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The Role of Solar Photovoltaics and Energy Storage Solutions in a 100% Renewable Energy System for Finland in 2050

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Abstract: There are several barriers to achieving an energy system based entirely on renewable energy (RE) in Finland, not the least of which is doubt that high capacities of solar photovoltaics (PV) can be feasible due to long, cold and dark Finnish winters. Technologically, several energy storage options can facilitate high penetrations of solar PV and other variable forms of RE. These options include electric and thermal storage systems in addition to a robust role of Power-to-Gas technology. In an EnergyPLAN simulation of the Finnish energy system for 2050, approximately 45% of electricity produced from solar PV was used directly over the course of the year, which shows the relevance of storage. In terms of public policy, several mechanisms are available to promote various forms of RE. However, many of these are contested in Finland by actors with vested interests in maintaining the *status quo* rather than by those without confidence in RE conversion or storage technologies. These vested interests must be overcome before a zero fossil carbon future can begin. The results of this study provides insights into how higher capacities of solar PV can be effectively promoted and managed at high latitudes, both north and south.

Keywords: PV economics; energy system modelling; storage; 100% renewable energy; Finland

1. Introduction

The Finnish energy system is at a crossroads due to an aging system of power generation, opinions about different modes of low-carbon energy generation, responsibilities to mitigate climate change, worries of fluctuating energy prices, and goals regarding national energy security. In addition, there is a wish to both retain a competitive industrial sector and meet the needs of a future society. Recently, the country has committed to an 80–95% reduction (compared to 1990 levels) in greenhouse gas (GHG) emissions by 2050 [1]. However, how these reductions will be shared across different sectors of life and the economy has not been fully explained. Currently, approximately 80% of all GHG emissions originate from the energy system (electricity, heating/cooling and transport). The balance of emissions comes from sectors such as agriculture and forestry, manufacturing, aviation, and waste management, among others [2]. Given that significant reductions in the agricultural and manufacturing sectors may be difficult, prohibitively expensive or disruptive to society [3], achieving essentially zero carbon emissions in the energy sector may be the only way of achieving the nation's overall goals without dependence on carbon flexibility measures, such as emissions trading. Recently, the Finnish Ministry of Employment and the Economy stated that rapidly developing technologies such as solar power may create opportunities and offer the possibility of a 100% renewable energy system for Finland [4].

For these reasons, an energy system based entirely on renewable resources was considered in previous work by the authors [5]. The scenario of a 100% renewable energy system was seen as being highly cost competitive to those with increasing shares of nuclear power installed capacity as well as a Business As Usual scenario. However, this study did not have within its scope a description of how such a system would work in detail nor did it provide suggestions in policy terms related to how such high levels of renewable energy generation, particularly solar photovoltaics (PV), could be achieved.

In many ways Finland represents a challenge to high levels of solar PV penetration in an energy system. While the country has very high amounts of solar irradiation during the months around the summer solstice, the opposite is true during the months around the winter solstice. The need for storage technologies on a daily and seasonal basis seems obvious [6]. This observation and the role of energy storage in mitigating the intermittency of high shares of solar PV and wind energy for Finland were recently described in [7,8]. This extreme situation could then serve as a model for other countries at high latitudes, both north and south, of how solar PV can play a role in a highly developed and industrious society. If it can work in Finland, perhaps it can work almost anywhere.

In 2014, total energy consumption in Finland was approximately 372 TWh_{th}, with about 32% of primary energy coming from renewable sources (mostly hydropower and biomass) [2]. Electricity consumption was 83.3 TWh_e, with about 22% of this total coming from net imports. Peak electricity consumption of 14,367 MW_e occurred on 20 January at 8–9 a.m., while peak output of 13,022 MW_e occurred on 12 January at 6–7 a.m. [9]. Of total output capacity, solar PV represented only 11.38 MW_e, or 0.1% [10]. There are currently only five solar PV plants operating in Finland which are greater than 500 kW_p, and the total installed capacity is approximately 20 MW_p [11]. At the time of writing, the two largest installations were found on the rooftops of supermarkets (both 900 kW_p) in the city of Turku [12] although there are several utility-scale projects in the range of 8.7 MW_p (single axis horizontal tracking) that are currently planned for different parts of the country [13]. No comprehensive statistics are currently available on small-scale ownership. However, it is estimated that a great majority of solar PV panels in Finland are roof-mounted and that a minor part of the installed capacity is grid-connected. Interestingly, the panels (each one is 285 W_p) of an 853 kW_p plant in the Kivikko neighbourhood of Helsinki are rented for a monthly fee of €4.40 to individual customers, who can then deduct the energy each panel produces from their electricity bill provided they are a customer of that distribution company [14]. Solar irradiation values for Lappeenranta, Finland and other European cities are found in Figure 1 [15,16].

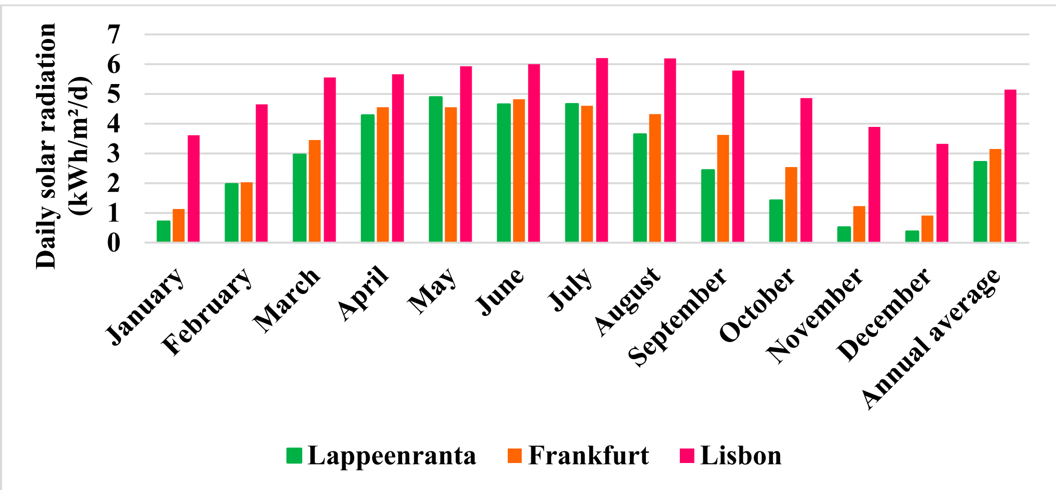

Figure 1. Daily solar radiation for three cities in Europe [15,16].

The 100% renewable energy scenario developed for Finland in 2050 in [5] has a very different composition from the current system, as seen from the representation of Annual Fuel Consumption for 2012 and 2050 in Figure 2. From the figure it is clear that the movement away from fossil-based energy includes greatly expanded roles for wind, bio-based and solar energy. For solar PV, this would represent 30 GW_p of installed capacity, roughly half of which would be rooftop and the other half ground-mounted. The associated annual energy, 29.5 TWh_e, represents only 10% of annual final energy consumption and 16% of total electricity generation, but solar PV dominates production in certain periods during the summer, and is quite insignificant during some periods of the winter.

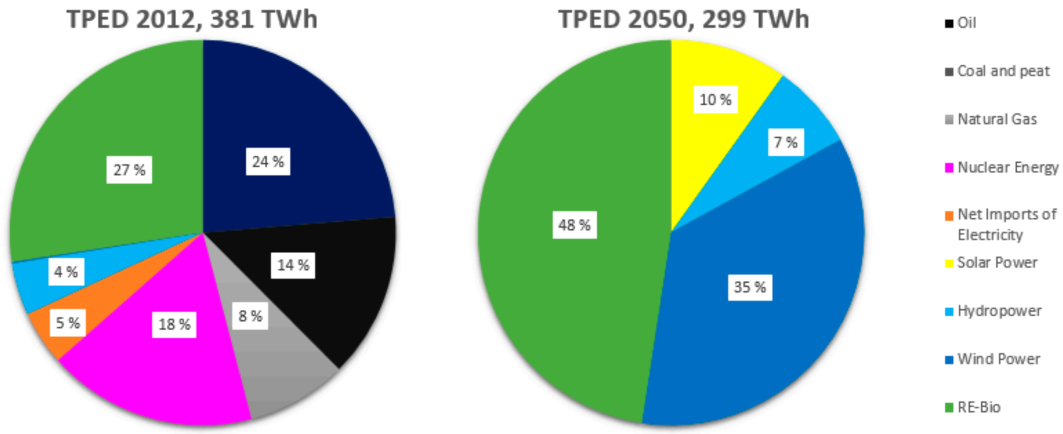

Figure 2. Annual Fuel Consumption in Finland in 2012 [1] and 2050 [4].

The huge leap from the current 20 MW_p of installed solar PV capacity to 30 GW_p allows consumers access to a generation technology that has already reached retail grid parity in Finland and appears to be one of the lowest cost sources of energy for the future [17,18]. Indeed, solar PV has reached a high level of competitiveness throughout Europe, and northern latitudes will see grid parity for rooftop PV prosumers in the near future [19]. This is due to a steep positive learning rate associated with solar PV that shows overall cost reductions as capacity is increased, unlike technologies such as hydro or nuclear power, which tend to show a negative learning rate [20]. Using Stockholm as an analogue for Helsinki, a recent report suggests that the levelised cost of electricity (LCOE) of solar PV could be below 40 €/MWh_e by 2050 [21]. This is based on a real weighted average cost of capital (WACC) of 5%, learning rate of 20% and solar PV module efficiency improvements of 0.4% per year from 2030 to 2050. Additional reasons for exploring the role of solar PV in this study is to determine if there may be some complementary relationship between solar PV and batteries, as has been documented in [22–25], whether there may be benefits for individual prosumers of energy [26], and if there would be a seasonal advantage of using more energy from solar PV during the long, bright, Finnish summers, and wind energy, biomass or gas based Combined Heat and Power (CHP) during the long, dark winters.

Achieving such high levels of solar PV capacity is not unheard of even in northern areas of Europe. Germany already has installed capacity of almost 40 GW_p and this number is set to grow in the years to come [27]. In addition, solar irradiation in northern Germany does not differ greatly from that of southern areas of Finland, where most of the population lives. Northern Germany has a solar irradiation on optimally inclined surfaces of approximately 1250 kWh/(m^2·a) while southern Finland's is approximately 1100 kWh/(m^2·a) (Figure 1). The amount of land required (not including rooftops) to achieve 30 GW_p of installed solar PV capacity represents only a fraction of Finland's land area, about 0.1%, given a future density of installation of 0.02 km^2/MW_p. So, even though the leap in solar PV installed capacity may seem prohibitively huge (growth by more than 2700%), in truth even greater growth has already occurred in the past two decades with the same technology just across the Baltic Sea in Germany. Finland would have 35 years to reach the 2050 level of the scenario described. High shares of solar PV and 100% renewable energy systems are already being discussed at high levels in Finland [4].

In this work, the results of Haukkala [28] describing several impediments to future solar PV installations for Finland are revisited and expanded. Primary among these impediments is widespread doubt that solar PV can ever be a competitive solution for a land at such northern latitudes. The work of Child and Breyer [5] confirms that solar PV can be an integral part of a competitive future energy system, leading the authors to wonder if any of the other barriers to implementation can so easily be disputed. Further, there is a need in Finland to not only dispel myths surrounding solar PV, but to begin discourse which will ultimately make the social and economic climate around all forms of renewable energy more favourable. Recent studies in Finland [29,30] have already advanced the discussion about distributed generation of renewable energy in terms of barriers, key drivers, benefits and the implementation of policies that would support future development.

