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1 **Towards positive energy communities at high latitudes**

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7 **Abstract**

8 Solar and wind energy are the significant renewable energy sources that can be used to tackle the climate change issue.
9 The aim of the study is to design and compare different architectures of community-level energy systems, in order to
10 find a positive energy community in cold climate. The design proposed is a centralized solar district heating network,
11 which is integrated with renewable-based electricity network to meet the heating and electrical demand of a community
12 of 100 houses. The renewable-based energy system consists of photovoltaic panels, wind turbines and stationary
13 electrical storage. In present study the demand of the building appliances, district heating network auxiliaries and
14 electric vehicles are included. TRNSYS is used to simulate these systems. Lastly, multi-objective optimization is done
15 using MOBO (Multi-objective optimization tool). The objective of the optimization problem is to minimize two
16 objective functions-the imported electricity and the life cycle costs. The onsite energy fraction, matching and exported
17 electricity are also evaluated for comparison. The optimization results illustrate that in terms of imported energy, the
18 cases with 600 kW (200 wind turbines) and storages are better compared to the cases without the turbines and storage.
19 For the high performing system (200 turbines with storages and 75 electric vehicles), the corresponding onsite energy
20 fraction (OEF) varied from 1% to 97% and the onsite energy matching (OEM) varied from 76% to 62%, respectively,
21 while the imported electricity can be reduced to 2 kWh/m²/yr. However without storage, the onsite energy fraction
22 (OEF) varied from 1% to 58% and the onsite energy matching (OEM) varied from 90% to 27% respectively. In all the
23 systems, initially investments are made in the wind turbines, storages and lastly in the photovoltaic panels to improve
24 the performance of the optimized solutions. It is found that storages can improve the onsite fraction and matching.
25 Moreover, photovoltaic becomes more important in the cases with higher number of electric vehicles.

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26 **Keywords**

27 Renewable energy community; electric vehicle; energy self-sufficiency; electrical storages; seasonal storage; multi-
28 objective optimization

29 **Nomenclature**

30	AX_E	Auxiliaries demand of the renewable district heating system (kWh/m ² /yr)
31	BL_E	Building appliances electricity consumption (kWh/m ² /yr)
32	BT_C	Stationary battery cost (€/kWh)
33	BTES	Borehole thermal energy system
34	CO ₂	Carbon dioxide
35	d_f	Discounting factor
36	DHW	Domestic hot water
37	DLSC	Drake Landing Solar Community
38	E	Imported or exported electricity (kWh/m ² /yr)
39	E_C	Export electricity price (€/kWh)
40	EV_E	Electrical vehicle demand (kWh/m ² /yr)
41	EXP_E	Exported electricity to the grid (kWh/m ² /yr)
42	EV	Electric vehicles
43	EU	European Union
44	FX_C	Fixed cost of the reference renewable district heating system (€/m ²)
45	GEN_E	Energy generated by the renewable sources (kWh/m ² /yr)
46	HP	Heat pump
47	HVAC	Heating, ventilation, and air conditioning
48	I_C	Import electricity price (€/kWh)
49	IMP_E	Imported electricity from the grid (kWh/m ² /yr)
50	IEA SHC	International energy agency- Solar heating and cooling
51	LCC	Life cycle costs
52	MOBO	Multi-objective building optimization tool
53	nZEB	Net zero energy building

54	nZEC	Net zero energy community
55	NSGA-II	Non-dominated Sorting Genetic Algorithm II
56	OEF	Onsite energy fraction for electricity
57	OEM	Onsite energy matching for electricity
58	PV	Photo voltaic panels
59	PV _C	Photovoltaic panels cost (€/m ₂)
60	RED	Renewable energy directive
61	SET-Plan	Strategic energy technology plan
62	SPH	Space heating
63	ST	Solar thermal collectors
64	STR _E	Stored energy in the stationary batteries (kWh/m ² /yr)
65	TRNSYS	Transient system simulation tool
66	WT _C	Wind turbine cost (€/unit)
67	Y ₁	Objective function 1
68	Y ₂	Objective function 2

69 **1 Introduction and literature review**

70 The European Strategic Energy Technology Plan (SET-Plan) [1] aims to accelerate the development and deployment of
71 low-carbon technologies. Several core topics are raised in the SET-plan. These include renewables, energy efficiency in
72 buildings, flexible energy systems, and sustainable mobility. Often holistic approaches considering several new
73 technologies are needed to demonstrate the real potential and impacts such new technologies may have.

74 The previous also supports the overall need to decarbonize energy systems [2]. In the EU, renewable heating is vital in
75 this transition [3]. District heating, as a source of secure and reliable heat, is also facing this decarbonizing challenge
76 [4]. The proposal of a recast of the EU Renewable Energy Directive (RED II) [5] is also addressing this issue.
77 Additionally, energy storage may play an important role in this process [6]. Even if Finland is one of the EU countries
78 with the highest share of renewables in heating, the country has ambitious coal phase-out targets [7].

