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Increasing flexibility of Finnish energy systems—A review of potential technologies and means

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A B S T R A C T

It is apparent that future energy systems need increased flexibility for example due to wider adoption of variable renewable production, general transition towards decarbonization, and bidirectional energy grids. When several energy sectors are considered holistically, the possible flexibility measures increase. This paper reviews potential means to increase flexibility of Finnish energy systems by comprehensively regarding both electricity and thermal systems. After introducing renewable energy data from Finland, the authors discuss how flexibility is defined. Then, several technological options to meet the increased flexibility needs are described and Finnish examples are given. These key technologies and solutions include energy storage, district heating and cooling, electric vehicles, smart meters, demand response, and ICT solutions. In addition, energy markets provide important flexibility means. Therefore, aspects related to electricity market design and heat trading are also assessed.

1. Introduction

Most likely energy systems will be more distributed in the future. According to some very extreme visions (Energiauutiset|26.01.2017 2017), the electrical grid will even be an irrational investment when distribution and transfer of electricity will cost more than the energy itself. However, grid infrastructure aggregates distant resources and in doing so brings important portfolio and scaling benefits across the entire power system (International Energy Agency (IEA) (2014)).

Energy production based on renewables often fluctuates due to seasonal or other weather conditions. On one hand this supports decentralization of the energy systems, on the other hand it increases flexibility requirements of the entire energy system. Also the more wider long-term target of energy transition towards decarbonization has similar effects (e.g., (Pleßmann & Blechinger, 2017)). In general, the four pillars of the Nordic energy transition involve renewable electricity and heat, energy efficiency, transport, and industry (Sovacool, 2017). In Finland, there are several pilots, experiments and demonstrations which support this transition (Energiakokeilut.fi, 2017).

Lund, Lindgren, Mikkola, and Salpakari (2015) present a broad review of available and future options to increase energy system flexibility measures to enable high levels of renewable energy. Even if the review is extensive, it is limited to the electricity side dealing with the demand side, electricity network, power supply, and the electricity markets. Also, other studies address flexibility options of the electricity sector (e.g., (Kondziella & Bruckner, 2016; Verzijlbergh, De Vries, Dijkema, & Herder, 2016)).

Bussar et al. (2016) take a step further as they analyze large-scale integration of renewable energies and impacts on storage demand in a European renewable power system of 2050. They demonstrate how a variation of system configuration is able to compensate the higher component cost through a change in the resulting optimal configuration of each studied scenario.

Kondziella and Bruckner (2016) present a thorough literature review on the topics of storage demand, flexibility requirements, and resource potential in future electricity systems in Europe and especially Germany. In addition, they evaluate strengths and weaknesses of previous studies categorizing them as technical, economic or market related. Finland is not included in the considerations.

Additional flexibility for the energy system can be supplied if additional sectors are included, like heat or transportation (Bussar et al., 2016). For example, storing heat within the heat system and utilizing hybrid systems provide a major potential for flexibility (Kiviluoma et al., 2017). Also smart energy solutions in buildings and districts enable more comfort, functionality, and flexibility through the

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Nomenclature

3G, 4G, 5G	3rd, 4th, 5th generation
BEV	Battery electric vehicle
CAES	Compressed air energy storage
CAPEX	Capital expenditures
CCGT	Combined-cycle gas turbine
CHP	Combined heat and power
DER	Distributed energy resource
DR	Demand response
DSI	Demand side integration
DSM	Demand side management
DSO	Distribution system operator
EPBD	Energy performance of building directive
EV	Electric vehicle
FMG	Flexible multi-generation system
GT	Gas turbine
HVAC	Heating, ventilation and air-conditioning
ICES	Integrated community energy system
ICT	Information and communication technology
IoT	Internet of Things
LNG	Liquefied natural gas
LTE	Long term evolution
MTC	Machine-type-communication
NB-IoT	Narrowband IoT
NFV	Network function virtualization
nZEB	Nearly zero-energy building
OPEX	Operation expenditures
PHES	Pumped hydro energy storage
PHEV	Plug-in hybrid electric vehicle
PtG	Power-to-gas
PtH	Power-to-heat
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable energy
RES	Renewable energy sources
SDN	Software-defined network
TSO	Transmission system operator
URLLC	Ultralow latency communications
V2G	Vehicle-to-grid
VRE	Variable renewable energy
WSN	Wireless sensor network

integration of energy generation, storage, distribution, and automated control (Mosannenzadeh et al., 2017).

According to the International Electrotechnical (2017), 'smart grid' is used as a marketing term rather than a technical definition. At EU level, there are several definitions of the term 'smart grid' (Zgajewski, 2015). Even if a uniform definition of the 'smart grid' does not exist (Xenias et al., 2015), the core of the concept is the bidirectional flow of information and reduction on CO_2 emissions using renewable energy sources in addition to the efficient generation and distribution of electricity (Alam, Sohail, Ghauri, Qureshi, & Aqdas, 2017). In Europe, smart grid projects are implemented in more than 550 different sites (Colak, Fulli, Sagiroglu, Yesilbudak, & Covrig, 2015). Parallel to smart electricity grids, the concept of smart thermal grids has been introduced (Lund et al., 2014). Both concepts focus on the integration and efficient use of potential future RES as well as the operation of a grid structure allowing distributed generation which may involve interaction with consumers (Lund et al., 2014).

Lund (2017) analyses Finnish policy decisions to phase out coal and cut oil use by a quarter by 2030. He highlights that the Finnish energy transition strongly relies on a non-fossil-fuel-based electric system and biofuels in transport, but less on variable renewable electricity, energy system flexibility, and electric mobility. However, Government report on the National Energy and Climate Strategy for 2030 (Ministry of Economic Affairs & Employment, 2017) concludes that the flexibility of electricity demand and supply will be improved. In addition, it is mentioned that increased mutual interactions between different energy use sectors is needed (Ministry of Economic Affairs & Employment, 2017).

The Directive 2010/31/EU (Official Journal of the European Union, 2010) imposes that all the new building should be nearly zero-energy buildings (nZEBs) by the end of 2020. In Finland, legislation (Valtioneuvosto, 2016) for adopting the energy performance of building directive (EPBD) recast (EN 15603) was established in 2016. The law will be enforced in the years 2018–2020. Flexible energy systems also enhance adaption of the new building regulations.

According to IEA (2017), the greatest transformational potential for digitalization is its ability to break down boundaries between energy sectors, increasing flexibility and enabling integration across entire systems. Additionally, the large-scale deployment of distributed generation and storage are boosting the evolution from passive systems towards more proactive ones that can react on various dynamics of the energy systems with improved efficiency and agility. As the energy flows become more bidirectional, the amount of required information increases and demands for ICT become more versatile. This poses new challenges for communication systems, since communication quality, availability, response time, and security do not always meet the expectations. In the future, communications can be one of the key enablers or a hindrance in the transition towards flexible energy systems.

In flexibility related questions, the focus should not be limited to current power exchange schemes or players currently taking part in it. If a market-driven approach is chosen, electricity market design looked from the perspective of market rules, allocation of different functions between actors, etc. needs to be better taken into account (e.g., (Milligan, Holttinen, Söder, Clark, & Pineda, 2012)). Furthermore, International Energy Agency (IEA) (2014) highlights that VRE integration changes market design in order to value flexibility correctly and optimize system operations. Similarly, heat trading (e.g., (Nystedt, Shemeikka, & Klobut, 2006)) will change district heat markets.

This article aims to review enablers and means that could increase flexibility of the Finnish energy systems. Since energy systems have interactions, both thermal and electricity sectors are considered. More specifically, the contribution of this paper is threefold: the paper 1) enlarges the flexibility considerations to cover integrated energy systems and other supply sources but only electricity, 2) assesses the potential key technologies and solutions from the Finnish perspective and gives Finnish examples of all of them, and 3) considers how energy markets affect energy flexibility.