Barriers to renewable energy technology (RET) penetration in general and to PV energy specifically are very much global. In addition, they appear quite similarly in extant literature, with only some country or technology specific differences. Painuly [31] has categorised major barriers to RET penetration in six categories: market failure/imperfection, market distortions, economic and financial, institutional, technical, and social, cultural and behavioural. These include, for instance, lack of information and awareness, favouritism towards conventional energy production, disregard of externalities, economic unviability, clash of interests, lack of Research and Development (R&D) culture, lack of professional institutions, lack of skilled personnel/training facilities and lack of consumer acceptance of the product.

Margolis and Zuboy [32] have drawn on a broad literature search to determine nontechnical barriers to solar energy use, including market, institutional and political barriers. In addition, according to [33], the main technical barriers include batteries and unresolved problems of storage. The economic barriers mainly consist of system costs. Cost comparisons are made with established conventional technologies that exploit economies of scale, have uncounted externality costs, receive public subsidies, and have accumulated industry experience. Path dependence and lock-in have been identified as barriers also in other studies [32,34]. Institutional barriers include the lack of a skilled workforce. The role of bureaucracy in delaying investment efforts in PV is also discussed in [35].

It was assumed at the beginning of this work that part of the doubt surrounding solar PV is the country's lack of experience with such technology as well as an overall lack of understanding of how solar PV would work as part of the energy system [28]. For that reason the first part of this work is dedicated to determining how electricity from solar PV would be utilised either directly, or through utilization of daily and seasonal storage technologies. The roles of Power-to-Gas (PtG), Vehicle-to-Grid (V2G) connection, stationary batteries as well as gas and thermal energy storage (TES) solutions were explored. The second part of this work focussed on examining a more complete range of barriers to achieving high penetrations of renewable energy in Finland, particularly with regards to solar PV. From this knowledge, several possible solutions towards overcoming such barriers were compiled and final suggestions were made regarding policies that could best support the realisation of a 100% renewable energy system for Finland in 2050.

2. Materials and Methods

In the first part of this work, the EnergyPLAN advanced energy system analysis computer model [36] was used to represent a 100% renewable energy (RE) scenario for Finland in 2050. This scenario was one of several used in the study by Child and Breyer [5], and was selected for further detailed analysis as it represented the most cost competitive of the scenarios studied. A thorough description of the tool used and the scenario parameters can be found in [5]. In addition, the main inputs to EnergyPLAN and other important assumptions and scenario parameters can be found in the Supplementary Material.

From the outputs of the model, hourly data was gathered and analysed to determine the detailed workings of several aspects of the energy system. EnergyPLAN provides yearly output graphics on an hourly resolution for production, demand and storage of electricity, district heating and grid-based gas (in this case biogas, Synthetic Natural Gas from biomass gasification and PtG methane). From these yearly graphics, several weeks of interest were identified and represented in more detail to determine how energy in various forms was being generated, and how it was possibly being stored and ultimately consumed. Although hourly data of boiler-based home heating is not included by EnergyPLAN, an examination of the three categories of electricity use, district heating and grid gas is assumed to provide a reasonably full picture of energy demand, supply and storage to allow for interpretation of results. The weeks of interest corresponded to those which witnessed:

1. Peak electrical consumption—Hour 810 of the year.
2. Minimum electrical consumption—Hour 4204 of the year.
3. The summer solstice—21 June.
4. The winter solstice—21 December.

The period of study was then chosen as the week surrounding the hour or day of interest, with that moment of interest as close to the midpoint of the study period as possible while maintaining the start of the study period as the first hour of a calendar day (01:00) and the final hour of the study period being the last hour of a calendar day (00:00). Due to the time around the summer solstice being extremely popular for beginning summer holidays and temporarily shutting down businesses and reducing industrial output, this was also the period of minimum electricity consumption. Therefore, the three weeks of study were: 1–7 February (Hours 744–912), 20–26 June (Hours 4104–4272), and 20–26 December (Hours 8469–8664). Tables 1–3 show the categories of demand, supply and storage that were represented on an hourly basis for each of the weeks of study. Results were then compiled and analysed.

Table 1. Study categories for electricity.

Electricity Demand (MW_e)	Electricity Supply (MW_e)	Electricity Storage (MWh_e)
End-user consumption (individual and industry)	Onshore wind	Stationary batteries
Cooling	Offshore wind	V2G batteries [1]
Flexible demand (individual, industry and electric vehicles [1]	Solar PV	
DH heat pumps	Hydropower	
PtG Hydrogen	Industrial power production	
PtG Methane	Combined heat and power	
Residential heat pumps	Condensing power plants	
Residential electric heating	V2G	
V2G (Smart charge BEVs and storage)	Stationary batteries	
Stationary batteries		
Curtailment		

[1] Demand for electricity for electric vehicles was divided into two categories using EnergyPLAN. Half of the estimated 3 million vehicles are so-called Smart Charge Vehicles. The other half represented a so-called Dump Charge. This Dump Charge is found within the category of Flexible Demand in the Demand column due to the integration of these elements by EnergyPLAN. In the Supply column, the category V2G represents the discharging of storage into the electricity grid. In the demand column, V2G represents the charging of storage that takes into account the driving patterns and demands of end-users. It is further assumed that 20% of Smart Charge Vehicles will be in use during periods of peak demand and that the share of parked Smart Charge Vehicles that are grid connected is 70%. For these reasons, charging and discharging of V2G vehicles can occur simultaneously at times.

Table 2. Study categories for district heating (DH).

DH Demand (MW_{th})	DH Supply (MW_{th})	DH Storage (MWh_{th})
End-user demand	Waste heat from PtG, biogas production, and gasification of biomass [1]	Thermal energy storage capacity
Storage	Waste-to-energy	
	CHP	
	CHP heat pumps	
	Boilers	
	Storage	

[1] EnergyPLAN treats these categories as a single constant heat supply even though production of gas is in fact quite variable. This is an unfortunate limitation of EnergyPLAN.

Table 3. Study categories for gas.

Gas Demand (MW_{th})	Gas Supply (MW_{th})	Gas Storage (MWh_{th})
Individual heating	Biogas	Gas storage
Transportation	Gasification	
Industry	Methanation	
Export	Storage	
CHP		
Boilers		

In order to put the study periods in a broader context and to investigate the possible seasonality of different types of energy production, a number of the hourly distributions were examined for the entire year. These included CHP electricity production, solar PV electricity production, onshore wind electricity production, offshore wind electricity production, and annual electricity consumption. CHP and consumptions data for 2012 was derived from [37]. Wind and solar PV distributions were derived from Child and Breyer [5], based on data originating from [38,39]. In addition, the state of charge (SOC) of stationary batteries, V2G batteries, DH storage and grid gas storage were examined for each study week and for the year as a whole.

In the second part of this work, the categories of barriers to success originally posited by Haukkala [28] that involved all relevant stakeholders including industry, utilities, firms, consumers, non-governmental organisations (NGOs), experts, policy makers and professional associations, were revisited and updated. A range of barriers constraining the deployment of solar energy technologies can be categorised, for instance, as technological, economical and institutional [33] or as economic, political, and behavioural [40]. Barriers to the larger deployment of solar PV in Finland which were identified in [28] were revised according to the results of a new survey on the barriers to the implementation of higher shares of renewable energy in Finland conducted in spring 2015. The new survey involved 31 people from the Finnish Local Renewable Energy Association and active citizens interested in the energy transition campaign. Barriers were divided into four categories: technological, economical, institutional-political and behavioural. Possible solutions to the barriers were then compiled and analysed following a more current literature search.

3. Results

Results are compiled in Figures 3–8 and 11–13 for the electricity components of the energy scenario under study for each of the three study weeks. DH and grid components are presented in the Supplementary Material. Annual hourly distributions are presented in Figures 14–18. Annual SOC data are presented in the Supplementary Materials.

3.1. The Energy System

In the first study period (see Figures 3–5), peak consumption of 14,369 MW_e of electricity was reached at Hour 810, near the beginning of a period of extreme cold. As is typical during Finland, such peaks are reached when it is not only cold, but also quite windy, facilitating the need for more heat in general, and electric heat more specifically. At the same time, due to generally high levels of wind energy and CHP production during winter months, electric storage was at maximum capacity. The SOC of stationary batteries was 100% for the entire week, and was above 95% for V2G batteries during the same period. Solar PV production was noticeable during a three-hour period surrounding midday. Both flexible demand and PtG were used effectively during these times to utilise corresponding peaks in electricity generation. As wind levels increased, so too did various forms of heat production: heat pumps, CHP and heat from PtG. The result was that the combination of electric production from wind power, CHP and solar PV meant that eventually curtailment was necessary. However, it can be noticed that DH storage was not filled to its maximum. This is due to the fact that the DH heat pumps are used by EnergyPLAN to create heat for the DH system but not for DH storage. In reality this may not be the case. It is also unclear why CHP plants are operating at a time of high availability of both heat and electricity. Instead of curtailment during hours 820–860, it is questionable why EnergyPLAN did not curtail CHP. However, the EnergyPLAN tool seeks to balance electricity, heat and gas demand as well as production and storage over the entire year. For this reason, short periods such as these are tolerable given a greater time horizon.

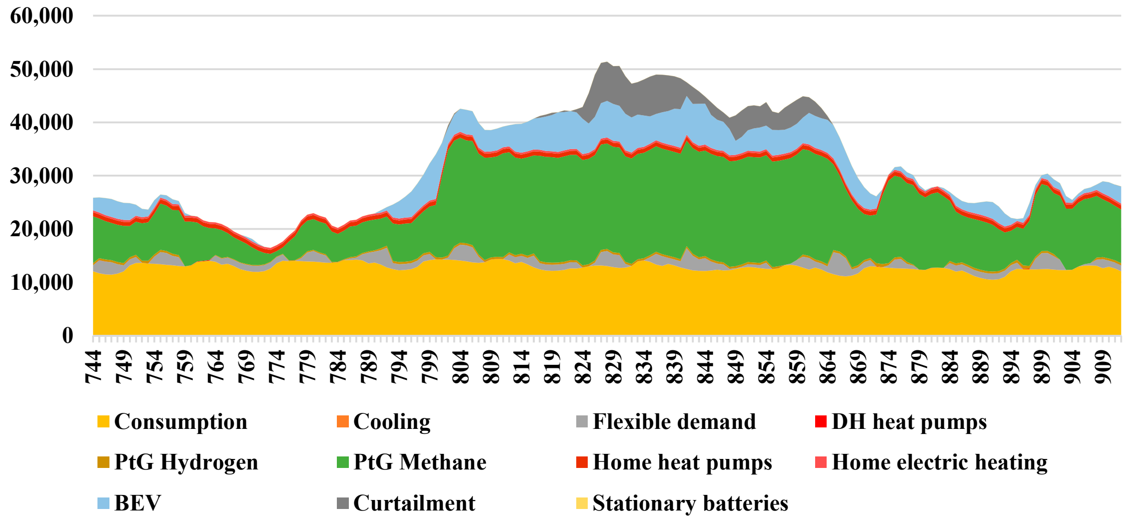

Figure 3. Electricity demand (MW_e): 1–7 February (Hours 744–912). Flexible demand and PtG utilised during all noon peaks of solar photovoltaic (PV) production.