79 After a noteworthy development of technologies and solutions for nearly and net zero energy buildings (e.g., [8–10]),
80 the international concept development has been towards positive energy buildings (e.g., [11,12]). For instance,
81 computational study in the North America shows that the passive buildings can be converted into a net zero energy

82 building by using photovoltaic panels in the cost-effective way [13]. Greenhouses are also studied in the Mediterranean
83 climate to be converted into nearly zero energy greenhouses, using a hybrid energy system that includes photovoltaic
84 and heat pumps [14] . Some research on nearly or net zero energy districts exists (e.g., [15–17]) but overall more
85 district-scale research and pilots are needed. According to the European Commission [18], Positive Energy
86 Blocks/Districts consist of several buildings that actively manage their energy consumption and the energy flow
87 between them and the wider energy system as well as have an annual positive energy balance. Mainly inspired by the
88 European Commission, some researchers have reached towards positive energy neighbourhoods (e.g., [19,20]). Net zero
89 energy community are studied in the Nordic conditions, that proposes solar district heating systems in cold conditions
90 [21]. Studies have also been carried out in the United States of America for net-zero energy residential area [22]. The
91 study proposes efficient Heating, ventilation, and air conditioning (HVAC), photovoltaic panels and heat pump
92 integration to reach such goals in various climate conditions of the United States of America. There are various ways to
93 reach net zero energy community level in the Nordic climate. However, further research is needed that can consider the
94 local conditions, costs, feasibility of the renewable energy generation and future market trends.

95 When a high share of variable renewable energy (VRE) is utilized, the energy systems are typically based on hybrid
96 systems (e.g., [23]) and a holistic approach is needed to analyse them. Furthermore, a system designed for one climate
97 conditions may not function optimally in another climate (e.g., [24]). Kiviluoma & Meibom [25] found out that systems
98 relying heavily on wind power and flexibility from heating, cooling and transport (EVs) could be more economical than
99 the alternatives if fossil fuel prices are high and CO₂ emissions have a substantial cost. Das et al. [26] found that solar
100 photovoltaic panels, biogas and batteries based hybrid energy systems can meet the demand of the buildings. Zhang et
101 al. [27] performed computational analysis of the hybrid energy system using weather forecasting, it is found that
102 forecasting can improve the flexibility of the hybrid energy systems. Hirvonen & Sirén [28] compared a fully electric
103 solar heating system to a solar thermal heating system for two energy community sizes in a Finnish climate. They found
104 out that the photovoltaic (PV)-based system performed better and it had lower costs. Additionally, they showed that
105 even in Finland it is possible to provide practically all heating by solar energy [28].

106 For example Hirvonen [29] introduces the benefits of the community approach including energy savings, reduced unit
107 costs, improved energy performance and easier energy system sizing for maximal self-consumption. In addition, Paiho
108 et al. [30] concluded that around 60% self-sufficiency in heating energy production and even 70% reduction in local
109 emissions compared to business as usual can be achieved with a community approach in a Finnish district.
110 Correspondingly, Marczinkowski & Østergaard [31] compared communal and building-scale batteries in an island
111 energy system. They conclude that both have advantages but the communal batteries reduce electricity import, improve

112 system efficiency, reduce losses, and increases local use of renewable energy sources. When analysing community-
113 scale options for heat and power generation based on local energy systems and utilizing seasonal thermal energy storage
114 in a Finnish case district, Paiho et al. [30] concluded that the most optimum solar collector area would be 5% of the
115 total building floor area in the district which would result over 30% self-sufficiency in heating. Additionally, the
116 emissions to air caused by heating of the buildings would reduce remarkably. However, the challenge is to build a self-
117 reliant community that can provide both the heating and the electrical requirements of the district through renewable
118 sources. Due to the miss-match between the availability of the renewable sources and the demand of the building, such
119 renewable based energy systems are vulnerable in the Nordic conditions [32]. Such self-sufficient district systems can
120 overcome the vulnerability using storages as proposed in [33] and also in [34]. Nevertheless, the optimization of such
121 complex hybrid energy systems for the net zero energy communities are important in order to provide techno-economic
122 viable solutions [35].

123 According to IEA [36], registrations of electric cars hit a new record in 2016, with over 750 000 sales worldwide. The
124 study shows that electric vehicles (EVs) can reduce the emissions from the transport sector [37]. In Finland, over
125 118 000 passenger cars are registered for the first time [38]. Only 0.4% of these are full electric cars and 2.2% are
126 hybrid ones. The share of electric vehicles (EVs) is still small in Finland but it is growing along with the public
127 recharging points [39]. The previous Finnish government has set an ambitious goal to have a minimum of 250 000
128 electric vehicles in total (fully electric vehicles, hydrogen-powered vehicles and rechargeable hybrids) in 2030 [40]. In
129 addition, it is often stated that electric vehicles may play a role in providing flexibility for the Finnish energy systems,
130 e.g. [41] However, high shares of EVs may influence power systems with consequences for adequacy and quality of
131 power supply [36]. Moreover, it is also important to provide electricity to the EVs using renewable source, this would
132 ultimately affect the current state of the art energy market and system [42]. Further research is needed to provide clean
133 energy to the EVs in a way that the district electrical grid can cope up with the demand of the EVs and can also handle
134 the variations.

135 On the other hand, the building's energy performance can be identified according to its net interaction with the energy
136 grids in terms of energy import and export. This is connected to the concept of Net Zero Energy Buildings (nZEB), in
137 which a building aims to balance its total energy import from the grid by exporting energy from on-site generation over
138 a pre-defined period of time- normally one year. When the annual exported energy form the building is higher than the
139 imported energy, the building is called a positive-energy building, and if the case is reversed, it is called a negative-
140 energy building. The concept expands from the scale of a net-zero single building to a net-zero energy community
141 (nZEC) following the extension of the boundaries through which the energy exchange takes place. A considerable work

142 in the definition of nZEB is made in the IEA SHC Task 40/EBC Annex 52 “Towards Net Zero Energy Solar Buildings”
143 [43].

