, such as in the Energy Web Chain (EWF, 2018).

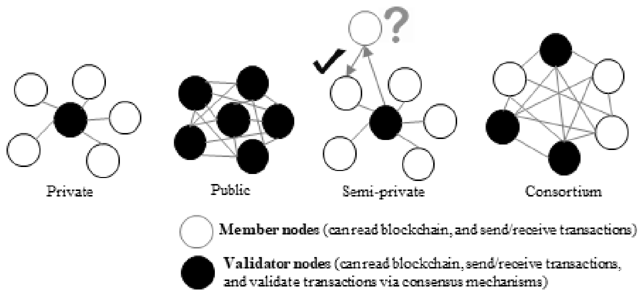


**Figure 20** Overview of potential blockchain topologies (Ahl et al., 2020)

An important question is – Can the surrounding digital infrastructure of the energy sector support blockchain integration? Blockchain interoperability and integration into legacy systems (Rocamora and Amellina, 2018), and smart meter infrastructure would call for gradual adjustment (Andoni et al., 2019). Blockchain transactions, syncing (Danziger, 2017), multi-chain setups, and off-chain advances (Stark, 2018) also need to be supported by high-speed, reliable internet connectivity. It is uncertain if current networks would be able to support scalable blockchain-based energy systems. In this discussion, it is important to note blockchain as part of a bigger picture of several emerging technologies that in turn may support its integration.

5G is a key emerging technology expected to drastically improve connectivity and support autonomous systems (Littmann et al., 2018). Light clients, software used to interact with the blockchain nodes, can be used to link IoT and blockchain networks (EWF, 2018). This may be highly relevant for smart meter infrastructure development (EWF, 2018). This is pertinent because IoT, machine-to-machine (M2M) communication, cloud-computing, and AI will be integrated to an increasing extent in smart grids (Camarinha-Matos, 2016). Machines may be autonomous entities acting based on smart contracts, 5G, and M2M setups. Smart grid advancements will also lead to an increase in data and data complexity, calling for improved communication networks (Boybat et al., 2018). In this regard, cognitive radios (CRs) may support spectral efficiency and larger networks (Boybat et al., 2018), including 5G. AI will also improve, such as via cognitive and neuromorphic computing (Boybat et al., 2018). This is relevant in the energy sector, as AI systems can be used to manage smart contracts, transactions, platform security (Orcutt, 2019), and auditable data trails (Casino et al., 2019).

In addition to digital advancements, energy technologies are also rapidly developing. Technologies like autonomous EVs (Litman, 2018), wireless power transmission (Assawaworrarit et al., 2017), and wireless energy-harvesting (Zhang et al., 2019) are increasingly influencing the energy transition. Energy systems may operate on far higher levels of automation and decentralization by leveraging blockchain and AI platforms. On such platforms, energy-as-a-service (EaaS) and decentralized trading may become the norm. In EaaS models, users pay for energy services per se, such as via subscription, rather than making upfront capital investments. Effective decentralized energy trading platforms would necessitate a diversity of technologies for analysis, balancing, and coordination (IRENA, 2018; Andoni et al., 2019). It can be suggested that blockchain may decentralize energy grids and the energy economy if effectively coupled with other innovative technologies.

This would call for a coherent and holistic approach to the management of technological innovation. The technological design of blockchain infrastructure would also affect the economic, social, and environmental dimensions. This is because blockchain topologies and communication protocols affect throughput, security, energy-intensity, network effects, trading mechanisms, user interaction (BDEW and SAP, 2019), and a multitude of other factors. Therefore, advancements of blockchain technology would need to be discussed in parallel with other developments in the energy sector, such as power market models.

### 3.2.2 Economic dimension

Subsidy-dependence, lacking market competition, uncertain contract interoperability, and platform market growth were identified as key issues in the economic dimension of the case. The case is mainly funded by the Ministry of Environment (MoE) of Japan. In fact, projects in the realm of smart energy in Japan have principally been backed by public subsidies (Yarime and Karlsson, 2018). This means that there is a need for further resource mobilization and business model development to reduce dependence on government funding (Yarime and Karlsson, 2018).

Subsidy-independent business models are an important question in the long term. However, incumbent companies and market barriers built by them inhibit decentralized blockchain-based platforms (Cohn et al., 2017; Cao, 2019; Buckley and Nicholas, 2017), including in Japan (Buckley and Nicholas, 2017).

The sustainable energy transition calls for technological advancements, as well as newfangled markets and business models (IRENA, 2018), indicating a need for multi-dimensional innovation. Blockchain can contribute to resource-tracking and information-sharing in decentralized and transparent markets. What will this signify for the energy sector? In Japan, new wholesale markets are being developed, including non-fossil value, base load, balancing, and capacity trading markets (Shinkawa, 2018; ANRE, 2018 a). This may open new windows of opportunity for distributed energy resources, renewable energy investment, and a sturdier ground for P2P-trading. Nonetheless, there are no market institutions for smart contracts or prosumers in Japan. In the case, prosumers cannot legally trade directly on the wholesale market and instead do so through an energy service firm called Digital Grid Corporation.

P2P energy markets would provide opportunities and stronger incentives for prosumers to fulfil the value of distributed energy resources (Morstyn et al., 2018). It is suggested that market decentralization would be necessary to support technological decentralization. This decentralization can be coordinated through smart contracts for cost-efficient disintermediation of transactions and P2P energy-trading, even for low-value transactions (Andoni et al., 2019). In the case, smart contracts and smart meters are used to automate purchases, sales, and transaction-scheduling. An auction-like procedure based on price and time, the Zaraba method, is adopted to match bids with flexible pricing mechanisms (Taniguchi et al., 2008). These bids are carried out in 30-minute intervals in a day-ahead market, with digital grid controllers (DGCs) for power control (Abe et al., 2019). In contrast to traditional power-balancing groups, this setup enables simultaneous power and financial flows.

Interoperability between smart and traditional contracts on the wholesale market would be an important point when discussing scalability. Improved spot price prediction would also be needed for more accurate smart contract bidding strategies (Maekawa et al., 2018). External data, such as solar radiation, is needed for accuracy in blockchain mechanisms (Cohn et al., 2017). Such data can be monitored via oracles, which are external digital agents integrated in smart contracts (Cohn et al., 2017). Price prediction accuracy can be furthered through machine learning and other AI techniques (Lago et al., 2018). However, with higher shares of distributed energy resources, marginal cost-based bidding may not sufficiently support revenues (Pikk and Vidding, 2014). This means that the market design and pricing mechanisms at large may need to change to support distributed energy resources and P2P-trading.

Advances in digital technology, such as blockchain and AI, can support the development of platform business models in the energy landscape (IRENA, 2018). End-user roles are becoming more significant as well as complex with the rise of distributed energy (Weiller and Pollit, 2013). Trends of distributed energy coupled with ICT progress are indicative of the potential of energy platform markets (Weiller and Pollit, 2013), with EaaS as one potential direction (EWF, 2018). A fee-based blockchain platform can act as a distributed ledger for maintenance, distribution, and tax cost-sharing (Lavrijssen and Parra, 2017). In addition to energy-trading, the nature of investment may also change in a platform economy (Andoni et al., 2019; BDEW and SAP, 2019). Shared investments (BDEW and SAP, 2019), such as crowd-funding for renewables (Bonzanini et al., 2016), may become more commonplace.

### 3.2.3 Social dimension

"Social structure assists or impedes economic performance" (Uzzi, 1996). Building on discussion pertaining to the economic dimension, a platform market is highly dependent on network effects (Weiller and Pollit, 2013), because its value to one user relies on the number of users (Eisenmann et al., 2006). Residential prosumer interest to engage in energy markets is also uncertain, and would strongly influence P2P platform scalability (WEC, 2018). This borders with the social dimension of the case. Key issues identified in this dimension include behavioral change, acceptance, stakeholder management, and skills.

Based on green marketing theory, assurance of renewable energy origin may increase the likelihood of people to purchase it (Kouhizadeh and Sarkis, 2108). Blockchain platforms can contribute in this regard, through transparency, certificates of origin, and assurance that data has not been tampered with (Casino et al., 2019; Kouhizadeh and Sarkis, 2018). Users in the case can access information about their electricity source, but cannot yet select specific source parameters. Users instead design their smart contracts based on three archetypes that affect the price ceilings/floors, energy source, storage, and bidding strategies. These archetypes are: 1) Cost-conscious, 2) Moderate, and 3) Renewable energy-conscious. However, while digital platforms can enhance consumer choice, this may not necessarily result in behavioral change (WEC, 2018).

Prosumers have diverse characteristics and interests, meaning that diverse incentives incur behavioral change (Morstyn et al., 2018). The participants in the 15 households of the case may be early adopters with an interest in emerging technology as opposed to mainstream residents. How may user behavior be on a larger scale? Socioeconomic incentives in P2P markets is a key area of interest moving forward. Utility customers in Japan are often uninterested or lack information about digital engagement with the utility (Accenture, 2017 b). At the same time, there are concerns about data security (Accenture, 2017 b), which may supersede financial benefits of P2P markets and prevent acceptance (WEC, 2018). This would be pertinent in innovation related to the grid, IoT-connected devices, and EVs (Andoni et al., 2019; BDEW and SAP, 2019).

User friendliness, convenience, and acceptance are needed to facilitate behavioral change (Mengelkamp et al., 2018 b; Wu and Tran, 2018). This can be supported by information transparency (Cao, 2018; WEC, 2018). For example, VPP information transparency can be enhanced through blockchain infrastructure, thereby possibly increasing its credibility and user participation (Cao, 2018). Trust is also vital for acceptance, especially if blockchain and IoT systems are integrated in smart homes (BDEW and SAP, 2019). Searchability among blockchain nodes can contribute to trust and user-friendliness, and is a feature that both startups and companies such as Google are investigating (del Castillo, 2019). User behavior is constantly shifting in parallel with the introduction of new applications and social platforms with growing levels of personalization (Munoz et al., 2016). User engagement is essential in the energy value chain and associated platforms, with a basis in flexibility and the continuous measurement of results (Munoz et al., 2016).

The stakeholder responsible for platform provision and management is a key point for discussion. In the short term, incumbent energy providers may be well-positioned as platform owners due to their current customer base (Valocchi et al., 2014). Engagement can be further supported by partnering with companies that are already active in platform markets, such as Amazon, Google, and Alibaba (WEC, 2018). AI can further facilitate the immediate responses and convenience that are in growing demand among users across all sectors (Accenture, 2017 a). In the long term, the platform may be autonomous to varying degrees. For example, decentralized autonomous organizations (DAOs) can reduce transaction fees by replacing the traditional intermediary with encoded conditions. A DAO is the most complex form of a smart contract, and may be valuable when facing growing demands for frequent, small-scale power transactions (Basden and Cottrel, 2017).