In the second study period (see Figures 6–8), which involves both the highest solar PV production around the summer solstice (15,508 MW_e during Hour 4236) and lowest electricity consumption (5431 MW_e during Hour 4204) as annual summer holidays begin, all batteries become fully charged during periods of excess electricity. However, there is still a minor period of curtailment towards the end of the week. This period of high solar PV production is also a time of relatively low wind and hydro production, indicating that variability of supply is partly smoothed by seasonality. During this time, thermal storage is full and excess heat from industrial processes is condensed. At the beginning of the week, stationary batteries are not used at all for daily storage of electricity, a trend that can also be noted for much of the year. In this regard, stationary batteries seem to be the storage option that is selected last by EnergyPLAN as well as being the storage option that is chosen first for discharge. This is seen as SOC begins the week at 0% and then quickly shoots up to 100% at midweek. Over the year, stationary batteries spend a vast majority of time either being fully charged or fully discharged, with just 5 full load cycles annually, which merits further investigation as other results clearly show about 200–300 full load cycles annually [41,42]. The daily function of electricity storage appears to be allocated to V2G batteries, with 159 full load cycles annually. At the beginning of the second study period, a typical period of charging during the day and discharging in the evening occurs over the first three days. These cycles of charging correspond directly to solar PV production peaks around midday. As electricity storage fills towards the end of the week, other storage options are considered by EnergyPLAN. Towards the end of the week, gas storage begins to fill as the PtG process utilises excess electricity when wind production increases.

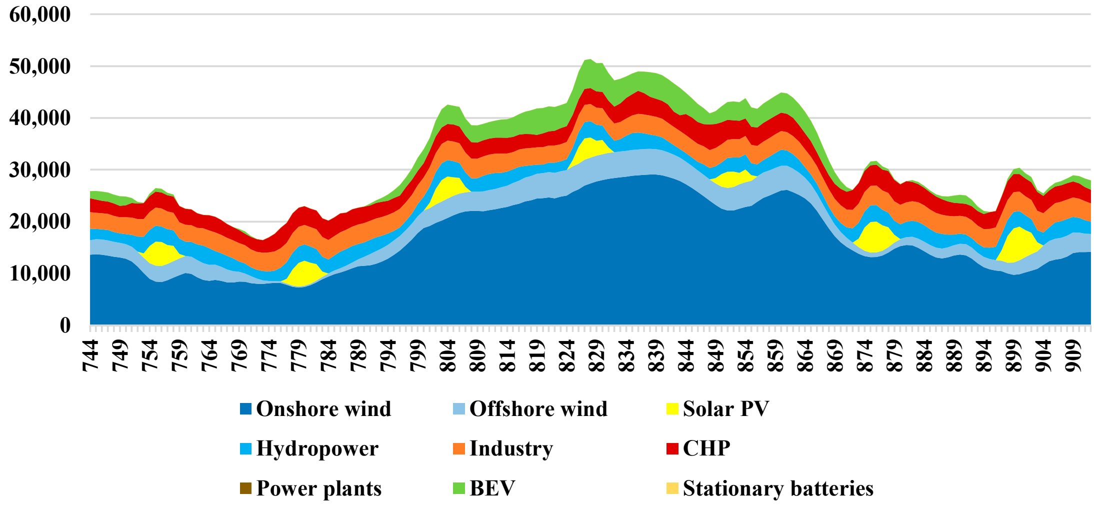

Figure 4. Electricity supply (MW_e): 1–7 February (Hours 744–912). Solar PV production occurs in the few hours surrounding the noon peak during study period. Winter months show relatively higher amounts of wind power and Combined Heat and Power (CHP) production.

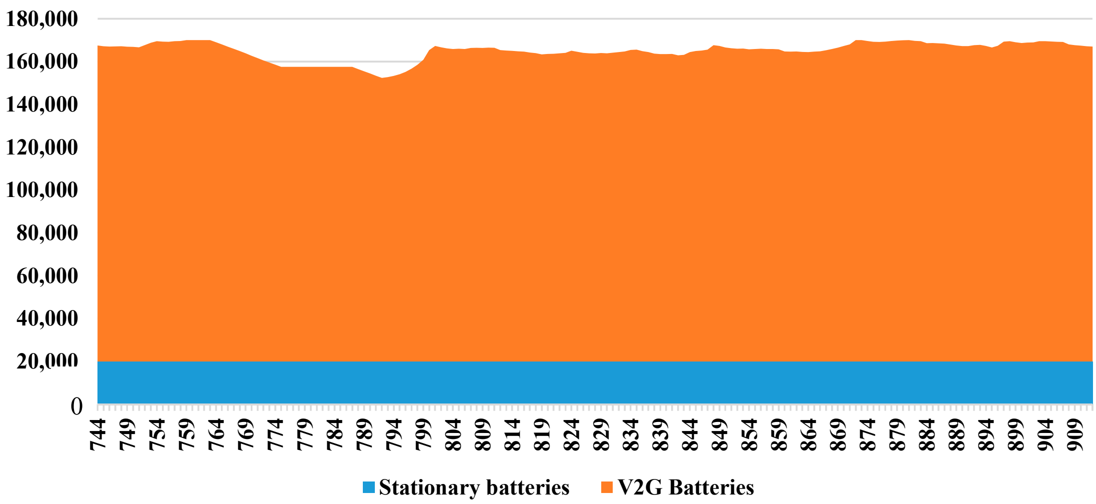

Figure 5. Electricity storage (MWh_e): 1–7 February (Hours 744–912). Maximum storage is 170,000 MWh_e. Electric storage levels are maintained throughout the study period due to relatively high wind power and CHP production. Stationary batteries are not used, while Vehicle-to-Grid (V2G) batteries serve a minor role in regulating daily power. This is most prominent at the beginning of the study period.

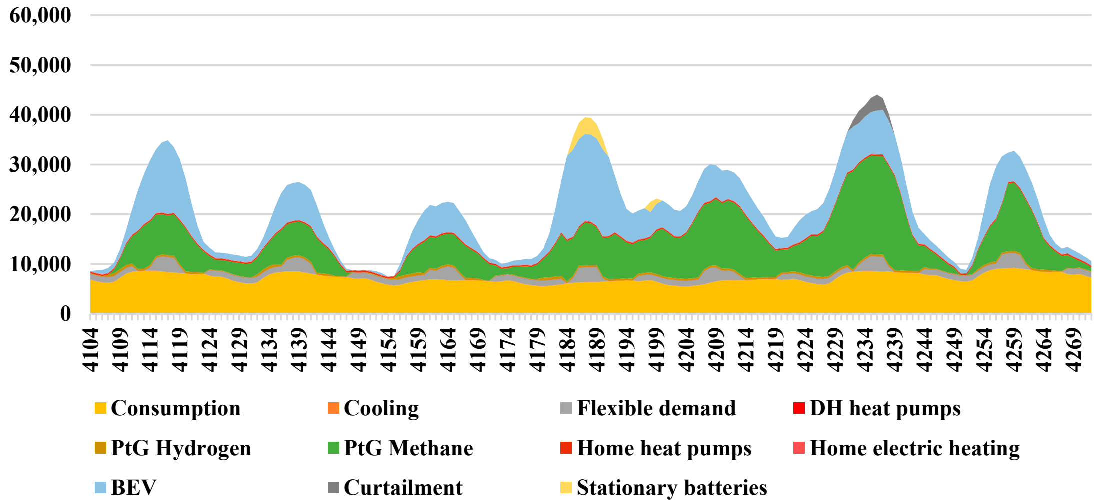

Figure 6. Electricity demand (MW_e): 20–26 June (Hours 4104–4272). Overall end-user demand for electricity is relatively low during the study period. Flexible demand and PtG production are utilised during peaks in solar PV production around noon of each day of the study period. Flexible demand by battery electric vehicles (BEVs) is also noticeable.

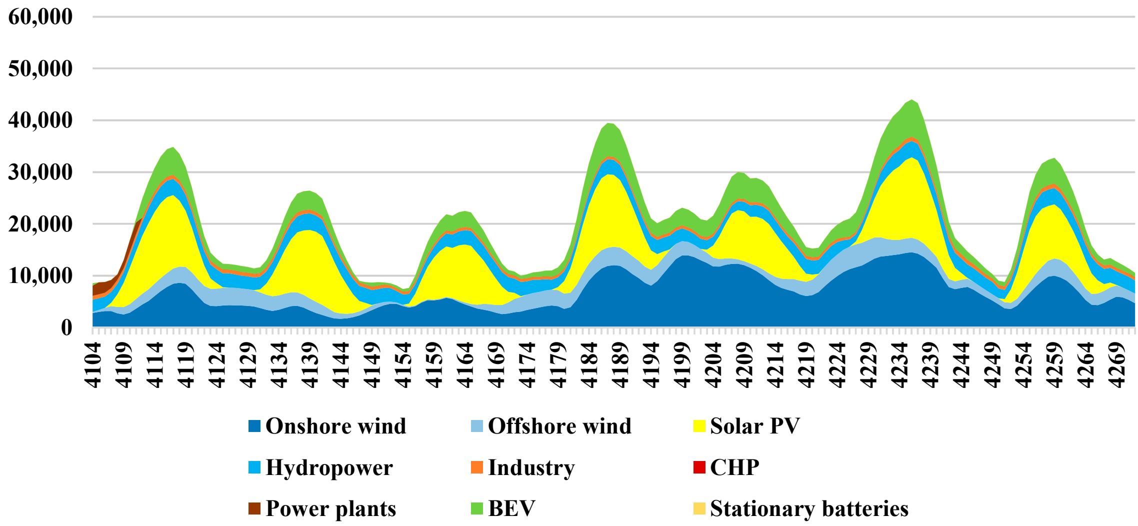

Figure 7. Electricity supply (MW_e): 20–26 June (Hours 4104–4272). Supply from solar PV production is high during the study period that encompasses the summer solstice. Solar PV power provides more than 100% of end-user demand during the noon peak on all days but the last of the study period. Solar PV power production represents 35–53% of total electricity generation during noon peaks.

The role of solar PV in this study period encompassing the summer solstice merits further comment. As can be seen from Figure 9, solar PV production exceeds 100% of noon demand in all but the final day of the week. During this week it can also be seen that flexible demand measures are being utilised during noon solar PV peaks to their maximum of 3000 MW_e in a given hour, assisting in higher direct utilisation of solar PV electricity. The share of solar PV in total electricity generation is shown in Figure 10. Values range from 35–53% during noon peaks.

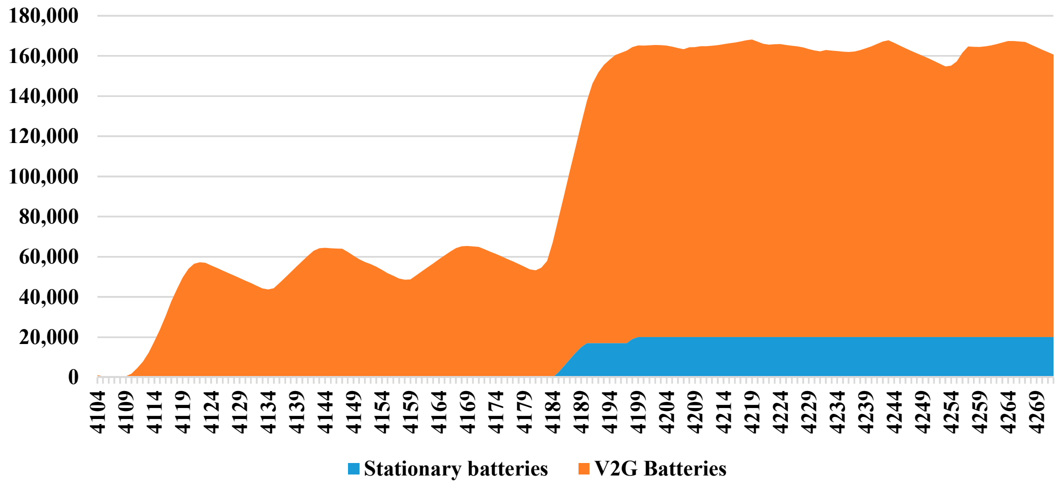

Figure 8. Electricity storage (MWh_e): 20–26 June (Hours 4104–4272). Maximum storage is 170,000 MWhe. V2G batteries are charged during the day and discharged at night, showing a strong relationship with solar PV production. Relatively higher winds and reduced demand near the end of the study period result in stationary and V2G batteries being fully charged.