144 The novelty of the paper is the integration and optimization of renewable based district heating system, renewable
145 electrical system, buildings, storages and electric vehicles at the community level, rather than at the single building
146 level that has been of interest earlier for instance by Cao [44], by Cao et al. [45], by Kılış [46], by Deng et al. [47] and
147 by Alajmi et al. [13]. Moreover, various combinations of storages, renewable energy generation and electric vehicles
148 are compared, both technically and economically for cold conditions. The renewable district heating system, seasonal
149 storages and buildings have been simulated and optimized in earlier studies [48,49]. In the current paper the focus is on
150 the optimized integration of the renewable electrical generation system, electrical storages, grid connection and electric
151 vehicles in the community and the comparison between various combinations (technically and economically).

152 The research aim and objective of this paper is to facilitate and propose the rollout of the community-scale renewable
153 electricity systems in Finland and also to widen the optimization study made in the previous work [48,49], where
154 community-scale renewable district heating system is only studied. The electrical, heating systems and buildings in the
155 community are integrated, optimized and studied together in the present paper. The analyzed energy solutions targets on
156 100% renewable energy production for the district heating demand and electricity demand of the buildings, energy
157 systems (auxiliaries) and electric vehicles. The solutions are optimized by means of imported electricity and life cycle
158 costs. In addition to this, each optimized solution and system is compared against various performance indicators such
159 as, exported electricity, onsite-energy fraction and onsite-energy matching are analyzed in order to propose net zero
160 energy community concepts in Nordic condition. With the increasing demand of the electric vehicles in the Nordic
161 countries [50] and particularly in Finland [51], and with the reduction in the photovoltaic panels prices [52], the future
162 energy market and energy systems has to adapt to such new trends in Finland. Therefore, the core objective is to design,
163 optimize and provide a self-sustaining or net zero energy community which would not only meet the local demand of
164 the whole community.

165 **2 Methodology principle**

166 The principle used for the investigation of various possible solutions of the proposed renewable energy systems
167 (electricity) for the community integrated with the earlier studied renewable district heating systems [48,49] is by
168 comparing the proposed energy system on two criteria, one representing the technical performance and the other
169 representing the economic performance. In addition to these criteria three other performance criteria are also used to

compare various possible optimal solutions of the proposed energy systems i.e. onsite-energy fraction (OEF), onsite-energy matching (OEM) and exported electricity. The simulation model of the energy system of the community in the TRNSYS software is explained in section 3, the optimization methodology is explained in section 4, the design variables properties, costs and ranges used for the simulations and optimizations are explained in the section 5, and different case studies used for the investigation of the energy systems for the community are explained in the section 6.

3 Methodology: Simulation model of the energy system

3.1 TRNSYS simulation

The simulation is carried out for a community with 100 houses and with 100 m² heated area each, using a dynamic simulation software [53]. TRNSYS [54] modules are used for the modelling of solar collectors (ST), weather data, short-term tanks, heat pumps (HP), borehole thermal energy storage (BTES), wind turbines, batteries, and photovoltaic panels. The weather profile chosen for the simulation is from the reference year of southern Finland [55]. In the present study, an already optimized centralized solar thermal based district heating system [48,49] is further expanded and integrated with photovoltaic panels, wind turbines, electrical batteries and electric vehicles in order to propose a positive energy community.

3.2 Solar based district heating system for community: Reference case

The solar collectors (ST) are used to charge the hot and warm tanks in parallel, when solar energy is available. The excess energy in the tanks is transferred to the boreholes thermal energy storage (BTES). During winters, when solar energy is not available the heat from the BTES is transferred to the warm tank. Moreover, the heat pump takes energy from the warm tank and charges the hot tank. The space heating and domestic hot water is provided via these two short term tanks to the houses in the community. The yearly heating demand for the domestic hot water is 35 kWh/m²/yr including the constant recirculation of hot water. The space heating demand of 25 kWh/m²/yr and the building appliances electricity demand of 40 kWh/m²/yr [56,57] are used. The detailed control strategies and the set points are described in the earlier publications [48,49]. The schematic representation of the system is provided in Figure 1.

energy produced by the wind turbines and photovoltaic panels is first used to meet the demand of the community. Any excess electricity produced is stored in the batteries. If the batteries are at the maximum charged level or if the batteries are completely discharged till 20% (active level), the excess generation or shortfall can be imported or exported via the grid.

Figure 2. Simple schematic representation of the centralized solar collector based energy system.

4 Methodology: Optimization of the energy system

Multi-objective optimization is used in the present study because it is difficult to find optimum solutions especially when there are multiple objectives which are conflicting in nature. Single objective optimization gives only one solution. On the other hand, the multi-objective problem offers a large number of possible optimal solutions, when there are many objectives. With trial and error method it is a tedious task to find the optimal solutions and exhaustive research method requires significant time and computational cost [32]. Therefore, multi-objective optimization is used in the present study, which is integrated with the simulation model to find various optimal solutions of the given problem and such method is used in the earlier studies as well such as in [32,58].

4.1 Optimizer and simulation integration: MOBO and TRNSYS

In the present study TRNSYS and MOBO (Multi-Objective Building Optimization tool) are combined to perform the optimization. MOBO [59,60] is an optimization software and it can handle both the discrete and continuous variables. It allows the use of evolutionary and classical optimization algorithms. For this study, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) algorithm is selected [58] and the detailed study of the NSGA-II is carried out by Deb et al.

228 [58]. MOBO uses the NSGA-II algorithm with an initial population of 16 individuals for 300 generations (i.e. 16 x 300
 229 = 4800 simulations runs) [49].