In addition to technological innovation, the objectives and norms of stakeholders are vital when facilitating low-carbon systems (Hughes et al., 2013). Corporations, startups, government officials, and researchers are important stakeholders in the case, in addition to the users. Stakeholders have different company cultures, ways of communicating, and expectations of the case. For example, large corporations typically require more documentation. In addition, decision-making tends to be speedier in startups than corporations. These discrepancies may lead to conflict and frictions. To manage this issue, an administrative role was created and assigned to a partner in the group in order to support coordination and communication among the stakeholders.

Inter-organizational factors, such as lacking standards for information-sharing and concerns regarding competitiveness (Saberi et al., 2018 a), may be key challenges if the case is scaled. Intra-organizational factors, such as internal management support and company policies, can also be key barriers of blockchain (Saberi et al., 2018 a; Saberi et al., 2018 b). This highlights effective intra- and inter-organizational stakeholder management as an important bridge between technological innovation and application, commercialization, and scaling. For example, backing from intra-organizational management is needed for agenda-setting to support blockchain skill development. This is important due to the current lack of skills pertaining to blockchain (Wu and Tran, 2018), and also other digital technologies such as machine learning (Bheemiah, 2017).

#### 3.2.4 Environmental dimension

Environmental challenges include emissions reduction scheme uncertainty, the integration of environmental regulation into smart contracts, and end-of-life procedures for microgrid equipment. Based on a 2013 baseline, the Japanese government targets a reduction of electricity-related emissions of 26% by 2030 and 80% by 2050 (ANRE, 2018 b). The Japanese non-fossil value market for FIT-certified generators initiated on the JEPX in 2018 (ANRE, 2018 a), with a price floor of 1.3 JPY/kWh (0.012 USD/kWh) and ceiling at 4 JPY/kWh (0.036 USD/kWh) (JEPX, 2018 a). While the creation of markets that encourage the trading of renewable energy may indicate positive aspects for sustainable energy, the market's actual benefit for renewables is unclear. In fact, average transactions were carried out at the price floor in August 2018, and the total trade volume was 2.24 MWh throughout that year (JEPX, 2018 a). When compared to JEPX sales contracts of 27,861 MWh April-June 2018, that 2018 volume is minor (JEPX, 2018 b).

There is indeed room for improvement of the incentives for clean energy in Japan (Yanaka et al., 2017). With this uncertainty, environmental regulation and emissions reduction targets are not yet included in smart contracts in the case. The DGR nonetheless records data on energy sources and carbon emissions, which in turn can inform renewables-trading and reinforce associated policies moving forward. How may blockchain can contribute in this context? For example, effective validation is a key prospect for emissions-tracking and –trading (Brilliantova and Thurner, 2018; Cao, 2019; Casino et al., 2019). Based on blockchain timestamps, due credit can automatically be recorded based on smart meter interval data stored in cloud databases (Ashley and Johnson, 2018). This can also contribute to fraud prevention due to the traceability and immutability attainable on blockchain platforms (Andoni et al., 2019).

This traceability would be valuable in numerous areas, from fraud prevention in carbon markets to end-to-end supply chain sustainability. Environmental data such as emissions, energy consumption, water use, waste, and toxic substances can be collected and shared on blockchain platforms (Saberi et al., 2018 a). The management and recycling of end-of-life equipment such as batteries (Mclellan et al., 2013) and solar panels (Fthenakis, 2000) is an important part environmental discussion. As blockchain can support end-to-end supply chain traceability, especially when integrated with IoT systems (Deloitte, 2017), it may be a valuable technology in tackling end-of-life issues.

There are several technologies to support sustainable energy systems, such as rooftop solar PV, as well as emerging technologies that can transform this landscape. Photosynthetic energy-harvesting (Calkins et al., 2013; Bioo, 2019; Plant-e, 2019), perovskite solar PV facades (Malinkiewicz et al., 2014), and liquid fuels that store solar energy (Wang et al., 2019) are a few examples of such technologies. While blockchain is one technology that may contribute to distributed energy, it would be important to also follow other advancements and remain adaptive for their incorporation. Coherent innovation management may thereby be leveraged to boost sustainability in the environmental dimension.

In reality, while the Japanese MoE stands in favor of carbon-pricing (MoE, 2017), METI is in opposition due to the potential of disadvantageous economic impacts on Japanese industrial players (Kawakatsu et al., 2017). Governmental unison with regard to market mechanisms, including carbon-trading, is a challenge not only in Japan but worldwide (UN, 2018 b). It is suggested that there is a need for silo reduction in the government with regard to environmental programs. This is related to the institutional dimension.

### 3.2.5 Institutional dimension

Key institutional challenges include low renewable energy targets, power grid interconnection, network consignment fees, prosumer licenses, role uncertainty, the smart meter measurement act, and centralized decision-making. Following Japan's FIT scheme, solar PV accounted for 95% of 2012-2017 renewable energy increases (Sato and Matsudaira, 2018), rather than resulting in a more diverse energy mix. The Japanese government also underlines the importance of distributed energy resources (Moore and Shabani, 2016), as well as regional and inter-regional grids (Yarime and Karlsson, 2018). However, the country's renewable energy shares and targets are low compared internationally (Zissler, 2017). The current level of renewables is at 7% of Japan's primary energy supply (METI, 2017 b), and in the METI Strategic Energy Plan, a renewable electricity share of between 22 and 24% is targeted by 2030 (ANRE, 2018 b). It is uncertain if governmental programs provide sufficient support for the expansion of distributed energy resources.

Physical as well as virtual grid connection would be a central factor in blockchain-based microgrids (Mengelkamp et al., 2018 b). Japan's power grid-related institutions were largely developed by ten regional power utilities on two different frequencies (Shinkawa, 2018). These institutions (Shinkawa, 2018), in parallel with expressions of intermittency and capacity concerns from incumbent utilities (Yarime and Karlsson, 2018), have resulted in grid interconnection difficulties among new players (Shinkawa, 2018; Yarime and Karlsson, 2018). This is a key driver of the low renewable shares (Yarime and Karlsson, 2018). Nonetheless, efforts for improved interconnection are growing in Japan, with attention to renewable energy integration and supply stability (Shinkawa, 2018; Zissler, 2017). Interconnection procedures shifted to implicit auction from a first-come-first-served basis in April 2018 (Shinkawa, 2018; ANRE, 2018 a). This means that day-ahead transmission capacity trading was incorporated into the electricity spot market.

While the aforementioned prospects do seem positive for prosumers, renewables, and P2P microgrids, network consignment fees are a key challenge. In Japan, 30-40% of electricity charges to end-consumers are comprised of these fees (METI, 2017 c). The consignment fees are approximately 7.8-9.9 JPY/kWh (0.07-0.09 USD/kWh; 2020-02-21) for low voltages and 3.5-5.2 JPY/kWh (0.03-0.05 USD/kWh; 2020-02-21) for high voltages (METI, 2017 c). P2P-trading would be low-voltage (Paudel et al., 2018; Ogushi, Personal communication). This fee structure means higher costs at low voltages due to an assumption of long-distance transmission and not proximate P2P-trading (Barton et al., 2018). These fees require review to enhance the feasibility of P2P power-trading. In fact, according to the 2018 Annual Report on Energy released by METI (2019), there are ongoing considerations of network consignment fee reviews in order to overcome location restrictions and support renewable energy.

Roles in governments, markets, and civil society are shifting along with the energy transition (Barton et al., 2018). Coordination of distributed energy resources is needed for energy-matching, information-sharing, and fulfilling consumer preferences (Morstyn et al., 2018). Roles need to be redefined, such as prosumers, distribution network and system operators (DNOs and DSOs) (WEC, 2018; Morstyn et al., 2018). DNO and DSO roles would need to change in order to support prosumers and P2P-trading (Lavrijssen and Parra, 2017). DNOs have traditionally been the managers of the distribution network (Bell and Gill, 2018). DSOs are involved in operating the system as a whole, such as adjusting voltage targets within DNO distribution networks (Bell and Gill, 2018). An important challenge in Japan is the lacking establishment of these roles (Dewaki, Personal communication). DNOs and DSOs may be active in the aggregation of distributed energy resources and support prosumer integration (Tesfatsion, 2018). Blockchain can contribute in this coordination of resources and flexibility at multiple scales (BDEW and SAP, 2019), especially when coupled with smart contracts for resource aggregation and ancillary service provision (Tesfatsion, 2018). Following the 2020 market unbundling, DSOs may act as platform providers and facilitators of distributed energy resource integration. This is one pathway to consider in the institutional dimension.

To support widespread prosumer integration, the actual role of the prosumer would be imperative to formalize. Prosumers are yet included in the Japanese Electricity Business Act, based on which licenses are required to purchase and sell electricity (Electricity Business Act, 1964). Retail licenses are one option, requiring continuous power supplies that can meet counterparty demands (Electricity Business Act, 1964) and customer protection (Hung and Pherson, 2017). However, for smaller-scale prosumers these requirements appear impractical. Another option is the "Specific Supply" license, which does not require registration as a utility and allows the registrant to supply electricity to pre-specified units (Electricity Business Act, 1964). However, the supplier must register each consumer, with information such as location and name (Electricity Business Act, 1964). In addition, the license assumes large-scale producers and consumers (Ogushi, Personal communication), which makes it appear impracticable for distributed prosumers and consumers.

In the current case, the prosumers acquired a "Specific Supply" license to sell power through a company for which they are compensated with digital tokens. This company manages balancing requirements as a "Retail Electricity Supplier." These licenses date back more than twenty years to the 1995 Japanese revised Electric Utilities Industry Law (TEPCO, 2019). It is suggested that with the rapid growth of new technologies, such laws are in urgent need of review. If also granted access wholesale trading, supported by new contract types (Andoni et al., 2019) and licenses (Lavrijssen and Parra, 2017), prosumers can gain economic benefit and may act as key players in the energy market (Morris et al., 2012).

In addition to licenses, smart meter infrastructure is needed to support coordination of the financial, information and power flows in P2P networks. Smart meters provide a foundation for energy management, bi-directional trading, and prosumer market integration. In Tokyo, 100% smart meter installation is targeted for low voltage entities by 2020, and in Japan by 2024 (Umejima, 2015). Smart meters are subject to the Japanese Measurement Act, with certification requirements from the Japan Electric Meters Inspection Corporation (JEMIC) (Dewaki, Personal communication). Currently, certifiable meters are on a Watt-hour (Wh) basis for electricity transactions (Dewaki, Personal communication). In the case, the DGC communicates with a certified smart meter, and the national targets for smart meter expansion appear positive if the case were to be scaled.