The remaining sections are organized as follows. Because flexibility needs arise to a great deal from an increasing share of renewables, Section 2 focuses on recent development of renewable energy in Finland. As a uniform definition for flexibility does not exist, Section 3 deals with definitions and issues identified from the literature and ends up to an explanation used in this study. Section 4 introduces and reviews several potential technological options to tackle flexibility requirements. Fig. 1 illustrates how core contents in Sections 2–4 are interlinked. Section 5 discusses how energy markets could support flexibility demands. Section 6 discusses about the findings and limitations, and Section 7 concludes the study.

2. Renewable energy in Finland

According to the government report on the National Energy and Climate Strategy for 2030 (Valtioneuvosto, 2017), the share of renewable energy in the end consumption will increase to approximately 50%

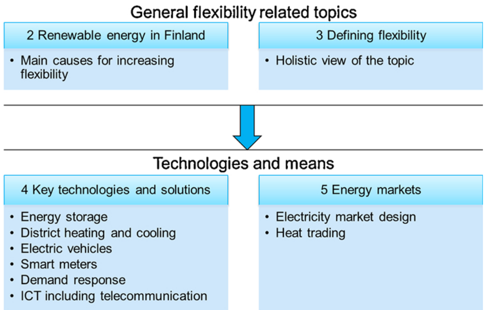

Fig. 1. Core aspects handled in Sections 2–4.

in Finland. According to Statistics Finland (2017), the share of renewables in total energy consumption was 35% and 126 TW h in 2015. Wood fuels represented 72% and bioenergy in total 79% of the renewables (Fig. 2, (Statistics Finland, 2017)). In 2015, heating and power plants consumed a total of 18.3 million solid cubic meters (34.9 TW h) of solid wood fuels (Natural Resources Institute Finland (LUKE) (2016)). The total solid wood fuel consumption has increased about 50% from 2001 to 2015 (Fig. 3). In 2015, the shares of different solid wood fuels were forest chips 40.2%, bark 37.9%, sawdust 11.8%, industrial ships 5.6%, recycled wood 3.8%, wood pellets and briquettes 0.7%, other forest industry by-products 0.1% (Natural Resources Institute Finland (LUKE) (2016)). Proskurina, Alakangas, Heinimö, Mikkilä, and Vakkilainen (2016) estimate that wood pellets could have a more important role in the future Finnish energy mix. In 2014, domestic consumption based on wood pellets was 1.1 TW h (Statistics Finland, 2015). Wood pellets are also exported from Finland.

In 2015, natural gas contributed to 6.3% to the total energy consumption by producing 22 878 GW h of energy (Statistics Finland, 2017). Mainly, heavy industry, and energy and power companies consume gas but it is an important energy source in combined heat and power (CHP) (Finnish Gas Association, 2016). In Finland, natural gas transmission network covers only parts of Southern Finland (Finnish Gas Association, 2016). However, Finnish Gas Association (Finnish Gas Association, 2018) visions that Liquefied Natural Gas (LNG) will be shipped to Finnish waterfronts in the future providing opportunities to increase natural gas consumption. In 2015, about 483 GW h of heat and about 147 GW h of electricity was produced from biogas (Huttunen & Kuittinen, 2016), corresponding to about 0.5% of the total renewable energy production. Tähti and Rintala (2010) estimate that in CHP 2.74 TW h of electricity and 3.92 TW h of heat, or alternatively 7.05 TW h of pure heat could be produced from biogas. Mutikainen, Sormunen, Paavola, and Haikonen (2016) estimate that biogas based energy production contributes to 3.2 TW h of electricity and 2.4 TW h of heat in 2030. In Finland, biogas is mainly produced out of landfill gas, bio waste, and sewage sludge (Huttunen & Kuittinen, 2016).

Wind power production has rapidly increased in the 21st century reaching about 2300 GW h in 2015 (Fig. 4). However, it still represents only about 2.8% of the total electricity supply (Statistics Finland, 2017). The role of heat pumps in Finland have increased even more than wind energy (Fig. 4). In recent years, nearly 5000 GW h of renewable energy production was due to heat pumps. According to the Finnish heat pump association (2016), in 2016 over 60 000 heat pumps were installed in Finland. Majority of these, 76%, were air-to-air heat pumps mainly installed to single-family houses as a supporting heat source. About 14% of the installations were ground source heat pumps, approximately 6% air-to-water heat pumps, and about 4% exhaust air heat pumps (The Finnish Heat Pump Association (SULPU), 2016). Altogether there exists 800 000 heat pumps in Finland (The Finnish Heat Pump Association (SULPU), 2016). Laitinen et al. (2014) estimate that the total number of heat pumps will reach about 950 000 units by 2020.

Fig. 5 shows the market growth of solar thermal and electricity in Finland. According to the figure, the capacity growth has recently accelerated. There is not yet any systematic process established to gather solar energy statistics in Finland, but in 2015, the Energy Authority started to compile statistics of grid connected PV systems. The domestic market growth started in 2014, since the global cost reductions in solar technologies made investments profitable with certain preconditions also in Finland (Auvinen et al., 2016).

3. Defining flexibility

A clear uniform definition of flexibility does not exist. Typically, definitions are limited to some parts or properties of energy systems. This section deals with flexibility definitions, aspects and features identified from the literature and ends up to an explanation used in this study. Table 1 reviews different approaches, strategies and technologies identified to be able to contribute on energy, mainly electricity, system flexibility on different areas of energy system.

According to Papaefthymiou and Dragoon (2016), flexibility is the ability of controllable power system components to produce or absorb power at different rates, over various timescales, and under various power system conditions. Kondziella and Bruckner (2016) consider flexibility as the short-term flexibility demand in electricity systems due to VRE integration. Lund et al. (2015) state that from the electricity system point of view, flexibility relates closely to grid frequency and voltage control, delivery uncertainty and variability and power ramping rates. System balancing has historically been performed by controllable power plants (Papaefthymiou & Dragoon, 2016). Even if they remain, increased share of renewables highlights the need for flexibility in all energy systems.

Koirala, Koliou, Friege, Hakvoort, and Herder (2016) define flexibility as one important criteria for integrated community energy systems (ICESs). It can be achieved through local demand response, local balancing, flexible load and supply. This flexibility can be utilized to provide energy and system services. Wu et al. (2017) state that innovative and competitive solutions of network coupling are also urgently required to enable and enhance the synergies and provide a significant amount of flexibility to energy networks.

Lythcke-Jørgensen, Ensinas, Münster, and Haglind, (2015) define flexible multi-generation systems (FMGs) as systems consisting of integrated and flexibly operated facilities that together provide multiple links between layers of the energy system. The approach includes both international/national and regional/local energy systems, and it is not limited to examining electricity production.

Sources outside the electricity sector can also contribute to flexibility (International Energy Agency (IEA) (2014)). For example Laitinen, Ruska, and Koreneff (2011) estimate that large scale penetration of heat pumps in heating of Finnish residential buildings would decrease the total heating electricity consumption of Finnish homes by 2% and increase the total power demand of heating these homes by about 18%. This example emphasizes that considering pure electricity

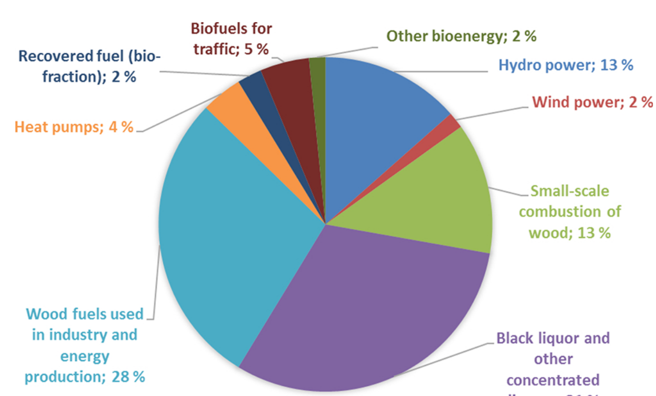

Fig. 2. Shares of different renewable energy sources in 2015 in Finland (data retrieved from (Statistics Finland, 2017)).