230 The integration, logic and flow of the MOBO optimizer and TRNSYS simulation software are shown in Figure 3. The
 231 values of the proposed design variables are created by MOBO at each iteration, and given as an input to the TRNSYS
 232 simulation model files. The TRNSYS simulation runs the model files and provides the results. These results are then
 233 evaluated by MOBO in order to meet the objective functions.

234

235 *Figure 3. The logic and flow chart of the integration of the TRNSYS simulation model and MOBO optimizer [32].*

236 4.2 Optimization problem

237 The energy system is optimized using a multi-objective optimization algorithm (NSGA-II), where imported electricity
 238 and life cycle costs (LCC) are minimized together. The life cycle cost and imported electricity are used because they
 239 both are conflicting in nature. In high performing cases, the imported electricity is less, however the costs are higher
 240 and vice versa. Therefore, these two objectives are used in the present study for optimization and comparisons between
 241 different solutions. Similar approach had been used in earlier scientific studies [32,61]. One of the reference optimal
 242 cases is selected from the multi objective optimized Pareto front from [49]. This reference case is selected in the present

study to analyse the impact on the energy system by the addition of energy generations, storages and demands (like PV panels, wind turbines, batteries and electric vehicles) in the community. The onsite-energy fraction, onsite energy matching, exported electricity and life cycle costs are also calculated to evaluate the systems.

4.3 Objective functions

The optimization problem is as follows:

$$\text{Min } \{Y_1(x), Y_2(x)\},$$

$$\text{for all } x = [x_1, x_2, \dots, x_n],$$

where Y_1 is the imported electricity and Y_2 is the life cycle costs for the system together with the building appliances, and 'x' is the vector of the design variables.

The first function (Y_1) is imported electricity and it is expressed as,

$$E = GEN_E + STR_E - (AX_E + BL_E + EV_E), \quad (1)$$

Where E is the imported electricity (IMP_E) when it is negative and exported electricity (EXP_E) when it is positive, GEN_E is the electricity generated by the renewable energy sources, STR_E is the stored electricity in the batteries, AX_E is the energy consumed by all the auxiliaries of the district heating system (pumps, heat pumps and backup electrical heaters), BL_E is the electricity demand of the building appliances and EV_E is the electricity demand of the electric vehicles in the community used for the charging of the vehicle's batteries.

The second function (Y_2) is the life cycle cost and it is expressed as [32,49,61] ,

$$LCC = FX_C + PV_C + WT_C + BT_C + \sum_{n=1}^{n=25} d_f \cdot I_C \cdot IMP_E - \sum_{n=1}^{n=25} d_f \cdot E_C \cdot EXP_E, \quad (2)$$

where LCC is the life cycle cost of the whole energy system and contains the investments and operational costs. The operation costs are calculated for 25 years. FX_C is the fixed cost, i.e. it is the cost of the reference renewable district heating system based on earlier publication [49] as explained in section 3.2. of the paper. PV_C is the cost of the photovoltaic panels, WT_C is the wind turbines cost and BT_C is the stationary batteries cost. The d_f is the discounting factor accounting for the electricity price escalation rate of 1%, and 3% interest rate [49]. The I_C is the import electricity price and E_C is the export electricity price. The import electricity price and export electricity price of 0.11 €/kWh and 0.04 €/kWh are used based on [62] respectively. IMP_E and EXP_E are the import and exported electricity,

respectively. Similar approach for the LCC calculation is done in the earlier studies for instance in [7], [21],[49]. The design variables values, specifications and their costs are discussed in detail in the section 5 of the paper.

4.4 Onsite energy fraction and matching

The onsite energy fraction (OEF) shows the part of the onsite demand covered by the onsite electricity generation [63]. The onsite energy matching (OEM) shows the part of the onsite electricity generation used for the onsite demand, rather than exported to the grid [63]. The system performance is better if the values of the OEF and OEM are higher (approaching value of 1), resulting in high matching characteristics.

5 Design variables

5.1 Design variables values and costs

The performance of the proposed renewable based flexible electricity system for the community described in the section 3.3 depends four design variables that are defined and considered in this paper which are namely: (1) photovoltaic panels area, (2) wind turbines capacity [64],(3) batteries capacity and (4) reference district heating system auxiliaries. The photovoltaic panels area, wind turbines capacity and batteries capacity are the variable values and these values are provided as variable input in the optimizer. In addition to the variable input, fixed value is also used for the reference renewable based district heating system and it includes solar collectors, warm tank, hot tank, seasonal storage and buildings costs. These fixed costs and values are optimized values. based on the previous study and publication [49].

The values or range of the design variables of the renewable based electrical system for the community are shown in Table 1. In addition to that, the fixed values are shown in Table 1 for the reference district heating system. The investment costs of all the design variables are also shown in Table 1.

Table 1. Electrical system design variables and investment cost of the components for the optimization problem.

Parameters	Values	Prices (€)	Variable used in Eq.(2)	References
PV area(m ²)	4.86-5000	450-230 €/m ²	PV _c	[25]
Wind (kW)	1-500 (one unit is 3 kW)	16800 €/unit	WT _c	[65]
Battery (kWh)	0.022-11MWh	450-400 €/kWh	BT _c	[65]
Reference solar based district heating system for the community	Fixed cost of the reference district heating system (solar collectors of 2500 m ² + warm tank of 230 m ³ + hot tank of	341.7 €/m ² (building	FX _c	[49]

107 m³ seasonal storage of
15000 m³ + building with space
heating demand of 25
kWh/m²/yr)

288

289 5.2 Design variables specifications and weather data

290 The energy systems may mostly depend on the following parameters, namely: (1) collectors [66], (2) the short term
291 storage tanks [67], (3) seasonal storage, (4) photovoltaic panels [68], (5) wind turbines, (6) electric batteries, (7) electric
292 vehicles and (8) building heating demand. The collectors, short term storage tanks, seasonal storage and buildings
293 demand are explained in earlier study in [48,49]. Each new parameter used in the present study and in the dynamic
294 simulation (wind turbines, photovoltaic panels, batteries and electric vehicles) are introduced and described in detail in
295 the following subsections along with the weather data.