However, the integration of blockchain and other digital technology advancements into smart meters lacks policy direction (Andoni et al., 2019) in Japan and worldwide. While smart meters facilitate energy decentralization, network security is low as encryption methods are outdated (Cohn et al., Ashley and Johnson, 2018). This makes the meters susceptible to cyber-threats (Cohn et al., 2017). Blockchain can enhance data security, immutability, traceability, and automation in smart meters (Cohn et al., 2017; Ashley and Johnson, 2018). Furthermore, it can facilitate efficient multi-energy platforms in an 'Energy Internet' (Yang et al., 2017; Cao, 2019; Wu and Tran, 2018), which would support additional energy services such as gas and heating. Therefore, it may be a technology of interest for consideration in associated measurement acts and programs pertaining to smart infrastructure.

The Japanese government established a "Society 5.0" agenda promoting smart infrastructure as well as new ICT-based services, as seen the 5th Science and Technology Basic Plan (2016-2020) (Iwamatsu, 2016). Core government-driven matters include renewable energy grid interconnection, power quality, and microgrids (Yarime and Karlsson, 2018). Energy innovation can benefit from entrepreneurial experimentation (Yarime and Karlsson, 2018) in both the public and private sectors. In Japan, while energy developments involve Japanese industry and local administrations (Morozumi, 2012; Yarime and Karlsson, 2018), the decision-making is still highly centralized in the national government (Johnston, 2017). Although government targets can act as a stimulus of innovation, innovation may also be inhibited by centralized forms of governance.

Blockchain is an emerging technology of which potential applications are still being explored, calling for an experimental approach. There is also a growing number and diversity of stakeholders in decentralized energy systems (Saveedra et al., 2018; Hansen et al., 2019). Therefore, it is suggested that institutional change would call for flexibility, knowledge-sharing, co-learning, and collaboration among multiple stakeholders.

Both short- and long-term outlooks may contribute to this flexible approach and integrate multiple perspectives in blockchain energy application development. Technological systems “are both socially constructed and society-shaping” (Hughes, 1987). The strong sociotechnical lock-ins in the energy sector call for cooperative efforts for substantial shifts (Hughes et al., 2013). Blockchain P2P platforms would need to be developed in a way that provides sufficient value, generates network effects, and enables gradual scaling. Innovation ecosystems, with a basis in collaboration among multi-sector stakeholders, can catalyze knowledge-building on both success factors and issues (EWF, 2018). Cooperative industry-academia setups would be valuable drivers in the development of an Energy Internet (Cao, 2019). End-users would also be imperative participants in such ecosystems (EWF, 2018). Finally, governmental entities would be important players, as their involvement can enable more informed policy development (Wee et al, 2012; Bale et al., 2015). Inter-disciplinary teams are vital in this picture, due to the multiple dimensions of energy transitions (Hansen et al., 2019; Saberi et al., 2018 b; Bale et al., 2015; EWF, 2018). A “transition assemblage” based on collaborative schemes and strategies for policy, regulation, and R&D may direct the energy transition (Chappin and Dijkema, 2008).

While blockchain has potential to contribute to smart grids and P2P-trading, more use cases would be needed to influence industry standards and government support (Basden and Cottrel, 2017). However, inflexible regulations can prevent innovation of business models and technology and thereby the development of use cases to begin with. Delays in government action to develop regulations would be a key barrier of blockchain applications (Bheemiah, 2017). Collaborative schemes between the private and public sectors can support this development based on co-learning (Cohn et al., 2017). This would, for example, be relevant for exploring smart contracts in the energy sector (Cohn et al., 2017). A pro-active approach to policy development should be adopted, such as through simulations to explore how agents react to different policy scenarios (Bheemiah, 2017; Saveedra et al., 2018; Tesfatsion, 2018). Complexity models, such as agent-based modeling, can be used to holistically address energy technology, policy, and behavior uncertainties (Bale et al., 2015). Gradual development would be needed to align new regulations with the objectives of the multiple stakeholders in P2P networks, from DSOs to prosumers to regulators (Morstyn et al., 2018; Tesfatsion, 2018). Modeling, field studies, and performance tests can contribute in this regard (Tesfatsion, 2018).

Living Labs and regulatory sandboxes may contribute to the inter-disciplinary, multi-stakeholder, and proactive approaches previously discussed. Living Labs are "physical regions or virtual realities, or interaction spaces, in which stakeholders form public-private-people partnerships (4Ps) of companies, public agencies, universities, users, and other stakeholders, all collaborating for creation, prototyping, validating, and testing of new technologies, services, products, and systems in real-life contexts" (Leminen, 2013). Regulatory sandboxes are areas where businesses can test products and services with a pre-defined level of regulatory freedom, based on discussion with regulators (FCA, 2015). With the regulatory ambiguity of blockchain in the energy sector, regulatory sandboxes may be valuable tools for experimentation in both the public and private sectors. Living Labs and regulatory sandboxes can be used to explore several use cases and associated challenges, such as smart contract interoperability with contract laws (Cermeno, 2016), power pricing mechanisms, and drivers of public acceptance. Such setups can facilitate the testing of technologies in real-life environments among companies and startups, as well as inform regulatory change.

#### 3.2.6 Summary

Section 3.2 set out to analyze the opportunities and challenges of blockchain-based electricity distribution in Japan. Based on this analysis, strategic indications for academia and practitioners are presented in Table 6. In this table, the challenges and opportunities discussed across the five dimensions are summarized. While these results are not empirically tested, it is suggested that they are a useful starting point with indications for blockchain energy applications. It is suggested that the dimensions do not develop in isolation and are inter-related. Converging opportunities can be seen across the dimensions, such as transparency and AI integration. This suggests that blockchain energy application development would call for multi-dimensional innovation strategies. Coherent management and multi-stakeholder ecosystems may contribute to this approach to innovation. Living Labs and regulatory sandboxes may support such ecosystems and act as a foundation for a holistic approach to blockchain in the energy sector.

**Table 6** Challenges and opportunities identified across multiple dimensions in the blockchain-based microgrid case in Japan (Ahl et al., 2020)

| | **Challenges** | **Opportunities** |
|---|---|---|
| Technology | Throughput, latency, data storage, high speed connectivity, interoperability, cybersecurity | Consensus mechanism development, sharding, multi-chain communication, off-chain storage, state channels, 5G internet, CR, AI solutions, machine learning, smart meter blockchain integration (such as via light clients), IoT, M2M, privacy measures, quantum resilience. |
| Economics | Subsidy-dependence, lacking market competition, contract interoperability, platform market growth | Business model innovation, market transparency, wholesale trading, pricing mechanism development, AI solutions, machine learning, DAO- and fee-based platforms for trading and infrastructure cost-sharing, EaaS. |
| Society | Behavioral change, public acceptance, stakeholder management, skill development | Platform transparency and user-friendliness, digital platform company partnerships, convenience, user interaction, AI solutions, blockchain searchability, expanded consumer/prosumer choice, university blockchain training and programs. |
| Environment | Emissions reduction scheme uncertainty, environmental regulation in smart contracts, grid equipment end-of-life management | Transparency and traceability in renewable energy trading, green wholesale market opportunities such as ancillary markets, emissions-tracking and trading, carbon taxation, validation of rights and meter data, environmental metric fraud prevention, end-to-end supply chain traceability, IoT, coherent technology management |
| Institutions | Low renewable energy targets, uncertain stakeholder roles, prosumer licenses, grid interconnection codes, network consignment fees, smart meter measurement act, centralized decision-making. | Market unbundling and competition, network consignment fee structure update, DNO and DSO role establishment, prosumer contract and license development, smart meter act and standard development for blockchain integration, smart meter security and data traceability, Living Labs, regulatory sandboxes, interdisciplinary teams. |

# Chapter 4 General discussion and conclusions

This dissertation set out to investigate how digitalization in the energy value chain can facilitate renewable, distributed energy in Japan. Chapter 2 explored renewable energy, and more specifically how digital technologies can facilitate woody biomass in Japan. Chapter 2 demonstrated opportunities for digital innovation to overcome challenges across the woody biomass value chain. Chapter 3 explored energy distribution, and how blockchain technology can facilitate distributed energy systems. Chapter 3 demonstrated key challenges and opportunities of the application of blockchain in energy distribution in Japan.

As was also discussed in section 1.3.4, this dissertation has a number of limitations. The focus on Japan means that the findings depend on the Japanese context, and reliance on expert interviews may incur biases, such as interviewer and confirmation bias. However, the integration of qualitative and quantitative data analysis techniques was adopted to reduce interview-related biases. In addition, the Japanese focus indeed may mean that the results are dependent on the context of the nation and of the studied cases. Still, it is suggested that the results can be valuable in discussing initial pathways for digital technologies in the energy value chain based on concrete sociotechnical challenges, exemplified based on cases in Japan.

Chapter 4 aims to assimilate findings into an overarching discussion on key implications and theoretical contributions. Based on this discussion, a framework for the assessment of digital applications in the energy value chain in Japan is created. Finally, energy innovation policy and governance are discussed, concluding with practical implications as well as suggestions for further research.

## 4.1 Theoretical contributions and framework creation

The energy transition worldwide and in Japan involves decarbonization, decentralization, and digitalization. The focus of this dissertation is on digitalization in the Japanese energy sector, explored and exemplified through concrete cases. Thereby, this dissertation shares substantive theoretical contributions pertaining to digital innovation in the renewable energy value chain, and adds to the broader base of literature on the energy transition. This is important because effective digitalization can in turn support both decentralization and decarbonization for a more sustainable energy sector. A large amount of research has indeed been carried out on the energy digitalization. However, this dissertation provides a different analysis of digital innovation in the energy sector by implementing a multi-dimensional approach, exploring concrete cases, and adopting interviews with practitioners. This enables the identification of concrete challenges in the renewable energy value chain, and of practical insights and opportunities for digital innovation to overcome these challenges. With this foundation, this dissertation contributes threefold. First, the gap between digital technology and woody biomass research is addressed and strategic implications proposed. Second, a holistic conceptualization and analysis of the opportunities and challenges of blockchain-based energy-trading is carried out. Third, based on the aforementioned findings across the upstream to downstream energy value chain, a framework for digital innovation is proposed.

Figure 21 shows the key prospects of digital technologies to contribute to concrete challenges across the renewable energy value chain. For each technology in a digital toolbox, a series of challenges and mechanisms by which the technology can overcome them are illustrated. Digital toolbox refers to all digital technologies that may be used as tools for innovation in the energy value chain. The list shared in Figure 21 is not exhaustive, but rather based on the key opportunities identified in this dissertation. The lines above each challenge portray where in the energy value chain this challenge and the digital technology applicable. It is clear that multiple technologies apply to numerous challenges, pertaining to technical, economic, as well social issues. Grubler et al. (2012) similarly emphasized the need to focus on multiple technologies, because “silver bullets” do not exist for energy technology innovation. How can a practical approach be taken to this innovation in the energy value chain? It is suggested that based on the challenges at hand and a toolbox of digital technologies, pathways for further development can be created.