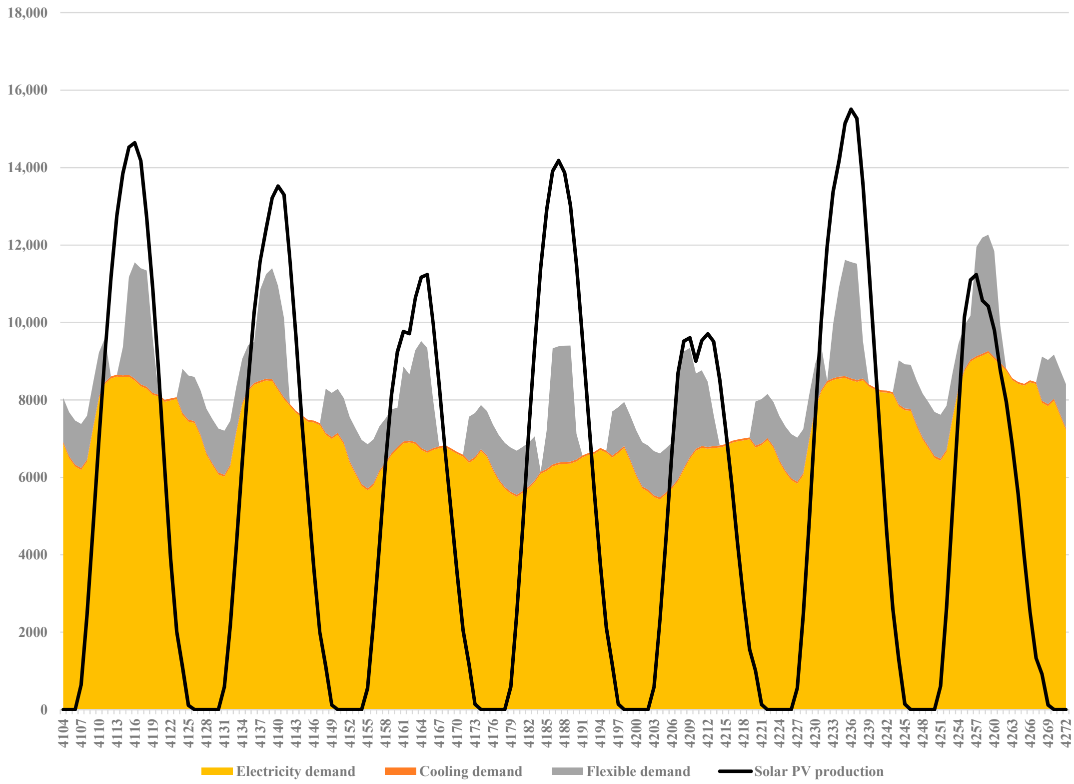

Figure 9. End-user consumption of electricity and solar PV power generation (MW_e) during the second study period (Hours 4104–4272). Solar PV production exceeds 100% of noon demand in all but the final day of the week. Flexible demand is used to its full potential during noon peaks of production during this period in order to facilitate higher direct utilisation of solar PV power

The third study period (see Figures 11–13) provides an interesting case. During the first part of the week, cold temperatures result in quite a high demand for electricity. At the same time, the pre-Christmas holiday period generally sees relatively high levels of individual electrical consumption. As levels of all categories of RE production are quite low at the beginning of the week, power plants provide a large share of production, partly due to the fact that batteries have been depleted. This situation changes as both milder temperatures and higher winds are present towards the end of the week. Enough electricity excess exists to begin charging V2G battery storage. Heat storage is also increased as CHP plants shift from condensing mode in the early part of week to backpressure mode later in the week. Hydro production is consistent and relatively high due to hydro reservoirs being at their fullest at this time of year. Also of interest is that grid gas is supplied through biomass gasification in the early part of the week and then by PtG after wind power increases towards the end of the week. The role of solar PV is minor during this week of lowest irradiation. However, this low generation is complemented by both wind power and generation from CHP plants utilising both biomass and stored synthetic grid gas.

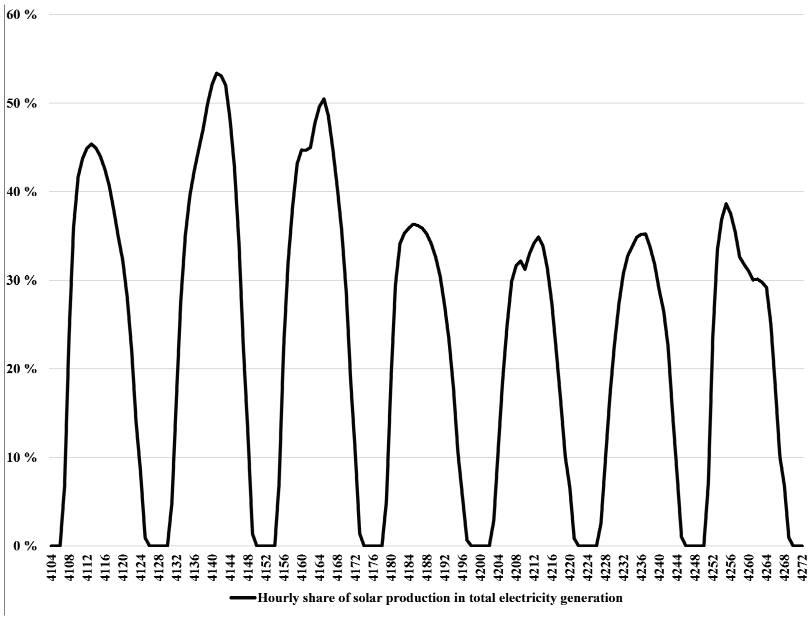

Figure 10. Share of solar PV (%) in total electricity generation during second study period (Hours 4104–4272). Values range from 35–53% during noon peaks of production.

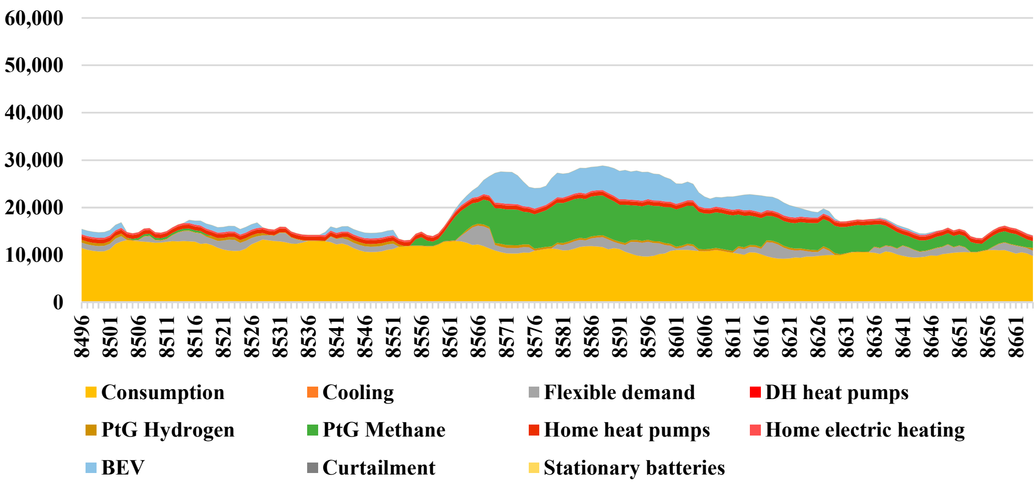

Figure 11. Electricity demand (MW_e): 20–26 December (Hours 8469–8664). Relatively high electricity demand during the winter solstice and during Christmas holidays. PtG methane production corresponds to higher levels of wind power production during the middle of the study period.

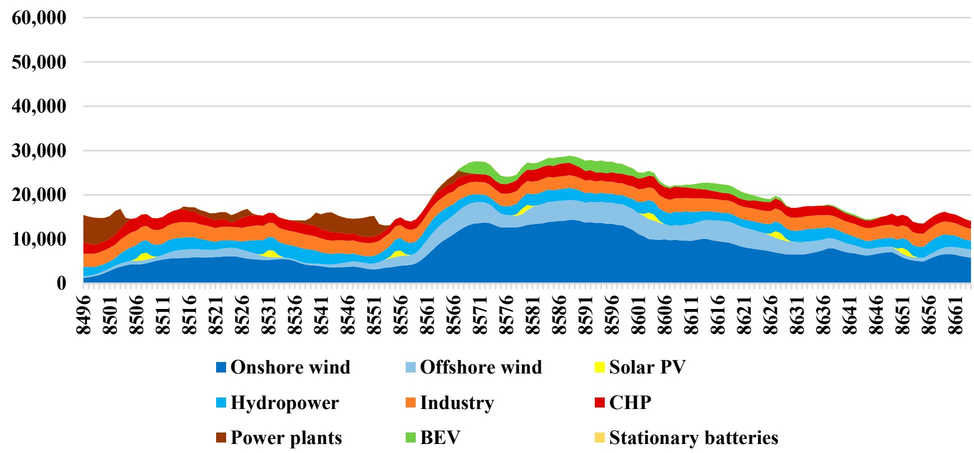

Figure 12. Electricity supply (MW$_e$): 20–26 December (Hours 8469–8664). Solar PV power production is at its lowest for the year during this study period. This necessitates the use of production from thermal power plants.

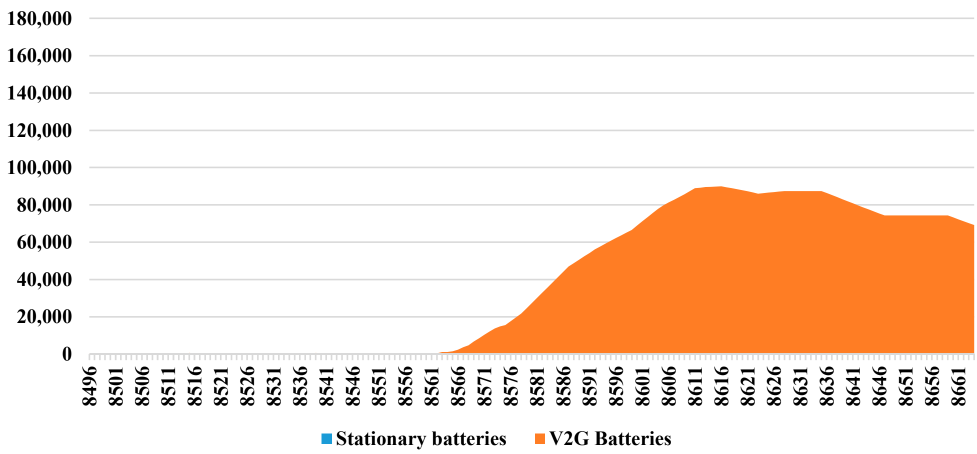

Figure 13. Electricity storage (MWh$_e$): 20–26 December (Hours 8469–8664). Maximum storage is 170,000 MWhe. Electricity storage is at its lowest levels for the year, causing maximum production of power from thermal plants early in the week. Storage is replenished somewhat after a period of high wind power production during the middle of the study period.