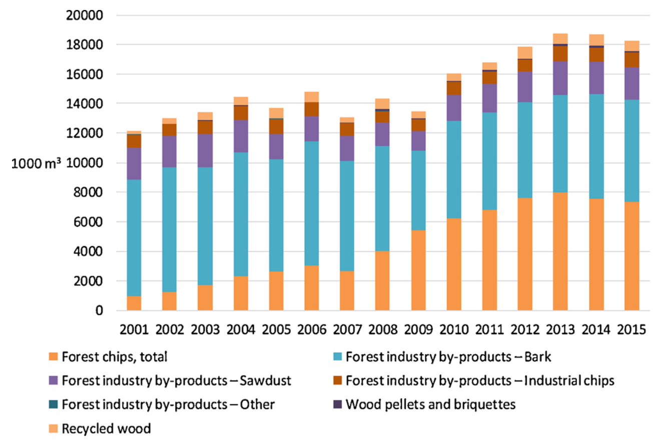

Fig. 3. Solid wood fuel consumption in heating and power plants in Finland in 2000–2015 (data retrieved from (Natural Resources Institute Finland (LUKE), 2016)).

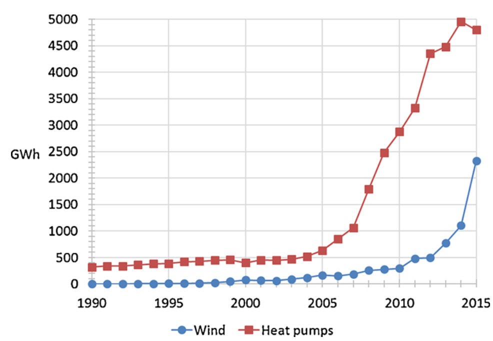

Fig. 4. Production of wind power and heat pumps from 1990 to 2015 in Finland (data retrieved from (Statistics Finland, 2017)).

sector may lead to misleading assumptions.

Connolly, Lund, and Mathiesen (2016) highlight that in future 100% renewable energy scenario, additional flexibility is created by connecting the electricity, heating, cooling, and transport sectors together. In the EU level, they use a minimum estimation of bioenergy, which underlines the change of energy infrastructure and institutions. In the Finnish context, such an assumption is not realistic since bioenergy is an important renewable energy source (Fig. 2). However, the core idea in Connolly et al. (2016) is to consider flexibility of the whole energy system instead of flexibility of individual branches which is also applicable to Finland. This emphasizes that different domains and energy sectors can provide flexibility services to other system parts even if the infrastructure is often separately owned and operated.

As stated before several studies deal with flexibility of pure power systems (e.g., (Bussar et al., 2016; Kondziella & Bruckner, 2016; Lund et al., 2015; Papaefthymiou & Dragoon, 2016)) even if different energy systems have interactions. Considering these interactions, heat and gas systems should also be taken into account since they can provide other flexibility means. In addition, all the system layers within the energy chain should be considered. Table 2 summarizes the assumed flexibility features by supply sources in different system layers utilized in this study. Similarly to the Mikkola's study (Mikkola, 2017), the whole energy system including both the electricity and thermal energy sectors are covered when considering flexibility measures.

4. Key technologies and solutions

This section deals with core technologies and solutions, which could improve energy system flexibility. The focus is on Finnish perspectives. Table 3 summarizes technology examples from Finland which are

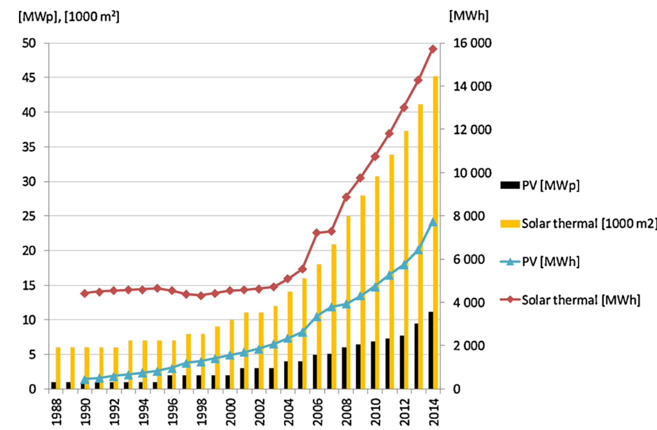

Fig. 5. Market development of solar thermal and solar electricity in Finland from 1988 to 2014 (data retrieved from (Statistics Finland, 2015)).

references in the following Subsections 4.1–4.6. Majority of the cases in Table 3 are pilots and there are other on-going trials as well. The subsections also include wider descriptions of the technologies and solutions.

4.1. Energy storage

Storages increase the flexibility to utilize sources of energy that are not available at the same time as the demand (Rutz, Doczekal, Zweiler, Hofmeister, & Laurberg Jensen, 2017). Storage technologies are often classified to 5 categories (European Association for Storage of Energy (EASE) (2014); Palizban & Kauhaniemi, 2016), namely chemical, electrical, electrochemical, mechanical and thermal. The level of maturity of storage technologies differs (OECD/IEA, 2014); many thermal storage technologies are already in commercialization phase while many electric storage technologies still remain in research and development or demonstration and deployment phases. Several reviews and assessments of energy storage solutions in different applications have been made (e.g., (Fuchs, Lunz, Leuthold, & Sauer, 2012; Huggins, 2010; Lupangu & Bansal, 2017; Mousavi, Faraji, Majazi, & Al-Haddad, 2017; Palizban & Kauhaniemi, 2016; Pinel, Cruickshank, Beausoleil-Morrison, & Wills, 2011; Xu, Wang, & Li, 2014)).

Electrical energy storage is still expensive (Zakeri, 2016; Zakeri & Syri, 2015, 2016). But batteries may prove competitive provided they are used for grid stability and balancing services as well (Pleßmann & Blechinger, 2017). Two large-scale commercial implementations of lithium-ion batteries were taken place in Southern Finland in 2016–2017 (Fortum, 2017a; Helen Ltd., 2016a). These electricity storages are the largest in the Nordic countries. They are both first used for experimental purposes and later on as parts of the distributed energy systems.

In the 1980s, the Kerava solar project was the first Finnish solar district heating system using seasonal heat storage. The Kerava solar village consisted of 44 terraced houses and a total of 1100 m^2 solar collectors capturing solar energy which was then stored in the underground rock pit and borehole storage (Oosterbaan, 2016). There were major problems with the system design and implementation leading to severe operational problems (Honkonen, 2016; Oosterbaan, 2016). Therefore, the solar systems were disconnected and the area was connected to traditional district heating.

After the Kerava solar village pilot (Heiskanen, Nissilä, & Lovio, 2014; Honkonen, 2016; Oosterbaan, 2016), large-scale seasonal thermal storage is not realized in Finland even if experiments from similar climate conditions (Bauer et al., 2010; Bauer, Marx, & Drück, 2014; Lundh & Dalenbäck, 2008; Sibbitt et al., 2012; Xu et al., 2014) indicate that it could be feasible also in Finland. A simulation study (Flynn & Sirén, 2015) shows that high solar fractions (up to 96%) can be achieved also in Helsinki with solar district heating if connected to

Table 1
Electricity system flexibility measures (based on (Lund et al., 2015; Palizban & Kauhaniemi, 2016; Salpakari, Mikkola, & Lund, 2016)).