Figure 22 illustrates how a concept for digital innovation in a value chain may be developed based on 1) concept creation, 2) multi-dimensional experimentation, and 3) scaling. This figure reflects the overarching theme of this dissertation: in order to enable digital innovation, readiness in technological as well as economic, social, environmental, and institutional dimensions is imperative. Both the private and public sectors are indicated as key players in the concept creation process, because companies and startups as well as regulatory actors influence opportunities for digitalization. The innovation ecosystems of energy as well as other sectors, such as transport, is multi-dimensional, and these dimensions are inter-related. For example, advancements in the technological dimension affect and are affected by user behavior in the social dimension. This is important to keep in mind because energy-related innovation is increasingly cross-sectoral, seen for example in EV developments intersecting the electricity and transport sectors. Starting with a digital toolbox and issues identified in the value chain, a concept for digital innovation can be created. Thereafter, an experimental approach acknowledging the multi-dimensionality of

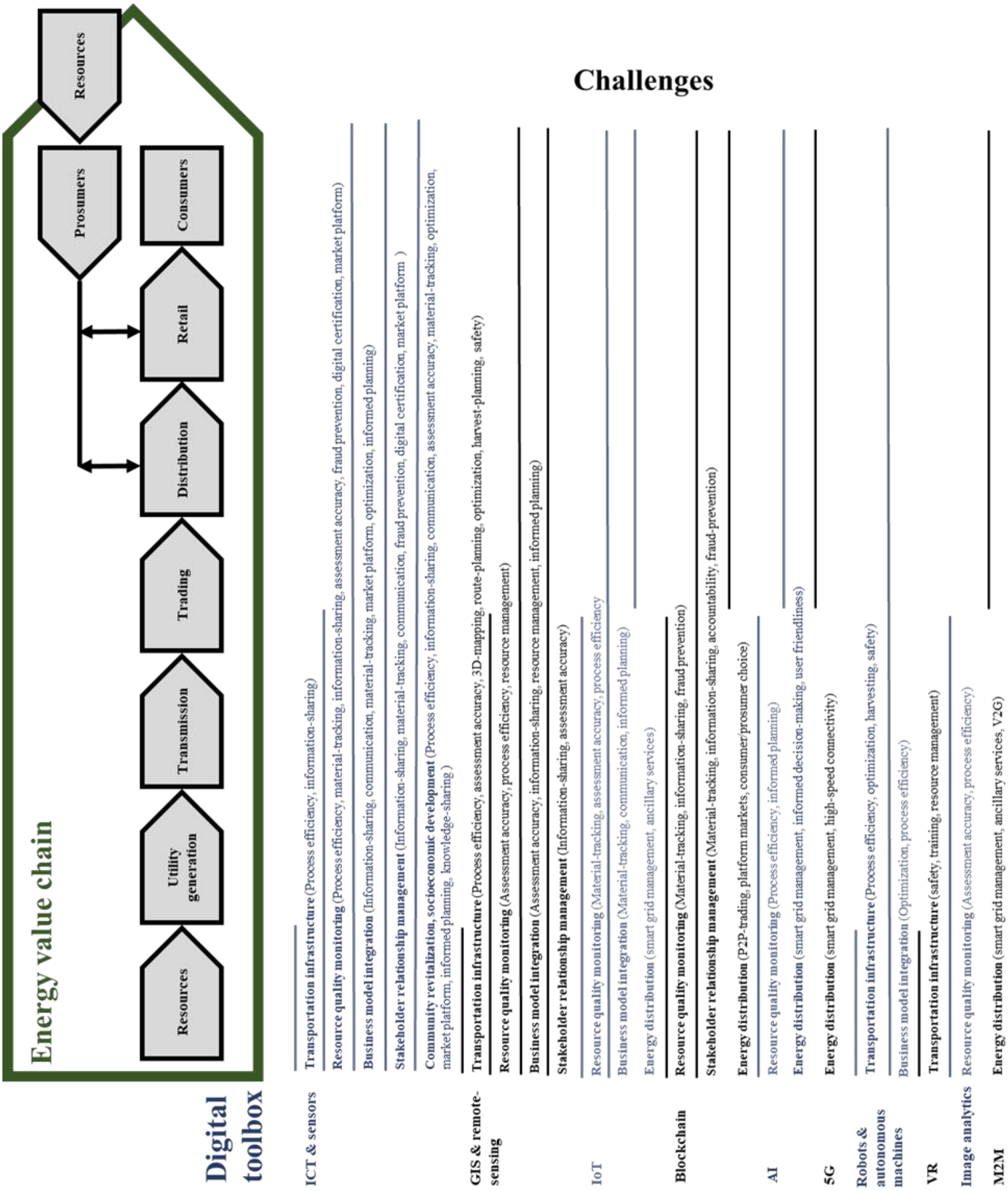


**Figure 21** Digital toolbox for challenges across the renewable energy value chain (Lines above challenge indicate relevance across the energy value chain) (Blue and black colours are solely to clarify distinction between digital technologies)

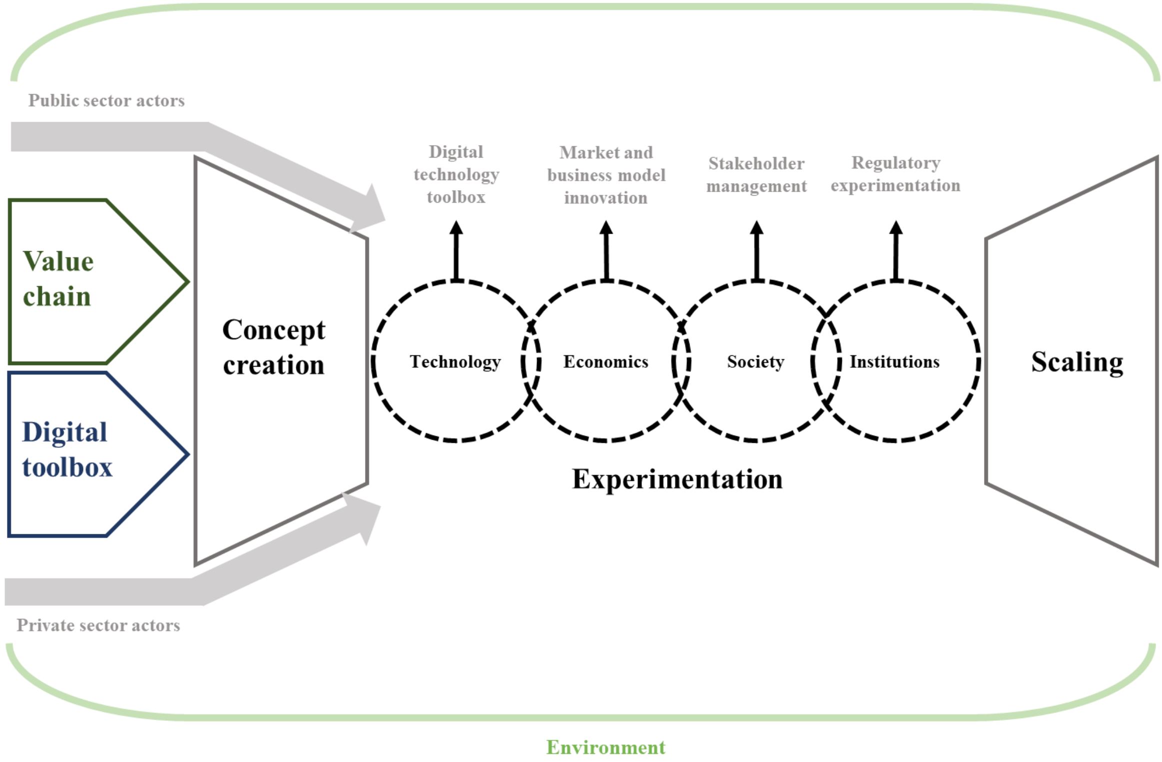


**Figure 22** Framework for the concept creation, experimentation, and scaling of digital innovation in a value chain. Grey text shows key points of experimentation.

innovation ecosystems can support the identification of use cases and pathways for scaling. Environmental sustainability is also shown as an overarching boundary condition for decision-making in the innovation process, from concept creation to scaling. This means that decision-making should be made in the interest of long-term environmental sustainability and carbon emissions reduction.

While Figure 22 introduces a general framework, this is applied to the context of digital innovation in the energy value chain in Japan in Figure 23. Figure 23 aggregates the key concepts derived in the studies of this thesis pertaining to a process for digital innovation in the energy value chain. (For examples of how the framework may be applied to other sectors, namely transport and agriculture, please see Appendix D).

It is suggested that stakeholder management can contribute to successful concept creation,

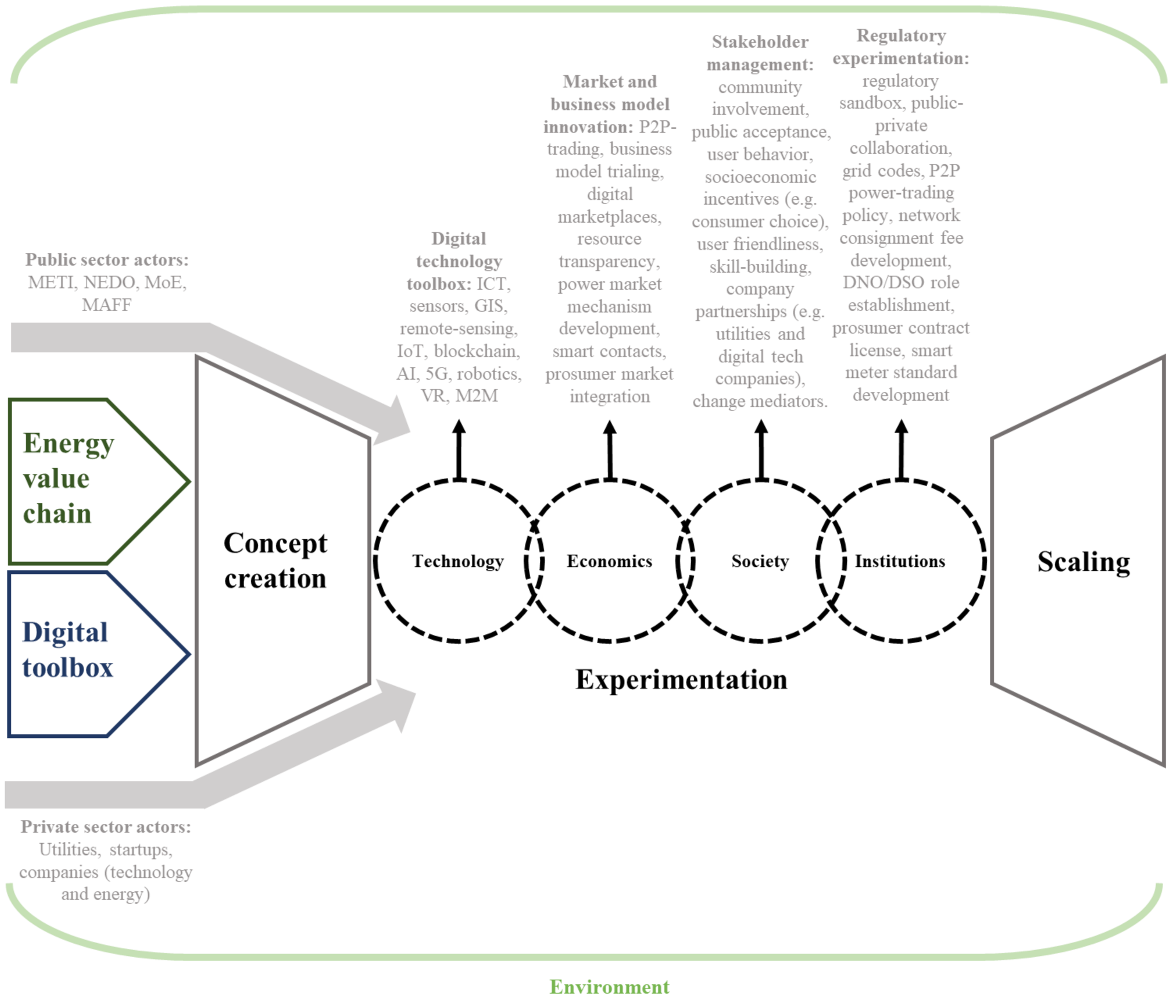


**Figure 23** Framework for the concept creation, experimentation, and scaling of digital innovation in the energy value chain in Japan (Based on general framework in Figure 22).