With both the second and third study periods, the weeks are divided into two fundamentally different parts. At the same time, the energy system makes a fundamental change in response, showing rapid adaptation through the use of various flexibility measures. This flexibility appears to come from both storage and generation technologies.

Figures 14 and 15 show how CHP and solar PV production complement each other seasonally. In general, CHP production is lowest when solar PV production is highest, and vice-versa. A noticeable seasonal complement also appears to exist between solar PV and onshore wind generation (Figures 15 and 16). While each is highly intermittent, solar PV generation appears higher at times of low wind and wind generation seems higher in the winter months when solar PV generation is at a minimum. Such a complementary effect of solar PV and wind energy has also been described for other places in Europe [43,44]. Offshore wind (Figure 17) is also intermittent, with a somewhat weaker generation phase during times of high solar PV generation. At the same time, overall generation is lower in magnitude than onshore wind. Electricity consumption (Figure 18) also has a seasonal pattern, with higher consumption during the colder months (November–April). In addition, there is still a significant level of base load demand for electricity even in the summer.

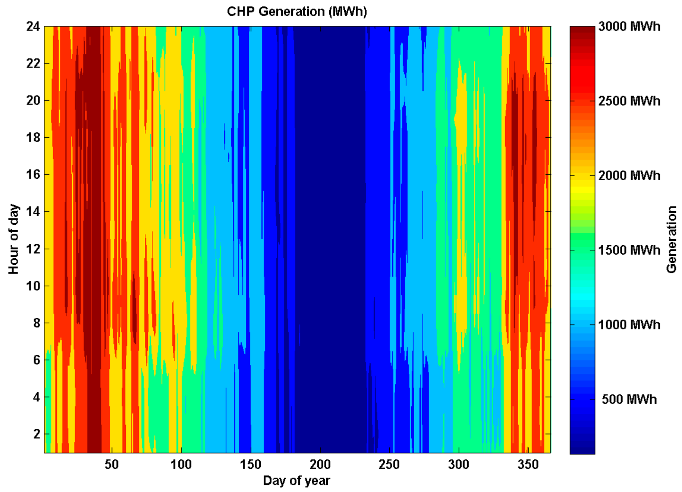

Figure 14. Hourly CHP electricity production (MWh_e). CHP can be used variably both seasonally and daily to correspond to peaks in demand or lower levels of solar PV production.

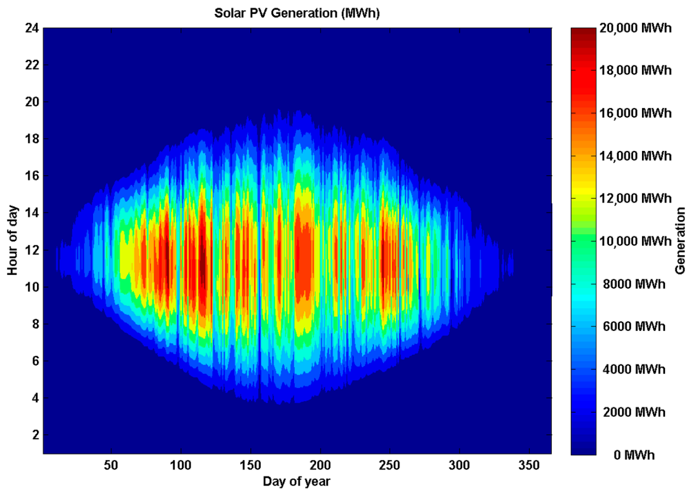

Figure 15. Hourly solar PV electricity production (MWh_e). The seasonality and diurnal nature of solar PV production is offset by variable CHP production.

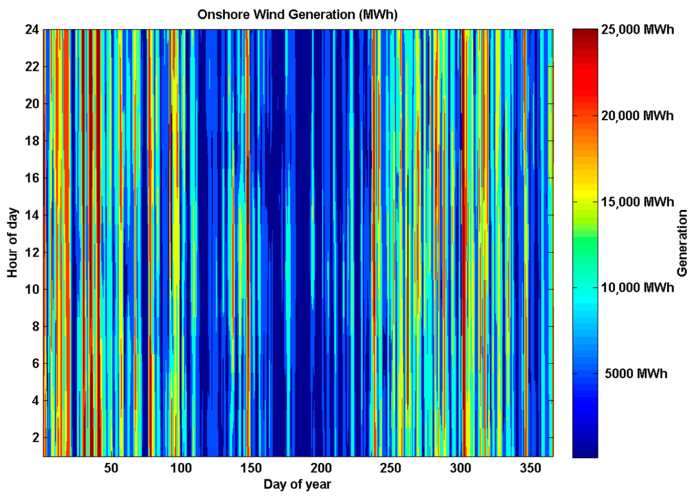

Figure 16. Hourly onshore wind electricity production (MWh_e).

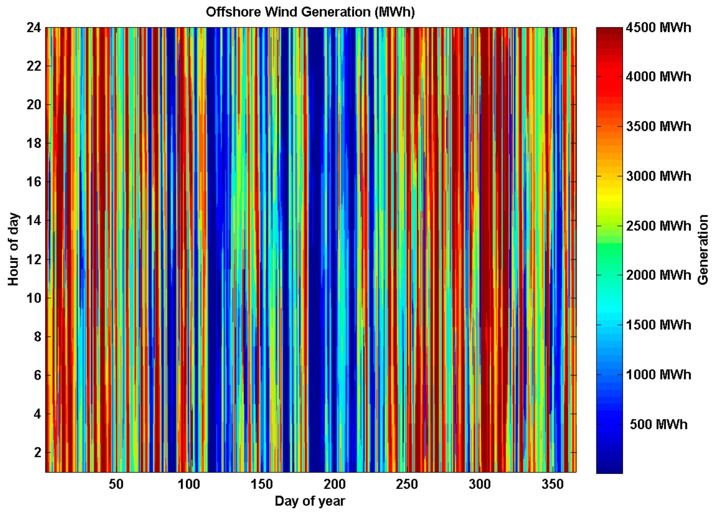

Figure 17. Hourly offshore wind electricity production (MWh_e).

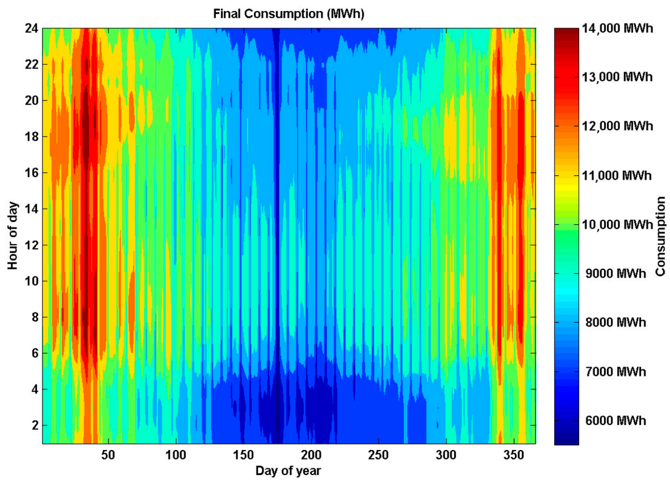

Figure 18. Hourly electricity consumption (MWh_e).

3.2. Barriers and Solutions

Results for the reinvestigation of barriers to the implementation of high shares of solar PV in Finland and their possible solutions are summarised in Table 4. A more in-depth analysis occurs in the following sections.

3.2.1. Technological Issues

Perhaps the biggest technological barrier in Finland has been the lack of energy storage systems [29]. Nevertheless, high growth of newly introduced storage solutions in Germany shows very fast progress. E.ON announced that a third of their newly sold PV systems are already sold with battery storage solutions [45]. It appears rather likely that solutions of front-running markets will be introduced finally also in Finland, which leads to the fact that the problem is no longer a technological one, but rather a problem of inefficient markets.

Table 4. Barriers and possible solutions to increased capacities of solar PV in Finland.

	Barriers	Possible Solutions
Technological	• Lack of energy storage solutions in Finland • Grid and grid monopoly	• Lessons to be learned from solutions available in Germany, R&D allocated to storage solutions • Sufficient and efficient grid, easier to access for small-scale producers, compensation for the producers
Economic	• Competitiveness • Module prices • Price of the electricity in the Nord Pool Area • A need for new electricity markets and rules • Inefficient markets of storage systems • Support and high subsidies for conventional energy system	• Solar has reached grid parity in some market segments and will become more competitive on its own in the future • Module prices are falling continuously • Storage solutions are available at least in Germany—a need to export solutions • As long as electricity prices are lower in Finland than in other countries, solar will not be as popular as elsewhere • Ideally there should be no support systems in the long run distorting markets • Subsidies for harmful emissions from conventional energy need to be eliminated • New business models
Institutional and political	• Current energy regime based on nuclear power, fossil fuels and bio energy • Vested interests • Path dependency • Lock-in • Incumbent electricity companies • Lack of support policy • Lack of powerful advocacy coalitions • Fossil fuels lobbying • Failure to overcome existing subsidies	• A possibility to build a more distributed energy regime • New business models • Some support policy seems to be needed in the beginning phase but type is less significant • More established and powerful solar energy advocacy coalition
Behavioural	• General attitudes • Psychological resistance • Political will	• More information and practical examples of successful installations provided

Grids and grid monopoly have most often been mentioned as technological problems [28,29]. There are concerns about possible impacts of distributed power on the electrical grid, the lack of standard procedures for grid connections, and issues with metering [29]. Grids also need to be made easier for small-scale producers to connect to and producers also should receive better compensation, for instance an hourly based net metering. At the moment, utilities still have to manage the costs of connecting solar households to the grid and make sure the grid is reliable and working efficiently. Respectively, the utilities usually pay for the electricity they buy from small-scale producers for less than the market price and take a monthly fee as compensation for the work done. More advanced utilities, however, already pay better prices and think of it as a sensible thing to do because at the same time they are able to maintain good customer relations with producers and prosumers.

3.2.2. Economic Issues

Cost comparisons with the conventional energy system and competitiveness are no doubt among the biggest barriers overall in Finland, both for utilities and for consumers [28,29]. From the perspective of utilities, the incumbent energy companies feel that an energy system that is based on higher shares of renewables is too expensive; without a well-functioning energy storage system intermittent renewables are expected to need a back-up system and incumbent energy companies still expect that they have to maintain that infrastructure and manage the costs. Eventually, the incumbents might also receive compensation for maintaining the old base load capacity if necessary.

However, instead of looking back to the way things were in the past, the incumbent utilities could treat solar as a gateway into a new market: utilities could sell solar modules, provide financing and grid connections, and build a service relationship [46]. Solar is anticipated to become the largest source of energy in the world by 2050 [47] and that means that there is also a vast market across borders as well. Well-functioning home markets would enhance the possibilities for firms to enter these attractive markets. To sum up, there is a need for new kinds of electricity markets and rules but also new business models.

From the perspective of consumers and prosumers, module prices have been higher in Finland than in other countries due to sales channel inefficiencies and very low market volumes in Finland, but module prices are falling continuously and will be competitive on their own in the future in a wider range of market segments [18,21,48,49]. Installation costs have been relatively high in Finland due to expensive labour and comparably less experienced installers in Finland. However, once the domestic market grows, installation costs will become cheaper as well. This could also be facilitated by training and certification of solar PV installers at a national level. Also, the fact that electricity has been quite cheap in Finland and the Nordpool area compared to other countries has provided little motivation for people to produce their own electricity [28,29]. This might change if electricity prices went up.