Flexibility measure	Key actions	Response time
Production		
Power plant response (GT, CCGT, CHP)	Peaking or load following	Minutes
Distributed/hybrid energy systems and production units	Smoothing rapid changes in RE generation and improving dynamic response of supporting production systems and energy efficiency	–
Curtailment	Limiting the power output in the case of e.g. limited transmission capacity, over supply of VRE power and too large share of inflexible base load generation	–
Supply		
Very short-term energy storage (batteries, supercapacitors, flywheels, superconducting magnets etc.)	Storing excess electricity, grid support services for power quality and reliability, and frequency regulation; rapid response time and high power ramping rate required	From milliseconds to 5 min
Short term energy storage (PHES, CAES, batteries, flow batteries, hydrogen)	Storing excess electricity, grid support services as spinning, non-spinning and contingency reserves, black-starts, power reliability, and frequency regulations; rapid response time and large energy capacity required	From 5 min to 1 h
Intermediate term energy storage (PHES, CAES, batteries, flow batteries, hydrogen)	Storing excess electricity, load leveling, improving the efficiency of transmission, spinning reserve	From 1 h to 3 days
Long-duration energy storage (PHES and gas storage), hydropower –large reservoirs	Seasonal power shifting when power consumption and generation have large seasonal variations; large energy capacity, inexpensive storage medium and low self-discharge required	Several months
Electricity-to-thermal (electric boiler, heat pump, thermal storage)	Excess renewable energy is converted to thermal energy, which is easier to store and can supply also cooling	From hours to days
PtX	Storing excess electricity, integration of energy sectors	
Network		
Grid extension	Transmission curtailment prevention	–
Gas grid	Storing synthetic CH_4 from RES	–
Super grids	Connecting remote RE power sites with demand	–
Smart grids	A total solutions to advance RE integration to the system by engaging all the key stakeholders	–
Micro grids	Supplying power to local consumers, balancing voltage fluctuations within a larger power distribution system	–
Demand side		
Load shifting	Rescheduling of energy demand without compromising the continuity of the process or quality of the final service offered	1–12 h
Vehicle-to-grid	Storing excess electricity, grid support services	Hours
Energy markets		
VRE support scheme	Affects the production decisions of VRE producers to market signals	–
Virtual power plants	Aggregating different VRE generators	

Table 2
Flexibility features relevant to different energy system layers and energy types.

Features	Layers				Supply source		
	Country	Region	District	Building	Electricity	Heat	Gas
Possibility to change the energy source				X	X	X	
Ability of buildings to manage their demand and generation according to the local climate, user needs and grid requirements				X	X	X	X
Very low barriers for participation in energy markets as a producer, especially for electricity and heat - (barrier, may be e.g., caused by regulation or monopolistic position)			X	X	X	X	X
Possibility to exchange energy (transmission and trade) with other countries, regions	X	X	X		X		X
High utilization of locally available renewable and waste heat (low-temperature networks and consumption)			X	X		X	
Interoperability and compatibility of systems (same sizes, adapters, plugs, everything fits and works everywhere - the "local" obstacles to using a product are minimal)				X	X	X	X
There is enough capacity	X		X		X		
Greater degree of demand response during high prices (automation)					X	X	

low temperature heating systems. In addition, solar assisted local energy solutions with seasonal heat storage could reduce the emissions and increase energy self-sufficiency of a Finnish district (Paiho, Hoang, & Hukkalainen, 2017). Short-term (from hours to days and even weeks) thermal storage is already utilized in connection with district heating in Finland (e.g., (Fortum, 2017a; Helen Ltd, n.d.)) to balance rapid consumption peaks. Additionally, some serious considerations of possible larger implementations of thermal storage are going on (Helen Ltd., 2018a).

4.2. District heating and cooling

Flexibility in district heating and cooling sector can include actions within the consumer buildings or it can be related to more efficient operation or alternative technologies of centralized production of heating and cooling. Energy storage solutions are a significant aspect in both. Even the network itself provides an option to store heat to a certain extend (e.g., (Kannari, 2012)). A Finnish pilot hybrid energy system is partly utilizing this feature (Vexve, 2017). In addition, a back-pressure cogeneration plant can temporarily continue producing electricity in absence of heat load (Colmenar-Santos, Rosales-Asensio, Borge-Diez, & Blanes-Peiró, 2016) or avoid turning on heat only boiler plants during e.g. morning peaks.

Finland is among the EU-28 countries where district heating is most widely used and where district heating prices are very moderate (Colmenar-Santos et al., 2016). According to the Energy Year 2014

Table 3
Finnish examples of technologies or solutions providing improved energy system flexibility.

Case	Section relevant to the example	Technology or solution	Possible impact on flexibility
Järvenpää battery (Fortum, 2017a)	4.1	Large-scale electricity storage with a lithium-ion battery (2.3 MW)	Enables more flexibility for the energy company to act on the electricity market Increases the share of CHP production
Suvilahti electricity storage (Helen Ltd., 2016a)	4.1	Large-scale electricity storage with a lithium-ion battery (Output 1.2 MW and energy capacity 600 kW h)	Balances electricity supply Helps to reconcile production and consumption Compensates brief peaks and dips in output needing rapid reaction
Suomenoja heat accumulator (Fortum, 2017a)	4.1	Thermal storage of district heating (800 MW h) for up to 1 month	More even production of district heating Heat can be stored in periods with lower heat demand Stored heat can be utilized during the consumption peaks as well as during possible plant and network disturbances Increases the share of CHP production
Heat accumulators in Salmisaari and in Vuosaari (Helen Ltd, n.d.)	4.1	Short-term thermal storage of district heating (in total 200 MW)	In the night, heat produced with cogeneration is stored in large water tanks. When more heat is needed in the morning, the heat is discharged from the accumulators.
Ristiina hybrid energy system (Vexve, 2017)	4.2	Solar district heating	Promotes the use of renewable energy Improves the efficiency of the heating plant Cuts the peak load of the bioenergy plant during the summer using solar heat Solar heat is partly stored in the district heating network and partly in a thermal storage
Kakola heat pump plant (Niemelä & Saarela, 2010)	4.2.1	Large-scale heat pump in district heating	Utilizes surplus heat Supports network integration Quick start-up of heat production
Katri Vala Heat pump plant (Helen Ltd., 2016b)	4.2.1	Large-scale heat pump in district heating	Postpones the start-up of large CHP plants in the autumn Advances the downturn of CHP plants in the spring Enables an option to react on market risks Utilizes surplus heat Quick start-up of heat production
Savo-Solar office building (Sipilä et al., 2017)	4.2.2	Thermally driven absorption chiller in connection to district heating	By using thermally driven absorption chiller, no additional grid stress or reserve capacity, either in summer or in winter, is caused. Surplus heat from district heating network is utilized for generating building-specific cooling during the summer. The chiller can also be powered by solar heat. Depending on the building demands, the absorption machine can be operated as a chiller or a heat pump.
Electric buses in Tampere (Vihreäkaista, 2015)	4.3	Electric vehicles	Nighttime recharging balances electricity demands. Recharging can be optimized for cost by depot charging management system. Enables power grid related services
Electric buses in Espoo (Pihlatie et al., 2014)	4.3	Electric vehicles	A possibility to reactive power support Can offer grid support within the frequency containment and frequency restoration reserves
Elenia smart metering pilot (Elenia, 2017)	4.4	New generation smart meters, measurements every 5 to 15 min (instead of every hour), data available immediately	Part of a platform for real-time services Electricity consumption and power data are available closer to real-time Private customers an easy access to demand response market The provision of new control services
Fortum virtual power plant (Fortum, 2017b)	4.5	Demand flexibility, over 100 kW virtual power plant from an aggregated network of roughly 70 water heaters located in single-family homes	The capacity of this power plant is offered to the Finnish national grid company Fingrid to maintain a continuous power balance in the electricity system. Based on remote control of the water heaters without any impact on the heating of the home or on the hot tap water Customers are offered real-time monitoring of household's electricity consumption Households and the energy solutions they use create a new player in the electricity markets
DSM in Heka apartment blocks (Helen Ltd., 2018b)	4.5	Heat demand response	Helps to optimize heat production in Helsinki without causing disruption to indoor temperatures in homes Utilizes the heat storage capacity of properties as part of the total energy system
Oulu district heating data underground (Telia, 2017)	4.6	NB-IoT technology in the district heating network	Real-time data supports maintenance of the district heating network Quicker responds to network changes and disturbances in the whole heat supply chain

(Statistics Finland, 2016), net production of district heat in Finland was 37.1 TW h of which 31% was produced in district heating plants and 69% in combined heat and power (CHP). Alternative production options are rarely utilized but their share is likely to increase (e.g., (Paiho & Reda, 2016)) for example due to the national energy targets (F. Government, 2013).