experimentation, use case identification, and scaling in the energy transition. Society and stakeholder management is vital, due to uncertainties in the rate of change of social systems alongside technological change (Rogers, 1962). There are always positive and negative effects of innovation, and both need to be managed (Rogers, 1962). Therefore, from the concept creation phase and onwards in Figure 22, the involvement of the private and public sectors, as well as civil society, would be important across all dimensions. It is further suggested that a gradual, syncretic approach can support progressive, realistic, and sustainable scaling of digital innovation. To build upon the key points of this dissertation, and place them in context of a broader base of literature, it would be useful to once again discuss innovation per se as well as energy innovation policy and governance.

### 4.1.1 Innovation and governance in the energy transition

As described by Rogers (1962), innovation refers to "an idea, practice, or objective that is perceived as new by an individual or another unit of adoption." Schumpeter (1934) discussed that innovation can pertain to a new product, service, process, market, and even structure (Schumpeter, 1934). Innovation systems, which involve business, academia, government, and civil society (Loorbach, 2010, Schot and Steinmueller, 2018), guide development on local, regional, and trans-national levels in so-called "glocal innovation systems" (Carayannis and Campbell, 2009). In addition to technological advancements, trends of globalization, individualization, and economic growth have led to a network society (Loorbach, 2010). This involves informal network processes for strategy and development, based on a new equilibrium of the state, markets, and society (Loorbach, 2010). The open source movement in the software industry (Carayannis and Campbell, 2009) is one example of this phenomenon.

How can the complex innovation systems of today be maneuvered? There is an abundance of literature on innovation systems and strategy. For example, Figure 24 shows the Innovation Pentathlon Framework developed by Goffin and Mitchell (2017). It has some similarities with Figure 22, including the initial creation of a broad range of ideas which are later narrowed down and prioritized. However, Figure 22 departs from Goffin and Mitchell (2017) in that it integrates experimentation with a foundation in technological, economic, social, as well as institutional dimensions prior to scaling. Finally, Figure 22 indicates circular experimentation, meaning that knowledge gained in each dimension can be fed back to contribute to other dimensions as well as to concept creation. In contrast, Figure 24 portrays a linear innovation process. It is suggested that this linearity is impracticable in energy innovation due to its complex, multi-dimensional nature. Grubler et al. (2012) similarly emphasized the importance of learning from and documenting both innovation successes and failures. The framework shown in Figure 22 attempts to address and incorporate this circular nature into innovation.

The energy transition involves sociotechnical system change which calls for system innovation (Schot and Steinmueller, 2018). This innovation involves invention, innovation, and diffusion based on a multi-stakeholder approach (Schot and Steinmueller, 2018). Advancements in climate-related technologies as well as investment, policy, and behavioral change are needed in in the energy transition (IPCC, 2018). IRENA (2019 a) suggested an 8-step innovation plan for renewable energy, which similarly incorporates technological, economic, social, and institutional factors:

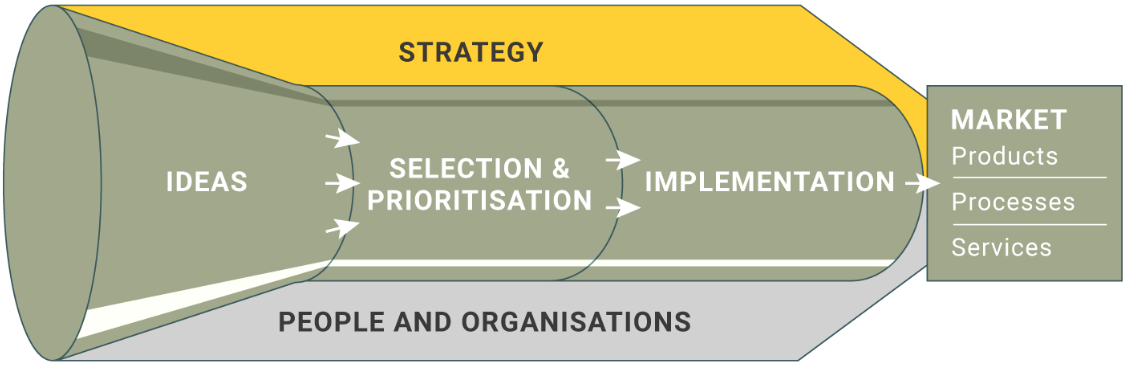


**Figure 24** Innovation Pentathlon Framework (Goffin and Mitchell, 2017)

1. **Policy:** frameworks that incorporate both current and forecasted power system needs.
2. **System:** holistic approach based on technology, markets, business models, and operations.
3. **Learning by doing:** experimentation, such as via regulatory sandboxes.
4. **Roles:** consider changing roles in the energy sector, such as prosumers.
5. **Markets:** design that supports flexibility.
6. **Synergies:** integration and coordination of renewable power, EVs, heating, and cooling.
7. **Digitalization:** integration of digital technologies, such as AI, IoT, blockchain.
8. **Multi-stakeholder:** open, multi-stakeholder innovation including public and private sectors.

Several authors have expanded on policy for energy innovation (IPCC, 2018; IRENA, 2019 a; Arcia-Garibaldi et al., 2018). Policies can promote economic and energy diversification for reduced reduce fossil fuel reliance and enhance climate change mitigation (IPCC, 2018). In order to do so effectively, policies must also be coordinated in a cross-cutting, multi-level manner (Schot and Steinmueller, 2018), and avoid contradictions (Kuzemko et al., 2016). Contradictions, such as incentivizing both increased energy efficiency and energy supplies, contribute to ineffectual sustainable energy policies (Kuzemko et al., 2016). Loorbach (2010) also discussed "policy tension," meaning conflict between new policies and current organizations and networks. For example, in Japan there are FITs for renewable power as well as public funding for fossil fuels. While several corporations and banks have indicated a move away from coal, 2016-2017 Japanese public finance for overseas coal-fired power was approximately 469.6 billion JPY (4.5 billion USD, March 11, 2020), making Japan the only G7 country with significant coal-fired power projects (ODI, 2019). It is suggested that this sends mixed signals to energy market players. There is a need of clear direction on a strategic level in new policies (Loorbach, 2010).

Policy contexts will always comprise of various rationales and policy instruments (Schot and

Steinmueller, 2018). Knowledge management and innovation in a glocal society calls for innovation policies in line with cultures and values (Carayannis and Campbell, 2009). There is no one-size-fits-all policy solution (Heuntler et al., 2016), as priorities differ among nations, such as depending on local energy markets, regulation, and electricity system objectives (WEForum, 2017). The basic objectives of the Japanese energy market reform are 1) supply stability, 2) power charge reduction, and 3) customer choice and business opportunities (METI, 2019 b). Policies specific to technologies and their development pathways can further benefit the deployment of energy innovation (Heuntler et al., 2016). For example, in Japan electricity data from the new information bank data-sharing scheme can contribute to businesses opportunities and new value creation (METI, 2019 b). The Japanese government is actively developing pathways and guidelines for this scheme, which may promote digital innovation across multiple sectors (Cabinet, 2017). Examples of such guidelines include security, data standardization, data quality, and education (Cabinet, 2017).

This indicates a potential shift toward enhanced public sector coordination and policy-making that can support digital innovation in the energy sector. It is important to note that policy must also continuously and proactively be updated to keep pace with technological advancements (IRENA, 2019 a). As innovation processes change, the role of policy changes (Soete et al., 2010), further indicating a need for a proactive, flexible, and syncretic approach to innovation. Setting direction based on multi-stakeholder dialog as well as incorporating the opportunities of green innovation, such as job creation, are important in innovation policy pertaining to sustainability transitions (Fagerberg, 2018). In addition, mobilization of key stakeholders, holistic policy-making, and improved governance are important factors in this context (Fagerberg, 2018).

Governance would be a key aspect throughout any project focused on digital innovation in the energy sector. As elaborated in section 1.3.1, Loorbach (2010) described four kinds of governance: strategic, tactical, operational, and reflexive governance. Tactical governance is carried out at the strategic level of individual players, and is often fragmented in terms of ministries and offices (Loorbach, 2010). For example, in facing the sustainability transition incumbent firms need to carry out strategic re-orientation (Schot and Steinmueller, 2018). This contributes to a lack of coordination and policy conflicts as discussed earlier, indicating the importance of both tactical and unified strategic governance. In terms of operational governance, Loorbach (2010) suggested to create a “portfolio of experiments” in order to find key opportunities, interrelatedness among solutions, and pathways for scalability. However, procedures of infrastructure selection and operation have remained unchanged for decades in multiple countries, leading to failure in systematically tackling inefficiencies (McKinsey & Company, 2013). Indeed, there is a lack of literature as well as practice pertaining to scaling up from experimentation phases (Schot and Steinmueller, 2018). This dissertation explores strategies for digital energy innovation that can contribute to a foundation for scalability through a multi-dimensional approach, as shown in Figure 22.