296 5.2.1 Weather profile

297 The weather profile and data used in the simulation (TRNSYS) is shown in Figure 4. TRNSYS type 15 [54] is used to
298 define and introduce weather data in the simulation model. Figure 4 shows the total solar radiation, ambient temperature
299 and wind speed of the Southern Finland for the test reference year 2010 [48,69].

300

301 *Figure 4. The ambient temperature, solar radiation and wind speed profiles in the Southern Finland [48,69].*

5.2.2 Wind Turbines

Wind turbines are an important energy generation component. It is used to provide electricity to the system and to reduce the grid dependency. TRNSYS Type 90 is used to model the wind turbines. The turbines performance with respect to the wind velocity is from the commercial data [65]. The specifications of the wind turbines used in the simulation are described in Table 2.

Table 2. Wind turbines for the simulations [65].

Wind turbines	
Site elevation	0
Data collection height	10 m
Hub height	18 m
Number of turbines	Variable
Site shear exponent	Obstructed flows
Pressure	1 bar

5.2.3 Photovoltaic panels

The photovoltaic panels are used in the study to produce electricity via solar. TRNSYS Type 194 is used in the study to define photovoltaic panel's module. The specification of the photovoltaic panels used in the study is shown in Table 3.

Table 3. Photovoltaic panels specification for the simulations [65,68].

Photovoltaic panels, polycrystalline modules (at standard conditions)	
Panels capacity or area	Variable
Nominal output	250 Wp
Short circuit current	8.71 A
Open circuit voltage	37.8 V
Module conversion efficiency	15.37%

5.2.3.1 Nominal production: Wind turbine and photovoltaic panel in Finnish conditions

Figure 5 shows the nominal production of both the photovoltaic panel of 1 kWp and wind turbine of 3 kWp in the Southern Finnish conditions [49]. The seasonal variation of the PV production and the short term variation in the wind production can be seen in the Figure 5.

Figure 5. The energy production profile of the photovoltaic (1 kWp) and wind turbine (3 kWp) - single unit, in the community [65,68].

5.2.4 Batteries

Batteries are an important component for storage. It is used to store electricity that is being generated in excess by the renewable energy sources. TRNSYS Type 47b is used to model the electrical batteries. The batteries data is from the commercial product. The specifications of the batteries used in the simulation are described in Table 4. Excess energy is either stored in the batteries and the rest is exported to the grid. It is assumed that the batteries can be discharged up to 80% to ensure better life time.

Table 4. Electrical batteries system for the simulations [65,68].

Battery (at standard conditions)	
Cell energy capacity	465 Ah
Cell in parallel	Variables
Cells in series	24
Charging efficiency	0.9
Max. current per cell charging	85 amp
Max. charge voltage per cell	2.8 volt

5.2.5 Electric vehicles (EV)

In this study, Citroen C car charging characteristic has been assumed. The vehicle contains lithium-ion battery and a capacity of 14 kWh. The profile used in the present study for the vehicle load and calculation is from a real measured and validated data from Sweden [70]. It has been chosen because Sweden is situated in the Nordic region and has similar life style compared to Finland. The daily electric vehicle (EV) load profile for a single car is given in Figure 6. Similar profile is considered for the whole year for the ease of simulation. However, scenarios emulating different

penetration of EVs in the district have been assessed as described in section 6. Figure 6 shows that maximum charging is done during the night and evening when the people are at home. During the day time and afternoon when people are at work, there is no or very less load of EVs on the grid.

Figure 6. EVs charging profile of 25 EVs in the community.

6 Case studies simulated

To provide a complete analysis of the flexible renewable energy system and for the ease, the heating section of the whole energy system is already optimized in the earlier publication [49]. To meet the community sized electrical demand, photovoltaic panels and wind turbines are considered. For storage electrical batteries are considered. Table 5, 6 and 7 shows the scenarios and cases being simulated and optimized to provide overall performance analysis of the renewable energy system. Photovoltaic panels area, wind turbines capacity and batteries capacities are optimized using MOBO. In each optimized case the numbers of electric vehicles are changed. Moreover, for each case of the electric vehicles, the onsite batteries storages are either included or excluded to study its impact as well. All the possible cases are shown in Table 5, 6 and 7. The wind turbines maximum ranges are varied from 500 to 200 and then to 0.

Table 5. Case study 1 (1-500 wind turbines range) for optimization.

Design variables	Scenario number	Number of electric vehicles	Onsite stationary batteries
Photovoltaic panels+wind turbines+batteries	1	0	Yes (a)
	2	0	No (b)
	3	25	Yes (a)

4	25	No (b)
5	50	Yes (a)
6	50	No (b)
7	75	Yes (a)
8	75	No (b)

Table 6. Case study 2 (1-200 wind turbines range) for optimization.

Design variables	Scenario number	Number of electric vehicles	Onsite stationary batteries
Photovoltaic panels+wind turbines+batteries	1	0	Yes (a)
	2	0	No (b)
	3	25	Yes (a)
	4	25	No (b)
	5	50	Yes (a)
	6	50	No (b)
	7	75	Yes (a)
	8	75	No (b)

Table 7. Case study 3 (0 wind turbines) for optimization.