4.2.1. Large-scale heat pumps in district heating

Large heat pumps increase the flexibility of district heating system and heat production, as they enable the use of electricity in heat production and, combined with CHP production, increase flexibility between electricity production and consumption depending on the price of electricity (Valor Partners Oy, 2016). In a Swedish case (Levihn, 2017), system flexibility is increased by utilizing heat pumps to preheat the DH water before a CHP lifts it to final supply temperatures. A Danish study (Bach et al., 2016) showed that it needs to be carefully considered whether to connect large-scale heat pumps to distribution networks or to transmission networks since it may significantly affect heat production.

In Finland, the Kakola heat pump plant utilize waste heat from treated waste water and produces both district heating and cooling for public buildings and homes in Turku (Niemelä & Saarela, 2010). Its annual district heating production is 160 GW h (about 8% of the district heating demand in Turku) and district cooling production is 90% of the demand. In 2015, the world's largest heating and cooling heat pump plant beneath the Katri Vala park in Helsinki produced 422 GW h of heat corresponding to 7% of all district heat in the Helsinki region (Helen Ltd., 2016b). Annual production of district cooling is about 90 GW h corresponding to about 70–75% of the demand (Valor Partners Oy, 2016).

4.2.2. Absorption chillers

Absorption chillers are an alternative to regular compressor chillers where electricity is unreliable, costly, or unavailable, where noise from the compressor is problematic, or where surplus heat is available (Rutz et al., 2017). An EU Strategy on Heating and Cooling (European Commission, 2016) recommends the exploitation of tri-generation (simultaneous generation of heating, cooling and power). Absorption chillers could provide savings in electricity production together with combined heat and power production especially during the summer, when space heating is not needed. Absorption chillers can also be powered by solar heat (Al-Alili, Hwang, & Radermacher, 2014; Kim & Infante Ferreira, 2008; Taha Al-zubaydi, 2011) which can increase the share of renewable energy. In Mikkeli, there is a Finnish pilot installation of a building-level solution in connection to district heating (Sipilä et al., 2017).

4.3. Electric vehicles

An electric vehicle can be defined as any vehicle in which some or all of the driving energy is supplied through electricity from a battery (Richardson, 2013). Electric vehicles (cars, buses and trucks) have been one of the key components in smart grid related research (e.g., (Aghaei, Esmaeel, Rabiee, & Rahimi, 2016; Mesarić & Krajcar, 2015; Mwasilu, Justo, Kim, Do, & Jung, 2014; Pearre & Swan, 2016; Pina, Baptista, Silva, & Ferrão, 2014; Richardson, 2013; Škugor & Deur, 2015; Torreglosa, García-Triviño, Fernández-Ramirez, & Jurado, 2016; Wang, Wang, Chu, Pota, & Gadh, 2016)) involving flexibility with demand response or other similar concepts.

In 2017, about 20 battery electric vehicle (BEV) models and about 30 plug-in hybrid electric vehicle (PHEV) models were on the Finnish market (Vihreäkaista|4.1.2017, 2017). The prices of BEVs varied between €14, 000–171, 000 and the prices of PHEVs between €40, 000–156, 000. The reported driving ranges of BEVs are between 150–613 km and of PHEVs between 30–56 km. By the end of 2016, there were about 18, 000 registered EVs in Finland (Solutive, 2017). At the same time according to Finnish Transport Safety Agency Trafi (2017), there were over 2.6 million passenger cars and in total over 3 million cars in traffic in mainland Finland excluding the small autonomous region Åland. The market share of EVs is considerably smaller in Finland than in the neighboring Nordic countries Norway and Sweden (International Energy Agency, 2017). The high investment cost of EVs has inhibited buying of EVs. In addition, lack of recharging infrastructure has reduces the popularity. However, the number of public recharging points is increasing all the time (sähköinenliikenne.fi, 2017). According to Finland's national programme for a distribution network for alternative transport fuels for 2017–2030 (Ministry of Transport & Communications, 2017), there should be at least 2000 public recharging points by 2020 and 25, 000 by 2030.

Vehicle-to-grid (V2G) can provide several services to the power grid, such as ancillary services, peak load shaving, load leveling and support for renewable energy resources (Tan, Ramachandaramurthy, & Yong, 2016). The stochastic nature of EV's storage to provide grid services can be a challenge. Lu, Zhou, Yang, and Liu (2018) use optimization to address this challenge and manage to shift charging loads from high-priced periods to low-priced periods under the coordinated charging mode of EVs. In his dissertation, Kiviluoma (2013) concluded that smart charging would be a more important source of flexibility than V2G in case of high penetration of EVs. Mozafar, Amini, and Moradi (2018) also highlight that the optimal management of charging and discharging is a necessity for network stability, security, and optimality. A recent study (Kester, Noel, Zarazua de Rubens, & Sovacool, 2018) on promoting V2G in the Nordic region calls for a further development of flexible electricity markets, support for pilot projects, and attention to information and planning.

In Finland, heavy-duty electric like busses and trucks have been tested and most of the experiences have been positive. In Tampere, an electric truck has a range of 250 km and recharging from empty to full takes 4 h (Vihreäkaista, 2015). Therefore, recharging can be done in nighttime and optimized for cost by depot charging management system. In addition, power grid related services could be possible during this time. An electric bus is also in operation in Espoo. The bus is charged in the beginning and at the end of route (Pihlatie, Kukkonen, Halmeaho, Karvonen, & Nylund, 2014) with some additional capacity left for variability of conditions like outdoor temperature and traffic flowing wellness. Results from the US (Gao et al., 2017) show that ultrafast charging increases battery degradation, but the magnitude of capacity loss due to ultrafast charging appears less significant than that resulting from normal repeated charging over time.

Perhaps, the most lucrative option for grid support or services in relation to electric vehicles is reactive power support. Reactive power affects to voltage level in power systems. Reactive power can be injected or drawn from power system (Latvakoski, Mäki, Ronkainen, Julku, & Koivusaari, 2015). Injecting reactive power (capacitive) raises the voltage level and drawing (inductive), it decreases voltage level. Reactive power can be outputted same time with normal battery charging (active power) when full capacity of the inverter is not used for charging. EV's can also offer grid support within the frequency containment and frequency restoration reserves which are used by TSO's for maintaining the grid frequency within a safe range.

4.4. Smart meters

The aim towards more efficient and less consuming economy requires more knowledge of the consumption both in large scale (districts) and in household scale. Smart meters can be defined as gateways for communication between energy systems' parties (Römer, Reichhart, Kranz, & Picot, 2012). In Finland, over 95% of homes are equipped with smart meters (De Groove, Volt, & Bean, 2017) but real time data is coming in later upgrade phase. In the future, smart meters can measure and record the real-time data at customers' site and supply it to service provider in order to enable demand response and monitor services leading to more coordinated grid management and improved energy efficiency. Even now, there are on-going pilots in Finland where new generation smart meters are being tested in 30 000 households (Elenia, 2017) in order to provide more flexibility to the electricity grid. These meter readings utilize 4 G technology (see Section 4.6).

Smart metering has been used in defining the load dependent price for electricity, which gives consumers the opportunity to shift the consumption and, thus, balances the grid load (Römer et al., 2012). Metering system should encourage consumers to decrease their electricity consumption with increased knowledge of their consumption behavior. Therefore, metering system could include also appliance detector in the future (Gajowniczek & Zabkowski, 2014). An easy-to-access display could give the consumer the possibility to interact with available information in almost real time and motivate the consumer to optimize their consumption (Benzi, Anglani, Bassi, & Frosini, 2011). With the specific information of the consumption patterns, the electricity retailers can offer special tariffs which gives competition advantages and increase the customer retention (Römer et al., 2012).

Smart meters could also address the specific needs of customers such as adapt the heating, air-conditioning and lighting depending on the boundaries such as number of family members at home or weather forecast (Benzi et al., 2011). Smart meters are also part of smart buildings, which can be enlarged to offer numerous other services including telemedicine (Jabłoński, 2015).