Governance is important because innovation is driven by non-linear processes of knowledge creation, diffusion, and use (Carayannis and Campbell, 2009). This is applicable both to policy-makers and to managers (Carayannis and Campbell, 2009). Innovation is influenced by a broad range of determinants, including industry structure, company attributes, intra-organizational characteristics, and institutions (Ahuja et al., 2008). This calls for understanding of both top-down policies and bottom-up technological progress (Carayannis and Campbell, 2009; Kuzemko et al., 2016). Especially startups benefit from bottom-up innovation policy, which can support multiple small-scale innovations and promote growth (Kuzemko et al., 2016). In addition, global tech diffusion and competition as well as cultural, technological, and socioeconomic divides are key points in innovation governance (Carayannis and Campbell, 2009).

Energy is a complex problem, involving multiple actors, perspectives, norms and values (Loorbach, 2010). The complex and contextual nature of the energy transition calls for a polycentric approach to innovation governance (Goldthau, 2014). This pertains to the creation of national as well as regional energy policies, and solutions with a strong foundation in local context and with local actors (Goldthau, 2014). The IPCC (2018) similarly emphasized participatory systems and multi-level governance for systemic sustainability transitions. A focus on local players and community to support digital innovation was also discussed in this dissertation, pertaining to woody biomass and blockchain-based energy distribution in Japan.

In addition, the IPCC (2018) shared policy instruments, institutional capacity-building, technological innovation, finance mobilization, and human behavior as important transition drivers (IPCC, 2018). These factors indicate technological, economic, social, and institutional dimensions as similarly shown in Figure 22. Partnerships may contribute to resource mobilization, such as among public and private actors, institutional investors, banks, and research institutions (IPCC, 2018). Private-public cooperation is important for energy infrastructure development leveraging industry expertise as well as policy support (McKinsey & Company, 2013, WEForum, 2017). Indeed, stakeholder mobilization and resulting knowledge production are vital elements in energy innovation and in innovation scalability (Väyrvynen et al., 2002).

In addition to governance for innovation, the innovation of governance per se is vital for effective stakeholder coordination and policy development in the sustainability transition (Fagerberg, 2018). The complexity of energy calls for an explorative, experimental approach that mobilizes stakeholders and society (Loorbach, 2010). Schot and Steinmueller (2018) discussed experimental, flexible policy-making and governance. Experimentation can be in the form of temporary spaces for stakeholders, including policy-makers, businesses, private funders, and users, to collaboratively explore pathways (Schot and Steinmueller, 2018). This is similar to the regulatory sandbox approach for blockchain-based energy-trading discussed in chapter 3. In the primary phases of a project, cross-functional team-planning and cross-authority coordination can contribute to scalability and the evasion of expensive modifications (McKinsey & Company, 2013). Väyrvynen et al. (2002) similarly emphasized multi-stakeholder cooperation and interactive learning processes from the early stages of renewable energy innovation. This enables innovation to form, to fit the needs of the market, and to attain "social embedding" (Väyrvynen et al., 2002). New institutional arrangements and governance that crosscuts governments, markets, and society are needed to support experimentation and scalability of sociotechnical system innovation (Schot and Steinmueller, 2018).

### 4.2 Conclusions

Facing the pressures of climate change, there is an ongoing energy transition of decarbonization, decentralization and digitalization. Digitalization is a key trend which is rapidly shaping not only the energy sector, but society at large. How can digital innovation be managed for effective sustainable development? This dissertation set out to explore pathways for digital innovation in the energy value chain in Japan. The key aim was to incorporate the multi-dimensionality of energy in a holistic framework for digital innovation. This is valuable in bridging technological innovation towards economic, social, and institutional readiness. A focus on the technological dimension has dominated the literature on digital innovation in the energy sector thus far. It is suggested that the insights attained in this dissertation can contribute to the formulation of more holistic, practical implications for digital energy innovation as well as of new research directions.

Pathways for digital innovation in the energy value chain were investigated based on exploratory research rooted in cases of woody biomass and electricity distribution. Chapter 2 set out to investigate key challenges in the woody biomass supply chain in Kyushu, Japan, and analyze how digital technologies can be used to overcome these issues. The identified challenges included transportation infrastructure; biomass quality monitoring and control; stakeholder respect, relationships and trust; local community revitalization and socioeconomic development. There is a lack of research on the nexus of woody biomass and digital technology. This dissertation addressed this research gap with initial implications on how digital technologies may contribute to woody biomass supply chains. ICT, robotics, GIS, remote sensing, blockchain, IoT, and AI were identified as key digital technologies in this regard. These technologies can facilitate several mechanisms, such as information-sharing, transparency, communication, value maximization, and automation, that can contribute to alleviating the identified challenges. For example, remote sensing can improve forest route and transportation planning, and blockchain can support transparency and thereby stakeholder trust and relationships. It is important to note that institutional and economic support would also be needed to support digital innovation in the woody biomass supply chain. This support can include participatory planning, change mediators, external experts, incentives for rural entrepreneurship, public-funding, and long-term financial self-sufficiency development.

Chapter 3 set out to describe the opportunities and challenges of blockchain-based electricity microgrids at large and also more specifically for a case in Urawa Misono, Japan. There is a lack of research on the holistic conceptualization of blockchain energy applications. This chapter contributed to lessening this gap. An analytical framework for blockchain-based P2P microgrids was developed, titled TESEI and including 1) Technological, 2) Economic, 3) Social, 4) Environmental, and 5) Institutional dimensions. This framework offers insights on the multi-dimensionality of blockchain energy applications, contributing to academia as well as practical development. TESEI was used in the analysis of a blockchain-based microgrid case in Japan, to identify concrete challenges and opportunities pertaining to its scalability. This case was a pilot project involving five prosumers, ten consumers, and one mall conducting power-trading on a blockchain platform. Key identified issues include technical throughput and interoperability, a lack of market competition, behavioral change and social acceptance, and regulations. Opportunities include blockchain consensus mechanisms development, platform markets, business model innovation, user-friendliness, enhanced user choice, renewable energy-trading transparency, emissions-tracking, and regulatory sandboxes.

In both chapters 2 and 3, the importance of institutional change as well as governance was highlighted. Digital technologies are still emerging and developing at a rapid pace. These dynamics present technical, economic, social, and political ambiguity. Governance is needed in maneuvering this multi-dimensional uncertainty as well as in managing the stakeholders of energy innovation. It is important to address the gap between technological innovation and socioeconomic as well as institutional readiness if energy innovations are to be scaled and impactful. It is suggested that multi-dimensional experimentation can contribute in this regard. Economic, social, and institutional factors would also be necessary in this experimentation, in addition to technological innovation.

Digital innovation across the energy value chain would call for multi-dimensional innovation strategies, coherent management, and multi-stakeholder ecosystems. Living Labs and regulatory sandboxes can support such ecosystems and multi-dimensional experimentation. Experimentation through regulatory sandboxes can substantiate development across the mentioned dimensions, supported by multi-stakeholder involvement, knowledge-sharing, public-private cooperation, and cross-sectoral integration. A multi-dimensional, syncretic approach to development can support interoperability between current and future systems in the energy transition. Based on this approach, institutional readiness may be attainable on a holistic level for digitalization in the woody biomass supply chain, for blockchain-based energy-trading, and other digital innovation pathways.

The contribution of this dissertation is threefold. The gap between digital technology and woody biomass research was addressed, a holistic conceptualization of blockchain energy-trading was created, and a framework and strategic implications for digital innovation in the energy chain was proposed. In short, opportunities for digital innovation as well as how to take advantage and scale these opportunities were discussed. Practically relevant implications include key opportunities of digital innovation for woody biomass as well as energy distribution, and strategic suggestions as to how to take advantage of these prospects. The convergence of opportunities for digital innovation was found throughout the energy value chain. For example, blockchain as well as M2M communication, IoT, and 5G were identified as potential drivers of innovation in energy distribution. This would suggest that there is no one-size-fits all solution, and that a broad range of technologies should be considered in the energy value chain. In addition, as specific digital technologies have multiple potential applications throughout the energy value chain, it is suggested that the full chain should be considered as opposed to a siloed approach. For example, blockchain can contribute both to energy distribution in the downstream, and to resource quality-monitoring from the upstream and onwards. This dissertation suggested a digital innovation process of 1) concept creation rooted in a digital tech toolbox and based on challenges in the energy value chain, 2) multi-dimensional experimentation, and 3) scaling. These implications would be of interest in academia, business, and among policy-makers that are working to support the energy transition.

The importance of governance in this regard was discussed in chapter 4. This importance arises with the complexity of energy innovation and the need of both resource and stakeholder mobilization. There is a need of further research on the nexuses of digital technology and woody biomass as well as energy distribution. In terms of woody biomass, this research can be on how digital technologies can specifically contribute to social, economic, and environmental sustainability in regional woody biomass supply chains. In addition, an important question is what forms of regulatory and policy support would be needed to facilitate this innovation. In terms of blockchain energy applications, further research may include the development as well as application of the TESEI framework. In addition, TESEI was developed for electricity microgrids in areas in which utility grid interconnection is possible. Interesting areas of further research include blockchain applications in microgrids in remote areas with no access to the utility grid, as well as for other energy services such as heating, cooling, or gas. Finally, on the whole, further research is needed on governance to support digital innovation in the energy transition. This is important, because governance can be a tool to catalyze innovation and support resource mobilization, multi-dimensional experimentation, stakeholder harmonization, and long-term scalability. Such research may delineate future development that assimilates digital technologies, renewable energy, and impactful sustainable development. This thesis offers holistic conceptualization and substantiated strategic implications for digital innovation in the renewable energy value chain. This may be an important step in integrating innovation in terms of digitalization, decarbonization, and decentralization for a more impactful, sustainable energy transition.

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# Appendix

**Appendix A**

As follows are additional examples of cases of 1) woody biomass (Appendix A1) and 2) blockchain-based peer-to-peer (P2P) power-trading (Appendix A2) projects in Japan.

Appendix A1

Woody biomass: Maniwa City and Akita City

**Maniwa City, Okayama prefecture, Honshu region**

An important initiative in forestry and bioenergy progress in Japan is the Maniwa City Biomass Initiative, of which the purpose is to leverage forest resources for value creation, biomass businesses, and re-investments into the forest (JLGC, 2016). The Maniwa Biomass Power Co. Ltd installation which holds a generating plant with a 10 MW capacity, and utilizes primarily unutilized timber from the Maniwa region as its fuel source (Takuma, 2015). There are approximately 30 timber mills in the City (NTT, 2018). Approximately 60% of the timber used for manufacturing is made into products, and the rest becomes industrial waste (NTT, 2018). This industrial waste can be combined with other forms of unutilized wood, such as scrap wood, to power the 10 MW power plant NTT, 2018). This avoids disposal costs, enabled new revenue streams for the local economy, as well as supports forest management (NTT, 2018). The full woody biomass supply chain, from forestry to markets for finished products, is kept within Maniwa City (JLGC, 2016). This is supported by aggregating both large and small businesses that utilize wood resources into one area, or in other words, aggregating supply and demand (JLGC, 2016).