Historically, the conventional energy system has received subsidies in different forms and has been able to grow and stabilise its position in the markets. In Finland, solar PV has not received practically any subsidies and this has further supported the conventional energy system. Ideally, there should be no support systems in the long run distorting markets. However, conventional energy technologies receive substantial subsidies due to no or considerable less pricing for harmful emissions [50]. Renewable and conventional energy technologies do not have a level playing field due to these unfair market inefficiencies. This distorts markets as well.

3.2.3. Institutional and Political Issues

There are also conflicting wishes and expectations of society that constitute vested interests [28]. Incumbent energy companies are likely to maintain the status quo as there are enormous investments in the old system. This creates path dependence and lock-in, as stated earlier. At the same time, there are new forms of energy generation that try to break the lock-in and this clashes with the current energy regime based on nuclear power and fossil fuels that exploit economies of scale to achieve profitability. Resistance from utilities or industry can be sensed in the context of path dependence and lock-in, and in the undermining of renewable sources of energy.

Despite the fact that there is hardly any support policy for solar PV in Finland, there has been a growing interest among citizens related to solar energy. In 2016, 88 per cent (or almost nine out of ten people) responding to a survey by Finnish Energy Industries felt that solar energy should be increased [51]. There are a range of different kinds of support instruments in use in other countries, such as feed-in tariffs, green certificates with quota systems, investment and tax incentives, and bids on quota systems, which have proven to create growing home markets in their respective countries. Even a coal-rich country, such as Poland, recently showed more progress than Finland, after a solar PV feed-in tariff was introduced in 2015 [52]. Lund [53] raises the important point that dynamic support structures for a range of new energy technologies can aid in increasing their market penetration. A period of high subsidy may be particularly important to establish early growth in market share, but should be followed by adjustments in subsidies to prevent markets from growing too quickly. At the same time, Ref. [29] reminds that support must go beyond financial measures to be sustainable. Furthermore, some forms of support are seen as preferable for a wide range of distributed generation technologies. Ref. [30] found that one-off investment support or tax rebates were preferable to feed-in tariffs, as they were deemed more cost efficient and were likely to instil greater confidence in Finnish investors.

Lobbying for the conventional energy system has been strong and, as powerful advocacy coalitions in favour of solar PV have been missing, there have not been many disagreements in public debate and decision-making [28]. During the past few years, though, new associations have been established and advocacy coalitions promoting solar energy have started to take shape and actively participate in promoting solar energy in Finland. This may change the current way of thinking as overall energy discourse becomes more representative of a wider range of opinions.

3.2.4. Behavioural Issues

Still, the main obstacles and challenges seem to be the general attitudes toward solar energy in Finland. According to the study by Haukkala [28], there is said to be an attitude problem, a resistance to change, toward new ways of doing things which is in line with Sovacool's [40] behavioural barriers that include public apathy, misunderstanding and psychological resistance. There is a strong belief that the sun does not shine in Finland and the political will has been missing to challenge this myth. In addition, there is a common misunderstanding that rare earth metals will limit the ability to produce solar PV modules in the future, and that modules will ultimately consume more energy than they produce. Despite the fact that research dispels such myths [54,55], the misunderstanding persists.

In order to integrate higher shares of solar PV, the existing barriers need to be overcome. As Painuly suggests [31], policy approaches can either eliminate barriers or promote conditions whereby the market is enabled to ignore the barriers. Solutions suggested are not difficult; some of them will happen on their own, for instance module prices are constantly falling and leading to higher shares of installations. Some solutions concern political decisions: whether to allocate research and development funds for energy storage systems or to introduce some support policy in the beginning phase for solar PV. The energy sector needs to be restructured and new business models should be promoted. Also, providing more information and correcting misunderstandings is just as important. Barriers can be overcome: solutions just need to be implemented or developed further. All this is relevant in countries other than Finland as well.

4. Drivers for Solar PV

Climate change has brought a global need to reduce greenhouse gas emissions. Solar PV offers no direct carbon emissions. According to [56], together with other renewable energy resources, solar PV is currently the leading economically viable and environmentally sound option to reduce CO_2 emissions and meet growing energy needs as long as and unless there are no technological and safety breakthroughs with other low emission technologies, such as nuclear power and carbon capture and storage (CCS). For a growing number of PV applications and regions in the world, one can observe financial CO_2 emission reduction benefits, i.e., no cost anymore, as a consequence of the rapidly increasing competitiveness of PV [57]. It also provides energy security and diversification of production. Further, there are new "green" jobs created in conjunction with installations in the domestic markets and growth opportunities in high tech business exports, for instance with technical equipment needed in panel manufacturing and installation. Lastly, solar PV can provide more access to electricity in rural areas, reduce the number of outages and hence lower economic losses in the future [56].

The drivers for solar PV are mostly technological improvements, cost reductions and government policies. For the first, solar energy has experienced a major technological shift from small-scale photovoltaic installations to large-scale PV systems that feed into electricity grids [33]. Secondly, the costs have dropped over the last 30 years and are expected to continue on this trajectory [21]. Thirdly, solar energy benefits from fiscal and regulatory incentives that have led to a rapid expansion of the solar energy market [33]. While the declining support policy for PV is reducing the European market and even increasing the PV electricity cost by increasing the risk and thus the cost of capital, the implementation of new feed-in tariff policies has led to an increase in markets in, for instance, China and Japan [58].

Río and Unruh [34] have identified barriers and drivers to PV energy in Spain. Surprisingly, the barriers do not differ much from those in Finland despite the fact that Spain has the best solar resources in Europe. Therefore, solar insolation cannot be the only explanatory factor. The barriers in Spain are high initial costs, lack of an accurate legal framework and insufficient support, administrative barriers, financial barriers, companies in the conventional electricity sector, training and skills of equipment installers, lack of information, connection to the grid and integration in buildings. In terms of policy, the authors [34] note a number of key drivers similar to the solutions suggested in this work that would aid in overcoming such barriers, including: expanding the solar PV market to promote scale and learning effects, supporting R&D, expanding financial support measures, mandating solar PV installations in new buildings, establishing minimum competencies for PV installers, and raising awareness of the many benefits of solar PV as well as the steps needed to begin enjoying them. Further, they suggest awareness campaigns targeted at individuals, professional groups, and architects. As pointed out by [21], an unclear public PV policy directly or indirectly increases the risk for PV investments and represents a major cost driver, as the cost of capital reflects the level of investment risk in a country. Therefore, a sound PV policy has to aim at reducing the risk for PV investors to reduce the overall cost of PV electricity generation, since cost of capital can represent an even higher cost fraction than the initial investment cost as emphasised by [21].

A recent study of the role and future of distributed energy generation in Finland suggests that there has been a general lack of understanding about which factors will promote its growth and the actual barriers which need to be overcome or removed [29]. However, the authors suggest that a comprehensive approach to the removal of barriers should go beyond promoting only one form of energy production and include all forms of distributed generation of heat and electricity. This "more profound process of transformation" must promote institutional change as well as the engagement of a wide variety of stakeholders and key actors throughout the energy sector. Investment support should be seen as only one part of a sustainable approach.

The same study [29], based partially on previous work [30] identifies four business models for distribution system operators (DSO) and other energy companies that are suited to small-scale renewable energy generation in Finland. The first is the one that currently dominates the landscape—a company or DSO as intermediator/facilitator. In this concept, the surplus electricity generated by prosumers is purchased and passed along to other areas of the grid for a modest profit to the facilitator. In general, prosumers earn very little from this sold electricity and so design their systems to maximise self-consumption. However, as interest in solar PV has grown in Finland, new models have begun to emerge. The second is the turn-key (energy optimisation) model, whereby utilities or large companies provide full-service solutions, from generation to possible sales of energy. Important features of this model is the ease for customers and the ability for utilities to optimise customer consumption. The third is the centralised solar PV concept. Accordingly, a company will plan, build and operate a large-scale solar PV plant, but individual investors share in the ownership and become indirect prosumers. These investors are generally viewed as having a high awareness of sustainability issues in general, and quite importantly, may have a higher ability to pay for sustainable energy. The fourth is a joint purchase model, whereby demand for small-scale generation is driven by groups that organise themselves as grassroots movements. Joint purchases can be performed as a collection of individuals, established purchase groups or large networks. Working together results in an ability to achieve discounts related to scale and learning effects. Each of these models are already present in Finland, and have allowed a greater number of individuals and groups access to a low-cost form of electricity. This may empower many to determine their own pathway towards long-term sustainability on more than economic terms.

Full empowerment of stakeholders can only be achieved through careful consideration of stakeholder needs and goals. Therefore, Goldstein [59] reminds that regular input from and engagement with stakeholders must be essential elements of the research process. In doing so, one can then "facilitate realism and traction" of the process so that momentum is generated. To accomplish this, stakeholders must have an honest accounting of the risks and rewards related to proposed choices. These risks and rewards, as well as what drives them, must also be accounted within the different realms of sustainability (economic, environmental and social) and for different groups within a society. In particular, raising awareness of the benefits of solar PV may be the most important step for stakeholders to be enabled to enjoy such benefits.

5. Discussion

A reliable energy system based on 100% RE seems technically feasible for Finland in 2050. PtG and energy storage solutions contribute significantly to the energy system by offering flexibility and integration of the electricity, heating/cooling and mobility sectors. Moreover, flexibility of the energy system is harnessed at times of lower RE resource availability through the use of methane storage over the long term, and battery storage over the short term.

In this study, solar PV makes a roughly 10% contribution to final energy consumption and is 16% of the total electricity generation, but that contribution is concentrated in approximately seven months of the year. In addition, that contribution is at times concentrated even more during daylight hours, necessitating daily and seasonal storage. On a daily basis, V2G batteries seem to have a much greater role than stationary batteries, although this may be due to how the model prioritises storage solutions. One could expect more use of stationary batteries in reality, especially on a daily basis.

Other studies have suggested a strong complement between solar PV and batteries [22–25]. This current study also shows such a complementary relationship, albeit to a lesser extent. At the same time, the way the EnergyPLAN tool allocates energy to the stationary batteries in the scenario under study appears to be the main limitation. This function will need to be considered in more detail in further studies.

On a seasonal basis, PtG technology bridges the gaps between demand and supply at times when generation is most intermittent. At the same time, these technologies are available to provide base loads of electricity, heating, cooling and mobility when they are needed. These results are in line with those for Germany [60,61]. What is more, PtX (Gas, Liquids, Chemicals) technologies are already showing promise of profitability in niche applications in Finland [62] and the role of PtX may expand outside of the energy sector [61].

Interestingly, there is no time when the sun does not shine and the wind does not blow. Indeed, other studies are also confirming the feasibility of solar PV systems in Nordic conditions [63]. The seasonal complement of solar PV and wind power production in Finland appears obvious, despite the intermittent nature of each. This intermittency appears manageable by the storage technologies utilised in this study. In addition, the ability of distribution networks in Finland to host large capacities of distributed rooftop PV generation appears not to be a technical impediment [64]. One must also remember the important role of hydro power in Finland. Up to 20% of end-user electricity consumption can be supplied by hydro. This study also does not fully explore the full potential of hydro storage available in Finland. Indeed, a full accounting of the potential of hydro storage in Finland is lacking. Should there be further potential flexibility in hydropower production as expected, this could lessen the need for other storage capacity, such as batteries or PtG production, or power plant capacity, and may in turn result in a decrease in overall costs.