4.5. Demand response

Active demand side response will provide a significant opportunity to enhance the power system flexibility (Wu et al., 2017). Demand response (DR) refers to the ability of loads to quickly respond to power system needs. Both residential (e.g., (Haider, See, & Elmenreich, 2016)) and industrial (e.g., (Shoreh, Siano, Shafie-khah, Loia, & Catalão, 2016)) DR applications have been introduced. In addition, several authors address enablers and/or barriers of DR ((Good, Ellis, & Mancarella, 2017; Oconnell, Pinson, Madsen, & Omalley, 2014; Paterakis, Erdinç, & Catalão, 2017; Vallés, Reneses, Cossent, & Frías, 2016)). Other terms such as load flexibility and active demand mean roughly the same thing, whereas demand side management (DSM) is a wider term. Demand Side Management (DSM) allows consumers to make informed decision regarding energy consumption, and helps energy providers to reshape the load profile and to reduce peak load demand (Esther & Kumar, 2016). Demand Side Integration (DSI) is a less-used term with normally the same meaning as Demand Side Management.

DR potential depends on the type of load, duration and timing of the response request, weather conditions, notification period in advance of the request, automation solutions at end users and contract types and benefits (Viinikainen, Soimakalliio, Kärkkäinen, Sipilä, & Helynen, 2007). In the residential sector, the potential is affected by the conflict between habitual practices, thermal comfort and altered electricity use. Also in the industrial sector a conflict with plant operations exists and the potential may be challenging to estimate because every plant has its own specific demand profile (Stötzer et al., 2012).

From the Finnish perspective, electrical HVAC loads are the most potential loads for DR in the residential and commercial sectors. Järventausta et al. (2015) estimated that in electrically heated single-family houses and semi-detached houses could provide 2900 MW DR during extreme cold periods. Ikäheimo (2013) estimated the maximum electrical heating DR potential of residiential buildings in winter conditions (8.7 °C) to be 630 MW during daytime and 1800 MW during the night. However, the duration of this resource is short and normally only a minority of the heating loads are switched on during daytime. If longer durations are sought, then the capacity is reduced accordingly. Naturally, in summer heating loads are mostly limited to domestic hot water heating. Air-conditioning and ventilation of office and other commercial buildings could provide 300–400 MW DR each in the extreme case (Järventausta et al., 2015). The maximum duration of this resource is short. As an example from Finland, the energy company Fortum has an on-going pilot dealing with demand flexibility of electrical loads in households (Fortum, 2017b).

DSM is also possible in district heating systems. There, demand side management does not necessarily save thermal energy, but the aim is the temporal transfer of heat consumption in the district heating system to make the whole system more optimal (Valor Partners Oy, 2015). A Finnish simulation study showed that predictive DSM with dynamic price signals reduces heating costs in buildings by 4% during the heating period (Salo, 2016). DSM can be used to improve utilization of power plants, to minimize the use costly peak production, to optimize the timing of CHP production based on electricity price, and to postpone investments needed to improve the capacity of the network (Valor Partners Oy, 2015). However, due to the varying structure of district heating systems and networks also the possible benefits are case-sensitive. Also head demand response pilots have started in Finland, e.g., (Helen Ltd., 2018b).

4.6. ICT including telecommunication

Communication technology is an important enabler in the future energy grids (e.g., (Alam et al., 2017; Bayindir, Colak, Fulli, & Demirtas, 2016; Emmanuel & Rayudu, 2016)). New communication technologies, such as the 5th generation mobile technologies (5 G) and Internet of Things (IoT), are excellent assets for enabling flexible and cost-efficient communication media between grid entities. The communication infrastructure is especially essential for the growth of DERs scattered over a large geographical area (SWECO, 2015).

After evolutions of 3G and 4G and variations of LTE (e.g., (Akyildiz, Gutierrez-Estevez, & Reyes, 2010; Akyildiz, Gutierrez-Estevez, Balakrishnan, & Chavarria-Reyes, 2014; Rinne & Tirkkonen, 2010)), development is now heavily focusing on 5 G (e.g., (Akyildiz, Nie, Lin, & Chandrasekaran, 2016; Blanco et al., 2017; Kumar & Gupta, 2017; Li, Gao, Huang, Du, & Guizani, 2017; Noh, Song, & Lee, 2015)). Flexibility for a wide range of use cases and services, and scalability to provide these services in a cost-efficient way, will be one of the key design principles for the 5G communication system (Blanco et al., 2017). 5G is expected to enhance not only the data transfer speed of mobile networks but also the scalability, connectivity, and energy efficiency of the network (Mitra & Agrawal, 2015). Potential applications of 5G networks include, for example, virtualized homes, smart societies, smart grids, and industrial usages (Panwar, Sharma, & Singh, 2016).

Also in the Finnish perspective, research and deployment of 5 G and IoT technologies are critical for both energy and communication industries. The business potential of introducing 5 G in the energy domain is exceptionally high. Ultra-reliable, Low Latency Communications (URLLC) and massive Machine-Type-Communication (mMTC) are anticipated to offer the waited support for critical machine type communication applications for energy grid protection and control, and for the massive volume of MTC type applications of the emerging smart metering. The performance and flexibility of 5 G are expected to fulfil the requirements of the emerging distributed generation, consumption, and storage use cases of 2020 and beyond (G Infrastructure Association, 2015).

The deployment of new communication technologies and services for future energy systems requires testbeds that enable more realistic experimentation and validation environment to ensure a quick deployment of new solutions and applications. Therefore, a high emphasis is put on combined energy and communications pilot systems in Finland (Horsmanheimo et al., 2015). Finnish industrial showcases have already launched where 5 G is utilized to connect energy sources to energy grids, e.g., (Fortum, 2018).

The future communication networks are software oriented, which allows higher network re-configurability than we have today. NFV, being a complementary concept to SDN (Godfrey, 2013) and emerging as a breakthrough in 5 G cellular systems, provides advantages in scalability and flexibility (Akyildiz et al., 2016) as well as reduces complexity in communication networks. The NFV/SDN concept is compelling, because it enables a transformation away from tightly integrated or proprietary solutions toward a more streamlined and flexible service delivery chain (NGMN Alliance, 2015). It also introduces the network slicing functions, which allow mobile operators to reconfigure customer specific service dedicated virtual networks on the top of a set of physical networks. With this concept, mobile network operators, DER operators/aggregators and ancillary service providers can offer new services in a more cost-effective and flexible way than done today (NGMN Alliance, 2015).

IoT is the network of everyday physical objects, vehicles, appliances, devices, buildings, etc. (Akyildiz et al., 2016). By putting intelligence into everyday objects, they are turned into smart objects able not only to collect information from the environment and interact/control the physical world, but also to be interconnected, to each other, through Internet to exchange data and information (Borgia, 2014). Possible application domains include: industrial, smart city, health well-being, transport, and utilities (e.g., (Borgia, 2014; Gubbi, Buyya, Marusic, & Palaniswami, 2013)). For example, IoT-based Big Data analytics consisting of various types of sensor deployment, including smart home sensors, vehicular networking, weather and water sensors, smart parking sensors, and surveillance has been proposed (Rathore, Ahmad, Paul, & Rho, 2016). A Finnish company has developed an IoT based thermostatic radiator valve for district-heated buildings which enables Demand Side Management (Fourdeg, 2018). In December 2017, Oulun Energia in Finland started a pilot project to study the use of new NB-IoT technology for operational development in an energy company (Telia, 2017). Security and privacy issues in IoTs are still partly unresolved and their importance cannot be underestimated (e.g., (Sicari, Rizzardi, Grieco, & Coen-Porisini, 2015)). The future network can be taught to be energy-aware through activation and deactivation of parts of the network in response to changing traffic loads. Renewable energy sources such as solar or wind power, advanced battery technologies and fuel cells will also improve the self-sufficiency of the base stations and make the communication networks more resilient against different types of outages.