Design variables	Scenario number	Number of electric vehicles	Onsite stationary batteries
Photovoltaic panels+batteries	1	0	Yes (a)
	2	0	No (b)
	3	25	Yes (a)
	4	25	No (b)
	5	50	Yes (a)
	6	50	No (b)
	7	75	Yes (a)
	8	75	No (b)

7 Results

To demonstrate the effectiveness of the proposed renewable generation components and storages integrated with the community heating and electric demand along with electric vehicles, the results of the following different cases are discussed in Table 8. Table 8 shows the cases designed for the simulation and the optimization study.

358 *Table 8. The cases used for the study, simulation and optimization.*

Design variables	Ranges					
	Case 1a	Case 1b	Case 2a	Case 2b	Case 3a	Case 3b
Photovoltaic panels area (m ²)	4.86-5000	4.86-5000	4.86-5000	4.86-5000	4.86-5000	4.86-5000
Wind turbines unit (3 kW each)	1-500	1-500	1-200	1-200	0	0
Stationary batteries	Yes	No	Yes	No	Yes	No
Electric vehicles (quantity)	0, 25, 50, 75	0, 25, 50, 75	0, 25, 50, 75	0, 25, 50, 75	0, 25, 50, 75	0, 25, 50, 75

359

360 7.1 Pareto fronts- Optimal solutions (Case 1a, 2a, 3a, 1b, 2b and 3b)

361 7.1.1 Importance of the wind turbines

362 Figure 7 and 8 shows the relationship between the LCC and the imported electricity of the non-dominated solutions of
363 the cases 2a and 3a respectively and the reference community case. The x-axis shows the net imported electricity and
364 the y-axis shows the LCC of the different configurations. Red point shows the reference community case. Moreover, in
365 Figure 7 and 8, the blue points, the orange points, the green points and the purple points are for the case with 0 EVs, 25
366 EVs, 50 EVs and 75 EVs respectively. The cases 2a and 3a are community systems with stationary batteries. Each
367 single point on the Pareto front represents a single non-dominated optimal solution or a single optimal configuration for
368 each case. These optimal solution's points are numbered in an ascending order from left to right for each case. These
369 optimal configurations are numbered in order to have a uniform pattern in their explanation in the following sections.
370 Within each optimal configuration the design variable values are different, such that they meet the both objective
371 functions. The design variables values, OEF and OEM of these configurations on the Pareto fronts are explained in the
372 next sections.

373 The solutions on the right side of the Figure 7 and 8 are the least expensive optimal solutions with the worst optimal
374 performance, while the solutions on the left side of the figure are most expensive solutions with best optimal
375 performance. Generally it is observed in all the cases in Figure 7 and 8 that, the addition of the renewable energy
376 generation system like wind turbines in the community are beneficial technically and economically compared to the
377 reference community. This shows that instead of investing and focusing on the solar thermal based district heating
378 network, the emphasis should be on the addition of various renewable energy sources for the community sized heating
379 and electricity demand, to have better LCC and lower imported electricity. In reference case (red point), no photovoltaic

panels, wind turbines, electrical storages and EVs are considered, therefore the LCC is slightly lower, due to less investments, while the imported electricity values are higher compared to all the cases 2a, Figure 7.

The main differences in the Pareto fronts of the cases 2a and 3a is observed due to the wind turbines. In case 2a, Figure 7 the maximum wind turbines are 200, while in case 3a, Figure 8 there is no wind turbine. It is observed that with 200 wind turbines (Figure 7) the imported electricity can be reduced to 0 in high performing cases. However the LCC is higher with 200 turbines and 75EVs i.e. around 1190 €/m² compared to other cases with 0 wind turbines. With 200 turbines case 2a in Figure 7, only in the scenarios where EVs are 0 or 25, the imported electricity can be reduced to 0 in high performing cases. Whereas in the scenarios with 50 and 75 EVs the imported electricity cannot be 0 even in the high performing cases. With 0 turbines case 3a in Figure 8, the '0' imported electricity cannot be reached in any of the EVs scenarios even in the high performing cases. Therefore results shows that change in the wind turbines and EVs can affect the behaviour of these community systems. In other words, if the system has batteries, than wind turbines can play important role in reaching towards 0 level of imported electricity. Moreover, solutions gets worst by having EVs in the cases, as it can be observed in Figure 7 and 8, as imported electricity range increases by adding EVs. Nonetheless, 0 level of imported electricity cannot be reached without wind turbines in any of the cases in Nordic conditions.

394

395 *Figure 7. Case study 2a (1-200 wind turbines) with batteries-Pareto front and reference community.*

Figure 8. Case study 3a (0 wind turbines) with batteries-Pareto front and reference community.

In Figure 8, there is a sharp increase in the slope of the fronts, when the LCC increases. This is because there is no turbine in this case 3a. Without wind turbines and with only PV, system is not able to meet the demand, no matter how higher the investments are made in the batteries. Therefore, it can be observed that wind turbines play an important role in reducing the imported electricity.

7.1.2 Importance of the batteries

Figure 9 is the case 1a (with batteries) and Figure 10 is the case 1b (without batteries). When comparing case 1a, Figure 9 and case 1b, Figure 10, it can be observed that without stationary batteries, imported electricity cannot be 0. In other words, without the batteries the energy system depends on the grid to meet the demand. Even in the case where EVs are 0 in Figure 10, the system is not able to reach 0 level of imported electricity. Without batteries, in case 1b, the LCC is lower compared to the case 1a, because in case 1a, the investments are made on the batteries. Without the batteries and storages in Nordic conditions, it is challenging to reach '0' level of the imported electricity and towards a self-reliant community solutions.