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**Akita City, Akita prefecture, Honshu region**

An additional woody biomass case in Japan is in Akita City. Akita has a developed silvicultural knowledge and practices of afforestation over several decades (Totman, 1985). However, compared to other areas in central and southwest Japan, Akita developed this relatively late, potentially due to its geographical isolation (Totman, 1985). Today Akita City is famous for a woody biomass power plant in Mukaihama, installed by the company United Renewable Energy Co. Ltd. (Renova, 2020). It runs primarily on wood chips from the Akita prefecture (Renova, 2020). More specifically, it is based on approximately 70% wood chips and 30% imported palm kernel shells (United Renewable Energy, 2020). The power plant runs on a steam turbine power generator with an output of 20.5 MW (United Renewable Energy, 2020). Similar to the Maniwa case, United Renewable Energy Co. Ltd. also hosts plant tours to the general public (Renova, 2020).

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**Main differences: Kyushu, Maniwa, and Akita**

The main difference between Maniwa and Akita with the Kyushu case study of this thesis, is that the case study was done on a broader regional level with companies present in multiple prefectures. Kyushu is region, while Maniwa and Akita are cities with known success cases. The timber corporation Meiken plays a key role in Maniwa (Meiken, 2020) and United Renewable Energy Co. Ltd. in Akita (United Renewable Energy, 2020). This would indicate that the successes of biomass in each city is highly dependent on these industrial players. This success may not be applicable to the entire Okayama and Akita prefectures or Honshu region.

Kyushu was the first region in which sawmills developed to be larger and more modernized. In addition, the region has among the highest potential for woody biomass in Japan, both with existing harvesting technologies, and in scenarios considering technical advancements (Kamimura et al., 2012). The region is the most active both in terms of forestry and biomass in Japan. For example, roundwood production is approximately one fifth of the Japanese total (e-Stat, 2018), and the generation capacity fueled by (unutilized) wood is about one third of the nation's total (FIT-Portal, 2019).

Kyushu was chosen due to its woody biomass potential, as well as to avoid the bias which may be incurred by solely studying a successful city or corporation. This was especially important because the purpose of section 2.1 was to explore challenges of the woody biomass supply chain in Japan. Finally, there are several forest-rich areas in Japan. Kyushu was also chosen due to the availability of interviewees from across the woody biomass supply chain (from forest owner to power producer), which was vital for the study in this thesis.

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Appendix A2

**Blockchain-based P2P power-trading: Fujimi Town, Nagano prefecture.**

Consulting firm elDesign, power retailer Mori Energy, and tech firm LO3 Energy launched a Proof-of-Concept (PoC) project for a local solar energy-trading market supported by blockchain in Fujimi, Nagano, in 2020 (LO3 Energy, 2020). This is the first project in Japan by commercial companies focusing on a blockchain platform to support end-users in local power-trading.

Participants in the PoC include both power consumers and prosumers (owners of solar rooftop households), which are allowed to trade local electricity in a mobile application called Pando (LO3 Energy, 2020). Pando aggregates supplies and matches bidders with sellers in a digital auction (LO3 Energy, 2020). While this PoC is a hypothetical virtual marketplace, it may eventually be expanded to larger scales (LO3 Energy, 2020). As put by an elDesign spokesperson: "We are always looking to help local communities, and have seen interest from the community that suggests accessing local energy is high on the list of consumer priorities. Innovative technologies like blockchain can support this."

**Main differences: Urawa Misono, Fujimi**

The main difference between this case and the Urawa Misono case explored in this thesis is that the Fujimi PoC is a hypothetical marketplace with no real financial or electricity transactions between participants. The Urawa Misono case is a leading project in Japan which incorporates actual electricity-trading supported by private power lines, smart meters, digital routers and controllers. These real transactions are automated and recorded on a blockchain platform. An additional difference is that the Urawa Misono project involves both companies and a university (University of Tokyo) in its development, while the Fujimi PoC is within the private sector. Hence the Urawa Misono project is a leading case in Japan both from the private sector perspective, and academically.

LO3 Energy. 2020. elDesign, Forest Energy and LO3 Energy launch first local solar energy trading market. Available at: https://lo3energy.com/eldesign-forest-energy-and-lo3-energy-launch-first-local-solar-energy-trading-market/ [Accessed June 3, 2020].

**Appendix B**

Appendix B1

Interview outline: Section 2.1: Sociotechnical challenges of woody biomass in Japan

What are key issues in the woody biomass supply chain for:

a) Forest management
b) Harvesting and collection of timber
c) Transportation of timber
d) Biofuel processing
e) Electricity/heat production from biofuel

f) Regulation
g) Others?

Appendix B2

Interview outline: Section 2.2: 2.2 Pathways: Digital innovation for woody biomass

1) What are some technical challenges you have seen for woody biomass?
   A) How can they be managed?
2) What are some social challenges you have seen for woody biomass?
   A) How can they be managed?
3) How do you think smart technologies and ICT (information and communication technology) can contribute to woody biomass systems?
4) Below is a list of challenges in the woody biomass supply chain. For each of the challenges, please discuss: How do you think smart technologies can contribute?
   A) Building stakeholder respect, relationships and trust
   B) Biomass quality control (moisture content, size, etc.)
   C) Business model integration for higher value creation
   D) Transportation infrastructure from forest
   E) Local community revitalization and socioeconomic development

Appendix B3

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Acknowledgements for section 2.2

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Energy Institute, Japan), Takeo Kato (Japan Woody Biomass Association), Tetsuya Maruta (NRI), Victor G. Walker (Idaho National Laboratory), Volker Lenz (DBFZ, Germany), Yoshiki Yamagata (National Institute for Environmental Studies, Japan).

Appendix B4

**Table 1.** Word frequency in interview responses for each of the five woody biomass supply chain challenges in Japan (f: frequency)

| Woody biomass supply chain challenge | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Transportation infrastructure | | Biomass quality monitoring and control | | Business model integration (cascading) | | Building stakeholder respect, relationships and trust | | Local community revitalization and socioeconomic development | |
| **Word** | **f** | **Word** | **f** | **Word** | **f** | **Word** | **f** | **Word** | **f** |
| Forest | 20 | Quality | 19 | Forest | 14 | Forest | 26 | Local | 31 |
| Transportation | 13 | Moisture-content | 17 | Data | 12 | Supply | 12 | Community | 26 |
| Infrastructure | 11 | Biomass | 12 | Value | 10 | Data | 10 | Supply | 18 |
| Need | 11 | Supply | 10 | Wood | 10 | Information | 10 | People | 13 |
| Big | 9 | Timber | 10 | Japan | 8 | Tracking | 10 | Rural | 13 |
| Cost | 9 | Wood | 10 | Energy | 7 | Biomass | 9 | Energy | 12 |
| Forestry | 9 | Control | 9 | ICT | 7 | Wood | 9 | Forest | 12 |
| Japan | 9 | Important | 9 | Market | 7 | Energy | 8 | Areas | 11 |
| Supply | 9 | Need | 9 | Area | 6 | Market | 8 | Good | 11 |
| Autonomous | 8 | Information | 8 | Bioenergy | 6 | People | 8 | Bioenergy | 9 |
| Information | 8 | Technology | 7 | Business | 6 | Transparency | 8 | Biomass | 9 |
| Wood | 8 | Condition | 7 | Material | 6 | Trust | 8 | Chain | 9 |
| Chain | 7 | Chain | 6 | Need | 6 | Forestry | 7 | Information | 8 |
| Timber | 7 | Chip | 6 | Power | 6 | Power | 7 | Need | 8 |
| Chipper | 6 | Digital | 6 | Resources | 6 | Communication | 6 | Resources | 8 |
| Road | 6 | Know | 6 | Sector | 6 | ICT | 6 | Wood | 8 |
| Route | 6 | Management | 6 | Apartment | 5 | Owners | 6 | Chains | 8 |
| Tree | 6 | Parameters | 6 | Companies | 5 | Value | 6 | Economic | 7 |
| Digital | 5 | Controlled | 5 | Consumers | 5 | Contract | 5 | Help | 7 |
| Europe | 5 | Fuel | 5 | Digital | 5 | Important | 5 | Important | 7 |
| Harvesting | 5 | Gas | 5 | Enable | 5 | IoT | 5 | Value | 7 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Help | 5 | People | 5 | Help | 5 | Resources | 5 | Renewables | 7 |
| Important | 5 | Sensors | 5 | Important | 5 | Stakeholders | 5 | Heat | 6 |
| Low | 5 | Side | 5 | People | 5 | Certification | 4 | Regions | 6 |
| Mobile | 5 | Users | 5 | Production | 5 | Chain | 4 | Use | 6 |
| Owners | 5 | Analysis | 4 | Side | 5 | Company | 4 | Behavior | 5 |
| Robotics | 5 | Condition | 4 | Technology | 5 | Industry | 4 | Business | 5 |
| Way | 5 | Conversion | 4 | Timber | 5 | Local | 4 | Incentive | 5 |
| Automation | 4 | Forestry | 4 | Use | 5 | Management | 4 | Infrastructure | 5 |
| Base | 4 | Human | 4 | Biomass | 4 | Operation | 4 | Small | 5 |
| Density | 4 | Measure | 4 | Bio | 4 | Owners | 4 | Socioeconomic | 5 |
| GPS | 4 | Price | 4 | Paper | 4 | Visibility | 4 | Contribute | 5 |
| Machines | 4 | Sensing | 4 | Problem | 4 | Business | 3 | Development | 5 |
| Mountain | 4 | Sharing | 4 | Properties | 4 | Customers | 3 | Economy | 4 |
| Onsite | 4 | Size | 4 | Public | 4 | Database | 3 | ICT | 4 |
| Side | 4 | Components | 3 | Trading | 4 | Difficult | 3 | Industry | 4 |
| Small | 4 | Count | 3 | Trust | 4 | Digital | 3 | Large | 4 |
| Systems | 4 | Data | 3 | Big | 3 | Direct | 3 | Owners | 4 |
| Technology | 4 | Drones | 3 | Cascading | 3 | Downstream | 3 | Power | 4 |
| Transport | 4 | Efficiency | 3 | Chemicals | 3 | Electricity | 3 | Trust | 4 |
| Trucks | 4 | Forest | 3 | Communication | 3 | Fuel | 3 | Agriculture | 3 |
| Business | 3 | Fraud | 3 | Demand | 3 | Issues | 3 | Biofuel | 3 |
| Chipping | 3 | Image | 3 | Develop | 3 | Network | 3 | Bad | 3 |
| Develop | 3 | Good | 3 | Education | 3 | Photo | 3 | Circulation | 3 |
| Difficult | 3 | IoT | 3 | Electricity | 3 | Price | 3 | Community | 3 |
| Drivers | 3 | Japan | 3 | Forestry | 3 | Registration | 3 | Connect | 3 |
| Satellite | 3 | Market | 3 | Future | 3 | Relationship | 3 | Cost | 3 |
| Sharing | 3 | Skills | 3 | Government | 3 | Truck | 3 | Creation | 3 |
| Tracks | 3 | Standards | 3 | High | 3 | Upstream | 3 | Developed | 3 |
| Virtual | 3 | Tag | 3 | Improved | 3 | | | Currency | 3 |
| Weather | 3 | Thinning | 3 | Industry | 3 | | | Digital | 3 |
| Drones | 3 | Tracking | 3 | Information | 3 | | | Digitalization | 3 |
| Future | 3 | Time | 3 | Local | 3 | | | Directive | 3 |
| Germany | 3 | Trust | 3 | Management | 3 | | | Ecosystems | 3 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Government | 3 | Trees | 3 | Needs | 3 | Forestry | 3 |
| GIS | 3 | Value | 3 | Optimized | 3 | Germany | 3 |
| Impact | 3 | Work | 3 | Picture | 3 | Government | 3 |
| Industry | 3 | | | Products | 3 | Interesting | 3 |
| Japanese | 3 | | | Plants | 3 | Issue | 3 |
| Logging | 3 | | | Quality | 3 | Japan | 3 |
| Long | 3 | | | Risks | 3 | Jobs | 3 |
| Optimize | 3 | | | Supply | 3 | Manufacturers | 3 |
| People | 3 | | | Traceability | 3 | Model | 3 |
| Roads | 3 | | | Transparency | 3 | New | 3 |
| Soil | 3 | | | Trees | 3 | Production | 3 |
| Subsidy | 3 | | | Utilized | 3 | Products | 3 |
| Support | 3 | | | | | Promote | 3 |
| Vehicle | 3 | | | | | Regional | 3 |
| | | | | | | Regulations | 3 |
| | | | | | | Scale | 3 |
| | | | | | | Sharing | 3 |
| | | | | | | Social | 3 |
| | | | | | | Solar | 3 |
| | | | | | | Support | 3 |
| | | | | | | Systems | 3 |
| | | | | | | Transparency | 3 |
| | | | | | | Villages | 3 |
| | | | | | | Work | 3 |