A wireless sensor network (WSN) consists of a number of sensor nodes which can sense, measure, and gather information from the environment and, based on some local decision process, transmit the sensed data to the user (Yick, Mukherjee, & Ghosal, 2008). There are a number of important parameters which need to be taken into account when instrumenting WSNs (Yuan, Kanhere, & Hollick, 2016). In energy systems, WSNs can be exploited to monitor a specific region or space in a remote location. WSNs can be applied in several applications, including power system applications (Rashid & Rehmani, 2016). The existing and potential WSN applications for smart grids include advanced metering, demand response and dynamic pricing, equipment fault diagnostics, fault detection, load control, distribution automation and remote power system monitoring and control (Fadel et al., 2015). IEEE 802.15.4 protocol is widely adopted in the WSNs (Wang & Hwang, 2015).

5. Energy markets

5.1. Electricity market design

In Finland, the day-ahead and intraday markets are covered by the Nordic-originated electricity exchange, *Nord Pool* (Nordic Energy Regulators, 2016) which operates the markets called *Elspot* and *Elbas*. The main focus in the Elspot and Elbas trading is on the management of volume (imbalance) risk, which arises if the consumption does not match the electricity procurements (Valtonen, 2015). The existing Nordic and Finnish electricity markets are described more in detail in (Gore, Vanadzina, & Viljainen, 2016; Valtonen, 2015).

In order to increase flexibility, a novel architecture of *two-market system* (Keay, 2016) is a potential new option where electricity market is divided into “on-demand” and “as available” markets (Forsström, Koreneff, & Similä, 2016). For increasing flexible components in competitive electricity markets, well-known measures include improvements in intraday and real-time markets, more efficient and dynamic prices, higher geographical or temporal resolution, capacity prices, and demand response participation (International Energy Agency (IEA) (2016)). A recently discussed element in electricity market design is whether any type of capacity mechanism, often primarily designed to tackle the capacity adequacy in the long-term, should be included.

In principle, current electricity market designs offer possibilities for trading flexible resources in various timescales. Even a timescale of minutes or seconds is tackled through trading mechanisms. However, the shorter timeframes are often run automatically or by the system operator (especially balancing markets or ancillary services). As these markets often work on pre-contracted capacities, a question raises if there would be benefits through more dynamic inclusion of bid-based flexibility supply and demand through appropriate market design.

Table 4 shows a conceptual framework of options for market participants to trade the products for flexibility. For each dimension, few examples of possible choices are mentioned. These choices must be applied in each subparts of electricity markets (e.g. day-ahead markets, intraday markets, balancing markets, capacity markets). In addition, fluent interplay between the markets must be considered.

Despite the general direction in European electricity markets towards liberalization and market rule harmonization (European Union, 2009), there is still significant discrepancy between the different market systems. Also network functions and regulation choices, such as tariff structure or subsidy schemes, have a significant impact on profitability of different solutions providing flexibility. This is especially true when the small-scale solutions are considered, as incentives for flexibility actions such as load shifting partly fall under an influence of the pricing practices applied by the DSO.

Market design barriers are related to legislation, insufficient pricing schemes, and conflicting interests (generator, network company, retailer, consumer), which, in turn, may result in inefficient pricing schemes giving distorted incentives for flexibility. From the market design point of view, the most obvious potential barrier for small-scale actors to participate in markets is the minimum size for bid. Other barriers suggested include permit procedures, ease of grid connection, and taxation laws (Ruggiero, Varho, & Rikkonen, 2015).

Enabled by integrated and advanced electricity trading between Nordic countries in international comparison, the large flexibility supply by hydropower in Nordic electricity system impacts the flexibility in Finland. Furthermore, the foreseen share of varying RES and the associated flexibility need in Finland are not among the highest in Europe or even in Nordic countries. Relying on these facts on supply and demand for flexibility, one could suggest the case for flexibility being not among the most acute in Finland in Nordic, European or global context. However, one should remember that this simplification

Table 4
A conceptual framework for the key elements of market design.

	Regional dimension	Time to gate closure	Temporal product definition	Load participation	Market organizer	Pricing	Unit commitment	Dispatch procedure	Minimum bid size
Choices in market design	Regional, national, international	24 h, 1 h, 30 min Dynamic offers	Hour, 30-min, 15-min or shorter	Yes/No	System operator, market operator	Nodal/ zonal/ national	Unit/aggregate	Centralized Self-dispatch: portfolio-based/ unit based	A volume specified

for illustrative purposes lacks a proper quantitative estimate, and does not account many important issues such as the local distribution or transmission grid operation related flexibility needs.

Still, the previous remarks demonstrate that one should not limit the flexibility considerations of electricity markets to national perspective of Finland to give it a relevant context. Especially, on 30 November 2016 the European Commisssion (2016) published its so-called Clean energy for all Europeans legislative package (a.k.a. Winter Package), which consists of eight proposals to facilitate the transition to a "clean energy economy" and to reform the design and operation of the EU's electricity market. Whereas the details of the implementation remain currently unclear, more integrated markets means that also flexibility will be traded more and more on international basis, implying the solutions and problems will not be limited according to national borders. Thus, from the perspective of markets, developing functioning market products on flexibility from ICT and smart metering perspectives to be piloted in well established Nordic electricity markets could also be a natural role for Finland in the future enabling trading of flexibility resources.

5.2. Heat trading

Unlike electricity markets (Energiateollisuus & Fingrid, 2013), district heat markets are not opened in Finland. Customers are free to choose whatever heating (Energiateollisuus ry, 2018) but district heating is typically produced and distributed by local municipal energy companies. However, there are several experiments going on where independent heat producers supply heat to the local district heating networks (e.g., (Fortum, 2016; YLE, 2014)). This emphasizes the change in the heat markets. In addition, the proposal of the European Union for a directive on the promotion of the use of energy from renewable sources (recast) (European Commission, 2017) promotes easier access of third parties to the heat markets provided that this does not affect for example high-efficiency cogeneration.

In open district heating, customers and independent heat producers can sell their surplus heat to the network. Then, someone has to take care of the operation of the network. In addition, it has to be solved which technical connections (e.g., (Ben Hassine & Eicker, 2013)) as well as other terms and conditions are utilized in heat trading. Someone needs to guarantee that heat is also available during the heat peaks. This also has impacts to the necessary investments and willingness to make them. New pricing mechanisms are also needed for open district heating (Li, Sun, Zhang, & Wallin, 2015; Zhang, Ge, & Xu, 2013).

6. Discussion

Increased flexibility does not come free. Costs depend on various factors including technical system structures, and they were not considered in this study. However, Mikkola (2017) show that, by viewing energy systems as a whole instead of focusing on only one energy form, the flexibility of the system can be remarkably increased, even without massive investments in traditional network infrastructure. Zakeri's results (Zakeri, 2016) from selected energy systems proved large-scale heat pumps in connection with the district heating system and heat storage to be techno-economically the most promising flexibility option in Finland. In addition, International Energy Agency (IEA) (2014) concludes that distributed heat storage and district heating applications are attractive options to make electricity demand more flexible. These results support the considerations of this paper.

The Finnish Electricity Market Act (9.8.2013/588) (Sähkömarkkinalaki 9.8.2013/588 (in Finnish), 2013Sähkömarkkinalaki 9.8./588 (in Finnish), 2013Sähkömarkkinalaki 9.8.2013/588 (in Finnish), 2013) does not recognize or mention electricity storage. According to the current interpretation of the Finnish legislation (Bröckl, 2016), an electricity storage facility can be classified as being both consumption and production. Therefore, taxes and distribution fees may have to be paid when charging electricity and a production fee when discharging electricity (Helen Ltd., 2016a). In addition to costs, this is a clear barrier to a wider rollout of the technology.

Lithium-ion battery prices have declined for years (Hocking, Kan, Young, Terry, & Begleiter, 2016; IHS Markit, 2018). When lithium demand increases (Hocking et al., 2016), there might be a change in this trend in the future. IHS Markit (2018) expects price increases for smaller purchasers and projects even now. Deutsche Bank (Hocking et al., 2016) forecasts that lithium-ion battery costs still reduce both for automotive and for energy systems. This would support a wider deployment of electricity storage and EVs. Deutsche Bank (Park et al., 2016) expects full-electric EV sales to be 2.6% of global sales by 2025 which would be 6-times the 2015 market. In Finland, the recent major increase has been on sales of hybrid cars (Tilastokeskus, 2018).