The integration of high shares of renewable energy sources in future energy systems will require a variety of complementary storage solutions. It has been previously determined that electricity storage devices will be needed once 50% of power demand is met with variable RE, and that seasonal storage devices will be needed once more than 80% of electricity demand is met by RE [44,65]. Currently, there is a long list of energy system flexibility measures available to support high levels of intermittent RE [66]. Developing a 100% RE scenario for a nation requires careful consideration of the right mix of these measures for each context. In turn, these measures should be suited to and complemented by the energy generation technologies that make up the energy system. Such is the case for solar PV and the energy storage technologies investigated in this work. Solar PV and energy storage solutions can play a significant role in a future energy system for Finland based on high levels of renewable energy generation. This conclusion is in line with other such analyses of the Finnish energy system [5,7,8,67]. As well, the role of EV batteries in mitigating the negative effects associated with the intermittency of some forms of renewable energy has been documented in studies performed on a broader context [68,69].

Other studies of the Finnish energy system have provided a wide range of projections for future solar PV installed capacities. In the most pessimistic assessment [9], solar power in Finland was described as "...not expected to be a profitable production method if connected to the grid in Finland" and would only be "...utilised to meet the increasing electricity consumption in holiday and second homes". Even the optimistic Greenpeace [70] offers only a conservative 4 GW_p of installed solar PV capacity in Finland by 2050. More recent analyses have taken into account the increasing role of solar PV in global energy systems as a low cost or possible breakthrough technology for the future. In turn, the most recent scenario models for Finland suggest much higher amounts of installed capacities or energy production. Ref. [71] suggests that approximately 7.2 GW_p would be technically possible for Finland in the future (5.6 TWh_e/a). In their Technological Breakthrough Scenario, Ref. [72] suggests that approximately 7.5 GW of distributed generation (primarily solar PV) would be possible, totalling roughly 10 TWh_e. Lastly, in their Change Scenario, Ref. [1] estimate that approximately 18 TWh_e could be generated from solar PV (about 20 GW_p installed capacity). The 100% RE scenario considered in this analysis suggests that 30 GW_p of installed capacity would generate approximately 29 TWh_e of power in 2050, or 16% of final electricity consumption.

There are several reasons for the differences between the current results and those of others. These can be divided into two main groups: scenario design and key assumptions. In terms of scenario design, the main aims of [5] included designing an energy system that had virtually no carbon emissions and that accomplished total energy independence (no imports of electricity, gas or other fuel). In addition, a wider range of flexibility mechanisms in the form of energy storage and energy sector integration were utilised that supported higher installed capacities of solar PV and other forms of variable RE. Furthermore, a least cost solution for the energy system requires solar PV for balancing the relative lack of wind in the summer months. Importantly, only one of the previously mentioned studies were based on such high shares of renewable energy, and almost all reported high shares of electricity import. In terms of basic assumptions, by utilizing a learning curve approach, this work assumes that solar PV will continue its exponential growth, resulting in lower prices for modules and the balance of the system components, as well as higher efficiencies of modules over time [21]. It is not surprising, then, that this study reports very different installed capacities than other studies.

6. Conclusions

This article has discussed the prospects of reaching an energy system based on 100% renewable resources by 2050 in Finland. To achieve such high installed capacities of solar PV, significant changes must occur in the Finnish energy sector. Most noticeably, storage solutions and other elements of flexibility, such as flexible demand and smart charging of electric vehicles, will need to balance the intermittent nature of electricity generation in an energy system based on high shares of wind energy and solar PV. Batteries will play a key role in providing short-term storage on a daily or multi-day scale, while PtG will provide storage on a seasonal level. An important complement between solar PV and battery storage, seen in several other studies, was also seen in this investigation. In the end, a technically feasible and economically competitive solution for Finland based on 100% renewable energy and high shares of solar PV is demonstrated in detail to reveal how such a system could work.

Such a future energy system represents a complete transformation away from what currently exists, and will by no means be easy or quick to achieve. A variety of technical, economic, institutional, political and behavioural barriers currently exist that prevent further solar PV capacity increase. However, these barriers can be overcome with new policy, regulation and understanding. The aim of this study was not to direct policy in any one particular direction, but to suggest several options available. Ultimately, the optimal mix of technological solutions and the policy measures that facilitate them will be determined based on how well they enable the achievement of a wide range of societal, economic and environmental goals. It is hoped that many of these suggestions could also be applied to other emerging RE technologies and could be very applicable in other northern countries as well.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/8/1358/s1, Table S1: Installed capacities of energy technologies for the 100% RE scenario for Finland in 2050; Table S2: Main scenario input parameters; Table S3. Storage parameters; Table S4: Technology efficiencies; Table S5: Main cost parameters for 2050 Finland. Figure S1: DH demand (MW_{th}): 1–7 February; Figure S2: DH supply (MW_{th}): 1–7 February; Figure S3: DH storage (MWh_{th}): 1–7 February; Figure S4: Grid gas demand (MW_{gas}): 1–7 February; Figure S5: Grid gas supply (MW_{gas}): 1–7 February; Figure S6: Grid gas storage (MWh_{gas}): 1–7 February; Figure S7: DH demand (MW_{th}): 20–26 June; Figure S8: DH supply (MW_{th}): 20–26 June; Figure S9: DH storage (MWh_{th}): 20–26 June; Figure S10: Grid gas demand (MW_{gas}): 20–26 June; Figure S11: Grid gas supply (MW_{gas}): 20–26 June; Figure S12: Grid gas storage (MWh_{gas}): 20–26 June; Figure S13: DH demand (MW_{th}): 20–26 December; Figure S14: DH supply (MW_{th}): 20–26 December; Figure S15: DH storage (MWh_{th}): 20–26 December; Figure S16: Grid gas demand (MW_{gas}): 20–26 December; Figure S17: Grid gas supply (MW_{gas}): 20–26 December; Figure S18: Grid gas storage (MWh_{gas}): 20–26 December. Figure S19: State of charge of stationary batteries; Figure S20: State of charge of V2G batteries; Figure S21: State of charge of DH storage; Figure S22: State of charge of grid gas storage.

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Author Contributions: Michael Child conceived and designed the simulations for the Finnish energy system with the help of Christian Breyer. Michael Child performed the numerical analysis of hourly energy system data. Teresa Haukkala proposed the initial barriers to high levels of renewable energy in the Finnish energy system and provided much of the theoretical background for this paper. All three authors were involved in the further analysis of barriers and provided insights into their possible solutions. Teresa Haukkala and Michael Child wrote the paper under the supervision of Christian Breyer.

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Abbreviations

BAU	Business as usual
BEV	Battery electric vehicle
CCS	Carbon capture and storage
CHP	Combined heat and power
DH	District heating
DSO	Distribution system operator
GHG	Greenhouse gas
LCOE	Levelised cost of electricity
NG	Natural gas
PtG	Power-to-gas
PtL	Power-to-liquid
PtX	Power-to-chemicals
PV	Photovoltaic
RE	Renewable energy
RET	Renewable energy technology
SOEC	Solid oxide electrolysis cell
SOC	State of charge
TES	Thermal energy storage
V2G	Vehicle-to-grid
WACC	Weighted average cost of capital
$_e$	Electric units
$_{gas}$	Gas units
$_{th}$	Thermal units
$_p$	Nominal or peak capacity

References

1. Parliamentary Committee on Energy and Climate Issues. *Energy and Climate Roadmap 2050*; Technical Report 50/2014; Ministry of Employment and the Economy: Helsinki, Finland, 2014.
2. Statistics Finland. Energy. Available online: http://www.stat.fi/til/ene_en.html (accessed on 24 March 2015).
3. Huan-Niemi, E.; Niskanen, O.; Rikkonen, P.; Rintamäki, H. Futures climate policy in Finland: Mitigation measures for agricultural greenhouse gas emissions. In Proceedings of the 17th International Conference of the Finland Futures Research Centre and the Finland Futures Academy: Futures Studies Tackling Wicked Problems, Turku, Finland, 11–12 June 2015.
4. Finnish Ministry of Employment and the Economy. *100-Prosenttisesti Uusiutuviin Energialähteisiin Perustuva Energiajärjestelmä*; Finnish Ministry of Employment and the Economy: Helsinki, Finland, 2016.
5. Child, M.; Breyer, C. Vision and initial feasibility of a recarbonized Finnish energy system. *Renew. Sustain. Energy Rev.* **2016**, *66*, 517–536. [CrossRef]
6. Schlachtberger, D.P.; Becker, S.; Schramm, S.; Greiner, M. Backup flexibility classes in emerging large-scale renewable electricity systems. *Energy Convers. Manag.* **2016**, *125*, 336–346. [CrossRef]
7. Child, M.; Nordling, A.; Breyer, C. Scenarios for a sustainable energy system in the Åland Islands in 2030. *Energy Convers. Manag.* **2017**, *137*, 49–60. [CrossRef]
8. Salpakari, J.; Mikkola, J.; Lund, P.D. Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion. *Energy Convers. Manag.* **2016**, *126*, 649–661. [CrossRef]
9. Finnish Energy Industries. Statistics and Publications. Available online: http://energia.fi/en/statistics-and-publications (accessed on 30 March 2015).
10. Global Data. Power Technologies. Available online: http://www.globaldata.com/ (accessed on 1 April 2015).
11. Ahola, J. *National Survey Report of PV Power Applications in Finland—2015, St. Ursen*; IEA: Paris, France, 2016.
12. NeroWatt Suomen Suurimmat Aurinkovoimalat, Aurinkoenergia Suomessa. Available online: http://www.aurinkoenergiaa.fi/aurinkoenergiaa.html (accessed on 21 April 2017).
13. ENE Solar Systems. ENE Solar Park. Available online: http://www.enesolarsystems.fi/en/solar-park (accessed on 20 January 2017).
14. Helsinki Energy. Kivikko Solar Panels Are in High Demand. Available online: https://www.helen.fi/en/news/2015/kivikon-aurinkopaneelit-myyvat-hyvin/ (accessed on 2 August 2015).
15. Šúri, M.; Huld, T.A.; Dunlop, E.D.; Ossenbrink, H.A. Potential of solar electricity generation in the European Union member states and candidate countries. *Sol. Energy* **2007**, *81*, 1295–1305. [CrossRef]
16. Huld, T.; Müller, R.; Gambardella, A. A new solar radiation database for estimating PV performance in Europe and Africa. *Sol. Energy* **2012**, *86*, 1803–1815. [CrossRef]
17. Breyer, C. Solar PV Market Potential Globally and in Finland. *Solar Energy in the North*; Helsinki, Finland, 2015. Available online: https://tapahtumat.tekes.fi/uploads/67f7f445/140617__Breyer_SolarEnergyInTheNorth_SolarPVMarketPotentialGoballyAndInFinland_final_pdf-3870.pdf (accessed on 28 July 2017).
18. Breyer, C.; Gerlach, A. Global overview on grid-parity. *Prog. Photovolt. Res. Appl.* **2013**, *21*, 121–136. [CrossRef]
19. Vartiainen, E.; Masson, G.; Breyer, C. True competitiveness of solar PV—A European case study. In Proceedings of the 32nd EU PVSEC, Muncih, Bavaria, 20–24 June 2016.
20. Grubler, A. The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy* **2010**, *38*, 5174–5188. [CrossRef]
21. Vartiainen, E.; Masson, G.; Breyer, C. PV LCOE in Europe 2015–2050. In Proceedings of the 31st European Photovoltaic Solar Energy Conference, Hamburg, Germany, 14–18 September 2015.
22. Zahedi, A. Maximizing solar PV energy penetration using energy storage technology. *Renew. Sustain. Energy Rev.* **2011**, *15*, 866–870. [CrossRef]
23. Lacey, S. Storage Is the New Solar: Will Batteries and PV Create an Unstoppable Hybrid Force? Greentech Media. Available online: https://www.greentechmedia.com/articles/featured/Storage-Is-the-New-Solar-Will-Batteries-and-PV-Create-an-Unstoppable-Hybri (accessed on 30 June 2015).