Figure 9. Case study 1a (1-500 wind turbines) with batteries-Pareto front and reference community.

Figure 10. Case study 1b (1-500 wind turbines) with no batteries-Pareto front and reference community.

7.1.3 Importance of the electric vehicles

By comparing the four fronts within case 2b in Figure 11, where the maximum number of the wind turbines is 200. It is observed that by having less number of EVs, the LCC and the imported electricity is less compared to the case with higher number of EVs. The electricity demand is less therefore the imported electricity, investments and operational costs are less, even in the worst optimal cases compared to the cases with 75 EVs. In the best performing cases where the imported electricity is least, in Figure 11, the LCC with 0 EVs is around 696 €/m². On the other hand for 75 EVs

the LCC is around 770 €/m². In the worst performing optimized cases, in Figure 11, the case where EVs are 0 the imported electricity. However, when the EVs are 75 in the worst performing cases, the LCC is higher compared to 0 EVs case because the imported electricity is higher in this cases due to the higher demand caused by 75 EVs. Similar phenomena can be observed in cases 1a, 2a and 3a in Figure 9, 7 and 8 respectively. By having EVs the behaviour of the optimized cases and fronts are affected. Therefore, it is necessary to consider EVs while designing such systems.

Figure 11. Case study 2b (1-200 wind turbines) with no batteries-Pareto front and reference community.

7.1.4 Importance of the photovoltaics

Figure 12 shows the relationship between LCC and the imported electricity of the non-dominated solutions of the case 3b and reference community case. Case 3b is the community system without stationary batteries and 0 wind turbine.

Figure 12 shows the importance of the photovoltaic in the community, as the photovoltaics area increases the performance of the system also improves. However compared to case 1b and 2b in Figures 10 and 11 respectively, the imported electricity is generally higher while the LCC is lower. This is due to the fact, that the costs of the photovoltaic panels are lower than the wind turbines. Moreover, the impact of the photovoltaic panels on the performance of the systems is thus lower compared to the wind turbines.

Figure 12. Case study 3b only PV: (0 wind turbines) with no batteries- Pareto front and reference community.

Table 9 shows the techno-economic comparison between the cases 1a, 2a and 3a with the batteries and with 75 EVs. Table 8 also shows the techno-economic comparison between the cases 1b, 2b and 3b without batteries and with 75 EVs. Table 8 shows that the case 2a is able to achieve significant reduction in the net imported electricity, with minimum increase in the LCC, therefore this case performed better compared to the other cases. However, case 3a performed worst with large increase in the LCC, the reduction of the net imported electricity is not significant.

Table 9. Techno-economic comparison between the cases 1a, 2a, 3a, 1b, 2b and 3b with 75 EVs, based on the Figures 7-12.

Objective functions			75 EVs					
			Case 1a	Case 1b	Case 2a	Case 2b	Case 3a	Case 3b
Reduction	in	imported	99%	72%	98%	59%	34%	17%
electricity (%)								
Increase in LCC (%)			58%	51%	53%	30%	47%	9%

7.2 Cost breakdown and analysis of the non-dominated solutions- with batteries (Case 1a, 2a, and 3a)

In this section all the cases 1a, 2a and 3a are shown in Figures 13, 14 and 15. These figures show the cost breakdown of the non-dominated optimized solutions of the cases 1a, 2a and 3a respectively. The cost of the solar thermal district

heating system is constant in this study, therefore it is assumed to be '0' and all the other design variables costs (wind turbines, photovoltaic panels and batteries) are relative to that base value '0'. It is done to illustrate the effect of each chosen design variable on the life cycle cost and the technical performance. The (x-axis) of the all the figures shows the configuration number of the optimized solution, while the (y-axis) shows the cost breakdown of the component in each optimal solution. Each single configuration on the x-axis represents the single optimal solution on the Pareto fronts in the section 7.1 for each case. The design variable costs in each of the optimal solution are represented in Figure 13, 14 and 15. These configurations are arranged in the similar pattern and numbering as the Pareto fronts in section 7.1 for each case.

Generally, the solutions on the left side near (configuration 1) are the most expensive solutions and are therefore high performance solutions in the Figures 13, 14 and 15. On the other side, the solutions on the right side near (configuration 500 and above) in all the Figures 13, 14 and 15 are the least expensive solutions and therefore the lowest performance solutions. For comparison within each case (1a, 2a and 3a), two scenarios are shown where the EVs are either 0 or 75. For instance, Figure 13i shows the scenarios for case 1a, where the maximum wind turbines are 500 with 0 EVs. Figure 13ii shows the scenarios for the case 1a, where the maximum wind turbines are 500 and with 75 EVs. Similar structure is used for the cases 2a and 3a in Figure 14 and 15 respectively. For the optimal solutions, the initial investment cost is around 65-90% of the total LCC.

Figure 13 show that the wind turbines and the batteries are the biggest investments. The investments are made initially in the wind turbines followed by the electrical storage to reach lowest imported electricity value. As the simulation progresses towards (configuration 1) in Figure 13i, where the performance improves, the initial investments are made in the turbines, as it helps to improves the performance As the number of wind turbines starts to increase the investments are then made on the batteries to store the excess electricity. Small investments are also made in the photovoltaic panels due to lower cost; however, the wind turbines are enough to meet the demand in the case with 0 EVs. It is evident that wind turbines and batteries can play a significant role in the reduction of the imported electricity.