The battery technology is still not supporting continuous charging and discharging of EVs (Motiva Oy, 2016) which restricts the use of EVs as a flexibility source. However, new solutions minimizing battery degradation may overcome this challenge, e.g., (Uddin et al., 2017; Wang, Coignard, Zeng, Zhang, & Saxena, 2016). In addition, consumer behavior is critical in (fast) charging and dependent on the charging fees (Motoaki & Shirk, 2017). The proposal amending Directive 2010/31/EU on the energy performance of buildings (Euopean Commission, 2016) reflects this issue by considering EVs as smartness aspects rather than flexibility providers. This emphasizes that the role of EVs as a flexibility source may be limited.

Experiences from early adaptors of EVs in Sweden (Vassileva & Campillo, 2017) show that EVs are mainly charged at home at night. Results from Ireland (Morrissey, Weldon, & O'Mahony, 2016) highlight that EV users prefer to carry out the majority of their charging at home in the evening during the period of highest demand on the electrical grid. With a large penetration of EVs this could lead to severe disturbances on existing distribution grids (Morrissey et al., 2016; Vassileva & Campillo, 2017). A similar pattern is possible also in Finland if smart charging, even if there is little notion of users' acceptance of the concept (Will & Schuller, 2016), is not introduced.

According to International Energy Agency (IEA) (2010), hydrogen can link different energy sectors and energy transmission and distribution networks and thus increase the operational flexibility of future low-carbon energy systems. Power-to-Gas (PtG) applications may play in important role there (Mazza, Bompard, & Chicco, 2018). Even if the role of gas is relatively small in the Finnish energy system (see Section 2), this topic should not be forgotten in the Finnish context. Some interesting Finnish papers have already been published. Tsupari, Kärki, and Vakkilainen (2016) studied the economic feasibility of integrating PtG to a biomass fired CHP plant. Pilpola and Lund (2018) analyzed different scenarios for Finnish energy system transition and provided flexibility through PtX, including coupling through PtG. Cao and Alanne (2018) analyzed a building-scale hybrid energy system integrated to a hydrogen vehicle.

The increased communication is not free. It includes operation expenditures (OPEX) generated from running and maintaining services, and capital expenditures (CAPEX) from investments and upgrades of hardware and software components. The critical questions are: when to exploit wired and wireless communication technologies, what we can and what we cannot do with them, how to measure and ensure experienced quality, how much we are willing to pay for it, and what are our future requirements for the communications.

From a market design point of view, the primary goal should be in setting an even-handed field for participants supplying and demanding flexibility. This being done, the market outcome should result the most efficient allocation for flexibility. However, due to regulated actors present and imperfections in practical markets, as well as technical requirements for reliable electricity supply, an amount of regulation is inevitably present in the design of electricity markets. Thus, trade-off between efficiency brought by markets and uncertainty related to outcome must be faced.

Development of flexibility resources discussed in this article challenge the current electricity market arrangements. Especially, the current electricity market design can be characterized as building on centralized operation and large industrial actors. Furthermore, the role of end consumer and demand-side especially in the small scale can be described as passive in electricity markets. These aspects contrast the fact that new innovations on flexibility resources such as batteries or micro grids can be small in scale of the national energy system. Thus, despite there are multiple alternatives to capture flexibility in large-scale operation in Finnish and Nordic electricity markets (Section 5), the ability of current market arrangement to efficiently capture the value of new flexibility resources can be questioned. Novel ideas of electricity market design development such as peer-to-peer trading, more local energy markets, e.g. blockchains, more efficient introduction of independent aggregators, or novel type of trading platforms present alternatives to improve the capability of electricity markets operation in local and smaller scale and transform it to be more demand-side inclusive. Thus, it is often suggested that these measures could be used as a market design based measure to increase flexibility. However, many of these ideas per se have to do with accounting the energy flows between market participants after the delivery and thus have no or limited contribution to flexibility. Thus, despite the market design evolution may be affected by the novel ideas, they are mostly driven by other drivers such as increasing RES based electricity than increasing flexibility. In particular, dividing the market in smaller small markets areas may actually increase the need for flexibility, as off-balances in larger market area counteract each other to a significant degree.

To discuss the efficient recipe for the Finnish case, it is beneficial to recall the fundamental idea of electricity market liberalization: a guideline of bringing all the resources in one pool and letting the market-based solution to determine the optimal mix and allocation of resources. Here, increasing the inclusion of small-scale resources and increasing flexibility in bids may serve the market in increasing its flexibility capacity. The examples presented in this article show various novel technologies to capture the quickly developing end-user flexibility resources. Thus, the landscape for most efficient flexibility solutions to several years ahead is subject to high uncertainty. This is also true in relation to their competiveness in relation to conventional solutions in Finnish and Nordic context. As a key driver in market evolution in Finnish context in making it more inclusive relates to capturing of small-scale solutions and being more interactive with demand side, a joint effect of possible market reforms and distribution and transmission tariff structures must be stressed for efficient design. For example, an idea of charging distribution tariffs more peak load based presents an example of affecting the profitability of small-scale flexibility solutions such as storages and DSM. As there are several simultaneous trends in market evolution, instead of centrally managing the electricity market towards incorporating a "right" flexibility solution foreseen by a regulator, a guideline of enabling and creating a level playing field can show particular advantages in Finnish context. Here, activities in pilots, demonstrations and experiments can pave the way towards efficient market reformation for flexibility resources.

This paper focused on flexibility means of Finnish energy systems due to the trend towards distributed local energy systems. In addition, heating is to a large extent local business (e.g., (Paiho & Saastamoinen, 2018)) and it offers many important flexibility options. However, Finland is not isolated from the Nordic electricity markets as shown in Section 5. Similarly to the Baltic countries (Møller Sneum, Sandberg, Koduvere, Olsen, & Blumberga, 2018), flexibility of DH in Finland is also partly coupled to the common Nordic electricity markets through CHP. Additionally, utilizing power-to-heat (PtH) (e.g., (Bloess, Schill, & Zerrahn, 2018; Yilmaz, Keles, Chiodi, Hartel, & Mikulić, 2018)) could attach Finnish flexibility aspects more closely into the Nordic energy systems and thus provide more flexibility (Kirkerud, Bolkesjø, & Trømborg, 2017).

Since there are various aspects in flexibility, there are also various supporting business model opportunities. Typically, literature (e.g., (Aslani & Mohaghar, 2013; Boehnke, 2007; Frantzis, Graham, Katofsky, & Sawyer, 2008; Gordijn & Akkermans, 2007; Hall & Roelich, 2016; He, Delarue, D'haeseleer, & Glachant, 2011; Hellström, Tsvetkova, Gustafsson, & Wikström, 2015; Huijben & Verbong, 2013; Karakaya, Nuur, & Hidalgo, 2016; Koirala et al., 2016; Niesten & Alkemade, 2016; Richter, 2012; Ruggiero et al., 2015)) does not directly address increasing flexibility through business models but rather concentrates on distributed renewable generation. However, some timing-based business models providing flexibility in the power sector have been studied (Helms, Loock, & Bohnsack, 2016). More focused work on flexibility creation through different business cases is clearly needed.

7. Conclusions

Even if a uniform definition for flexibility in relation to energy systems does not exist, it is evident that the topic is being increasingly important in Finnish energy systems. In this study, rather than considering only the power section, it was assumed that a more holistic view is needed. Therefore, both the electricity and thermal energy sectors were covered when considering potential flexibility measures in Finnish energy systems.

Several technological options to tackle the demand for flexibility in Finnish energy systems were introduced and reviewed. These included energy storage, district heating and cooling, electric vehicles, smart meters, demand response, and ICT solutions. In addition, from each mentioned Finnish examples were given. In the Finnish context, these technologies can be seen as the main flexibility enablers.

In addition to technology-based solutions, flexibility opportunities arise from energy markets. The rapidly increasing share of VRE production highlights the need of reform in electricity market design. Therefore, options and key elements for electricity market design were assessed. In addition, heat trading in open district heating markets was reviewed.

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