24. UBS. Will Solar, Batteries and Electric Cars Re-Shape the Electricity System? Q-Series®: Global Utilities, Autos & Chemicals. Available online: http://knowledge.neri.org.nz/assets/uploads/files/270ac-d1V0tO4LmKMZuB3.pdf (accessed on 11 November 2015).
25. Werner, C.; Breyer, C.; Gerlach, A.; Beckel, O. Photovoltaic with residential energy storage: An overview on economics, system design and politics. In Proceedings of the 27th European Photovoltaic Solar Energy Conference, Frankfurt, Germany, 24–28 September 2012.
26. International Energy Agency. Residential Prosumers—Drivers and Policy Options (RE Prosumers) Renewable Energy Technology Deployment. Available online: http://iea-retd.org/wp-content/uploads/2014/06/RE-PROSUMERS_IEA-RETD_2014.pdf (accessed on 12 January 2016).
27. Fraunhofer ISE. Energy Charts. Available online: https://www.energy-charts.de/index.htm (accessed on 15 April 2015).
28. Haukkala, T. Does the sun shine in the High North? Vested interests as a barrier to solar energy deployment in Finland. *Energy Res. Soc. Sci.* **2015**, *6*, 50–58. [CrossRef]
29. Ruggiero, S.; Varho, V.; Rikkonen, P. Transition to distributed energy generation in Finland: Prospects and barriers. *Energy Policy* **2015**, *86*, 433–443. [CrossRef]
30. Sipilä, K.; Konttinen, J.; Kalema, T.; Horttanainen, M.; Hiltunen, E.; Rikkonen, P. *Distributed Energy Systems—DESY*; VTT Technology 224; VTT: Espoo, Finland, 2015.
31. Painuly, J.P. Barriers to renewable energy penetration: A framework for analysis. *Renew. Energy* **2001**, *24*, 73–89. [CrossRef]
32. Margolis, R.; Zubov, J. Nontechnical Barriers to Solar Energy Use: Review of Recent Literature. National Renewable Energy Laboratories Tech. Rep. NREL/TP-520-40116; 2006. Available online: http://www.nrel.gov/docs/fy07osti/40116.pdf (accessed on 22 September 2015).
33. Timilsina, G.R.; Kurdgelashvili, L.; Narbel, P.A. Solar energy: Markets, economics and policies. *Renew. Sustain. Energy Rev.* **2012**, *16*, 449–465. [CrossRef]
34. Del Río, P.; Unruh, G. Overcoming the lock-out of renewable energy technologies in Spain: The cases of wind and solar electricity. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1498–1513. [CrossRef]
35. Patlitzianas, K.D.; Skylogiannis, G.K.; Papastefanakis, D. Assessing the PV business opportunities in Greece. *Energy Convers. Manag.* **2013**, *75*, 651–657. [CrossRef]
36. Lund, H. EnergyPLAN. Advanced Energy System Analysis Computer Model. Available online: http://www.energyplan.eu/ (accessed on 15 October 2015).
37. Fingrid. Electricity Market. Available online: http://www.fingrid.fi/en/electricity-market/Pages/default.aspx (accessed on 1 March 2015).
38. Stackhouse, P. Surface Meteorology and Solar Energy (SSE). Release 6.0; National Aeronautic and Space Administration (NASA): Langley. Available online: https://eosweb.larc.nasa.gov/sse/ (accessed on 17 November 2014).
39. Stetter, D. Enhancement of the REMix Energy System Model: Global Renewable Energy Potentials, Optimized Power Plant Siting and Scenario Validation. Ph.D. Thesis, Institue of Thermodynamics and Thermal Engineering, University of Stuttgart, Stuttgart, Germany, 2012.
40. Sovacool, B.K. Rejecting renewables: The socio-technical impediments to renewable electricity in the United States. *Energy Policy* **2009**, *37*, 4500–4513. [CrossRef]
41. Bogdanov, D.; Breyer, C. North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. *Energy Convers. Manag.* **2016**, *112*, 176–190. [CrossRef]
42. Bogdanov, D.; Breyer, C. The Role of Solar Energy towards 100% Renewable Power Supply for Israel: Integrating Solar PV, Wind Energy, CSP and Storages. In Proceedings of the 19th Sede Boqer Symposium on Solar Electricity Production, Sede Boqer, Israel, 23–25 February 2015.
43. Monforti, F.; Huld, T.; Bódis, K.; Vitali, L.; D'Isidoro, M.; Lacal-Arántegui, R. Assessing complementarity of wind and solar resources for energy production in Italy. A Monte Carlo approach. *Renew. Energy* **2014**, *63*, 576–586. [CrossRef]
44. Gerlach, A.; Stetter, D.; Schmid, J.; Breyer, C. PV and wind power-complementary technologies. In Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 5–11 September 2011.

45. SolarServer, E. ON Solar: Jeder Dritte Photovoltaik-Kunde Entscheidet Sich für Solarstrom-Speicher. *Solar-Magazin*. Available online: http://www.solarserver.de/solar-magazin/nachrichten/aktuelles/2015/kw30/eon-solar-jeder-dritte-photovoltaik-kunde-entscheidet-sich-fuer-solarstrom-speicher.html (accessed on 26 August 2015).
46. De Clercq, G. Analysis: Renewables Turn Utilities into Dinosaurs of the Energy World Reuters. Available online: http://www.reuters.com/assets/print?aid=USBRE92709E20130308 (accessed on 7 August 2015).
47. International Energy Agency. Technology Roadmap Solar Photovoltaic Energy. Available online: https://www.iea.org/publications/freepublications/publication/pv_roadmap.pdf (accessed on 7 September 2015).
48. Breyer, C.; Gerlach, A.; Mueller, J.; Behacker, H.; Milner, A. Grid-Parity Analysis for EU and US Regions and Market Segments—Dynamics of Grid-Parity and Dependence on Solar Irradiance, Local Electricity Prices and PV Progress Ratio. In Proceedings of the 24th EU PVSEC, Hamburg, Germany, 21–25 September 2009.
49. Gerlach, A.; Breyer, C.; Werner, C. Impact of financing cost on global grid-parity dynamics till 2030. In Proceedings of the 29th European Photovoltaic Solar Energy Conference, Amsterdam, The Netherlands, 22–26 September 2014.
50. Coady, D.; Parry, I.; Sears, L.; Shang, B. *How Large Are Global Energy Subsidies?* IMF—International Monetary Fund: Washington, DC, USA, 2015.
51. Finnish Energy Industries. Suomalaisten Energia-Asenteet 2016. Available online: http://energia.fi/ajankohtaista_ja_materiaalipankki/materiaalipankki/suomalaisten_energia-asenteet_2016.html (accessed on 29 April 2017).
52. Shumkov, I. Poland Okays FiT Scheme for PV Arrays up to 10 kW—Report. SeeNews. Available online: http://renewables.seenews.com/news/poland-okays-fit-scheme-for-pv-arrays-up-to-10-kw-report-471588 (accessed on 26 August 2015).
53. Lund, P.D. Energy policy planning near grid parity using a price-driven technology penetration model. *Technol. Forecast. Soc. Chang.* **2015**, *90*, 389–399. [CrossRef]
54. Raugei, M.; Sgouridis, S.; Murphy, D.; Fthenakis, V.; Frischknecht, R.; Breyer, C.; Bardi, U.; Barnhart, C.; Buckley, A.; Carbajales-Dale, M.; et al. Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response. *Energy Policy* **2017**, *102*, 377–384. [CrossRef]
55. Görig, M.; Breyer, C. Energy learning curves of PV systems. *Environ. Prog. Sustain. Energy* **2016**, *35*, 914–923. [CrossRef]
56. Sener, C.; Fthenakis, V. Energy policy and financing options to achieve solar energy grid penetration targets: Accounting for external costs. *Renew. Sustain. Energy Rev.* **2014**, *32*, 854–868. [CrossRef]
57. Breyer, C.; Koskinen, O.; Blechinger, P. Profitable climate change mitigation: The case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems. *Renew. Sustain. Energy Rev.* **2015**, *49*, 610–628. [CrossRef]
58. European Photovoltaic Industry Association. Global Market Outlook for Photovoltaics 2014–2018. Available online: http://www.cleanenergybusinesscouncil.com/site/resources/files/reports/EPIA_Global_Market_Outlook_for_Photovoltaics_2014--2018_-_Medium_Res.pdf (accessed on 28 September 2015).
59. Goldstein, D. Climate-Adaptive Technological Change in a Small Region: A Resource-Based Scenario Approach. Available online: https://sakai.allegheny.edu/access/content/user/dgoldste/Goldstein-TFSC-2June2014.pdf (accessed on 25 September 2015).
60. Palzer, A.; Henning, H.M. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part II: Results. *Renew. Sustain. Energy Rev.* **2014**, *30*, 1019–1034. [CrossRef]
61. Agora Energiewende. Stromspeicher in der Energiewende. Available online: http://www.speicherinitiative.at/assets/Uploads/19-AgoraEnergiewende-Speicherstudie-Langfassung.pdf (accessed on 22 November 2015).
62. Breyer, C.; Tsupari, E.; Tikka, V.; Vainikka, P. Power-to-gas as an emerging profitable business through creating an integrated value chain. *Energy Procedia* **2015**, *73*, 182–189. [CrossRef]
63. Adaramola, M.S.; Vågnes, E.E.T. Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions. *Energy Convers. Manag.* **2015**, *90*, 458–465. [CrossRef]

64. Lassila, J.; Tikka, V.; Hapaniemi, J.; Child, M.; Breyer, C.; Partanen, J. Nationwide photovoltaic hosting capacity in the Finnish electricity distribution system. In Proceedings of the 32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, Bavaria, Germany, 20–24 June 2016.
65. Weitemeyer, S.; Kleinhans, D.; Vogt, T.; Agert, C. Integration of Renewable Energy Sources in future power systems: The role of storage. *Renew. Energy* **2015**, *75*, 14–20. [CrossRef]
66. Lund, P.D.; Lindgren, J.; Mikkola, J.; Salpakari, J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev.* **2015**, *45*, 785–807. [CrossRef]
67. Child, M.; Breyer, C. The role of energy storage solutions in a 100% renewable Finnish energy system. *Energy Procedia* **2016**, *99*, 25–34. [CrossRef]
68. Zakariazadeh, A.; Jadid, S.; Siano, P. Integrated operation of electric vehicles and renewable generation in a smart distribution system. *Energy Convers. Manag.* **2015**, *89*, 99–110. [CrossRef]
69. Morais, H.; Sousa, T.; Vale, Z.; Faria, P. Evaluation of the electric vehicle impact in the power demand curve in a smart grid environment. *Energy Convers. Manag.* **2014**, *82*, 268–282. [CrossRef]
70. Greenpeace & European Renewable Energy Council. Energy [R]evolution. A Sustainable Finland Energy Outlook, 2012. Available online: http://www.greenpeace.org/finland/Global/finland/Dokumentit/Julkaisut/2012/Energy_scenario_report2012.pdf (accessed on 12 February 2015).
71. Zakeri, B.; Syri, S.; Rinne, S. Higher renewable energy integration into the existing energy system of Finland. Is there any maximum limit? *Energy* **2014**, *92 Pt 3*, 244–259. [CrossRef]
72. Pöyry Management Consulting Oy. Suomen Energiatase 2050, 2014. Available online: http://www.gasum.fi/globalassets/gasum/tutkimukset-ja-raportit/energiatase2050_julkaisu.pdf (accessed on 16 January 2015).