## Appendix C

### Appendix C1

Interview outline

Please discuss challenges of blockchain-based peer-to-peer power-trading microgrid applications in the following dimensions:

a) Technology
b) Economics

c) Society
d) Environment
e) Institutions

Appendix C2

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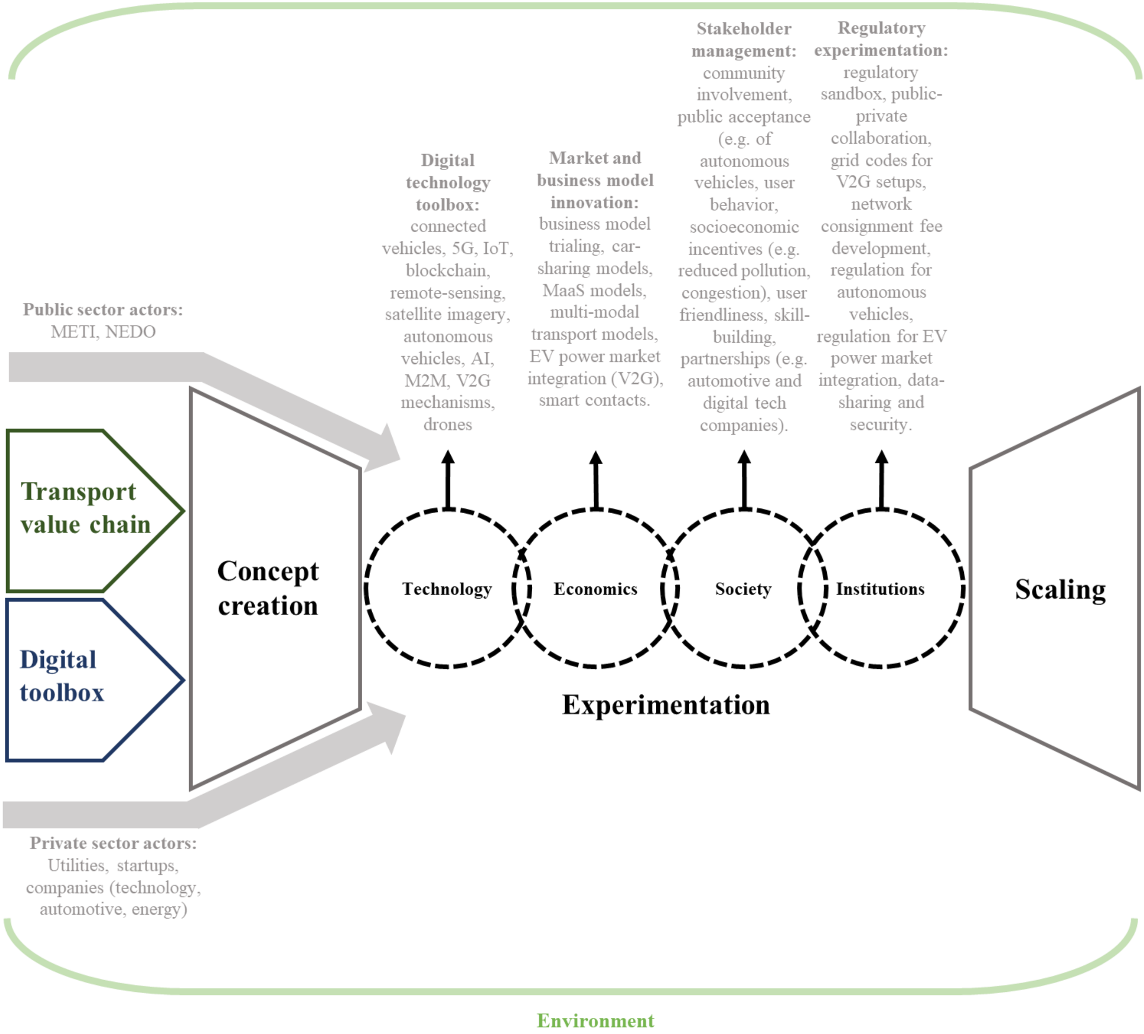
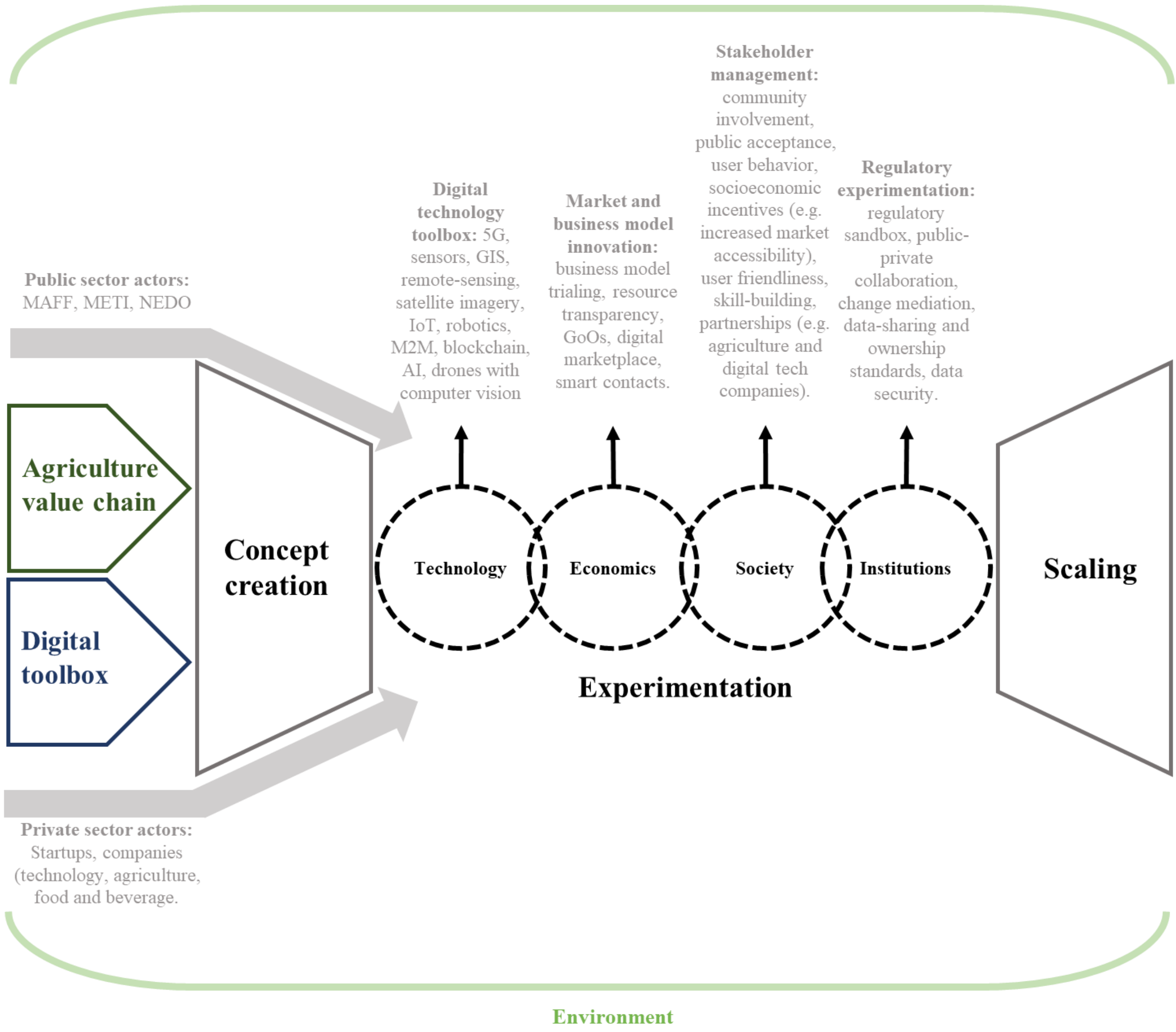
**Appendix D**

The scope of this thesis focused on the renewable energy value chain. As follows are two examples of applications of Figure 22 on other sectors: transport and agriculture. These sectors are outside the scope of this thesis and would require extensive research in exploring challenges in each sector and appropriate digital innovation strategies. These diagrams solely indicate the hypotheses of the author, and would require further research.




Framework for the concept creation, experimentation, and scaling of digital innovation in the **transport** value chain (Based on general framework in Figure 22; initial hypotheses of author) (AI: Artificial Intelligence; IoT: Internet of Things; M2M: Machine to Machine [communication]; MaaS: Mobiltiy as a Service; V2G: Vehicle to Grid)




Framework for the concept creation, experimentation, and scaling of digital innovation in the **agriculture** value chain (Based on general framework in Figure 22; initial hypotheses of author) (AI: Artificial Intelligence; IoT: Internet of Things; M2M: Machine to Machine [communication]; GoO: Guarantee of Origin)