When comparing Figure 13i with 13ii for case 1a, it is observed that overall behaviour of the design variables is similar. However, the system where EVs are 75 in Figure 13ii, it has larger wind turbines, batteries and photovoltaics in configuration 1, compared to system where EVs are 0 in Figure 13i. In Figure 13i (configuration 1), the number of wind turbines are 313, and in Figure 13ii (configuration 1) the number or wind turbines are 466. In addition to that the maximum area of the photovoltaics in Figure 13ii (configuration 1) is 1385m² on the other, in Figure 13i (configuration 1) the area of the photovoltaics is 5m². This shows that without the EVs in the community, the wind turbines and

477 batteries are enough to meet the demand of the community and photovoltaics has less significance. However, it is
 478 important to note that as the number of EVs increases from 0 to 75, the importance of the photovoltaics also increases in
 479 the system to improve the performance this is due to higher demand by the 75 EVs compared to 0 EVs.

480
 481 *Figure 13. Case study 1a (1-500 wind turbines) with batteries – relative cost breakdown for the scenarios with (i) 0EVs and (ii) 75*
 482 *EVs with respect to base case.*

483 Generally Figure 14 (case 2a) shows the similar behaviour like Figure 13 (case 1a). The number of wind turbines and
 484 storages increases as the imported electricity reduced in configuration 1 in Figure 14i. In Figure 14ii (case 2a)
 485 configuration 1, where the EVs are 75, the number of wind turbines is 200 and the photovoltaic area is 5000 m². On the
 486 contrary when the EVs are 0, in Figure 14i, configuration 1, the number of wind turbines are 194 and the photovoltaic
 487 area is 5 m². This shows that the number of EVs can significantly affect the PV capacity.

489 *Figure 14. Case study 2a (1-200 wind turbines) with batteries – relative cost breakdown for the scenarios with (i) 0EVs and (ii) 75*
 490 *EVs with respect to base case.*

491 Generally the Figure 15 (case 3a) shows similar behaviour like Figure 13 (case 1a) and Figure 14 (case 2a). However, in
 492 case 1a and 2a there is wind turbines and in case 3a (Figure 15) there is no wind turbines. The number of photovoltaic
 493 and storage increases as the imported electricity reduces in configuration 1 in Figure 15. It can be observed that both the
 494 systems reached maximum level of photovoltaic area in configuration 1 in both cases in Figure 15. However, as the
 495 number of photovoltaic panels increased to the maximum limit, the imported electricity still remains high compared to
 496 the other cases 1a and 2a because of the absence of turbines. It shows that wind turbines are needed to reduce import of
 497 electricity.

498
 499 *Figure 15. Case study 3a (0 wind turbines) with batteries – relative cost breakdown for the scenarios with (i) 0EVs and (ii) 75 EVs*
 500 *with respect to base case.*

501 When comparing the cases 1a, 2a and 3a and Figures 13, 14 and 15 respectively, few differences can be observed.
 502 Firstly, when comparing Figures 13, 14 and 15 it is observed that, wind turbines and storages played an important role
 503 in the reduction of the imported electricity and increase in the costs. With higher number of wind turbines in case 1a
 504 and in case 2a, the imported electricity can be 0 or close to 0. However, with no wind turbine in case 3a, the imported
 505 electricity cannot be 0 or close to 0, but the cost can be lower compared to case 1a and case 2a. Secondly, with 0 EVs in
 506 cases 1a and 2a, the photovoltaic has less significance compared to cases with 75 EVs.

7.3 Cost breakdown and analysis of the non-dominated solutions- with no batteries (Case 1b, 2b, and 3b)

In this section all the cases 1b, 2b and 3b are shown in Figures 16, 17 and 18. These figures show the cost breakdown of the non-dominated optimized solutions of the cases 1b, 2b and 3b respectively. All these systems have no batteries. These figures are arranged in similar way like in Figure 13, 14 and 15. Each single configuration on the x-axis represents the single optimal solution on the Pareto fronts in the section 7.1. The design variable costs in each optimal solution are represented in Figure 16, 17 and 18. These configurations are arranged in the similar pattern and numbering as the Pareto fronts in section 7.1.

Figure 16 and 17 shows that the wind turbines forms the biggest part of the investment, followed by the photovoltaics. In Figure 18, it has no wind turbines therefore only photovoltaic formed the largest part of the investments. Overall similar behaviour can be observed as explained above in section 7.2. However in the present section, all the cases 1b, 2b and 3b has no storage, therefore large investments are made in the wind turbines and photovoltaic panels in all the cases of the EVs as shown in Figure 16, 17 and 18. This shows that electrical storage is an important component to reach high performance and self-sustaining community. In cases 1b (Figure 16i), 2b (Figure 17i) and 3b (Figure 18i), the area of the photovoltaic panels is higher in configuration 1 compared to the cases 1a, 2a and 3a with 0 EVs. Similarly in cases 1b, 2b and 3b with 75 EVs, the photovoltaic panels are still needed to reach certain lower values of the imported electricity. This shows that the optimization algorithm tries to achieve 0 levels of imported electricity by investing more in the photovoltaic panels to produce electricity in the absence of storage. With 500 turbines and 0 EVs (case 1b) in Figure 16i, the imported electricity can be nearly 0 in configuration 1. However, with all other cases 2b and 3b (Figure 17 and 18), the imported electricity cannot be 0 even with higher investments in configuration 1.

Figure 16. Case study 1b (1-500 wind turbines) with no batteries – relative cost breakdown for the scenarios with (i) 0 EVs and (ii) 75 EVs with respect to base case.

Figure 17. Case study 2b (1-200 wind turbines) with no batteries – relative cost breakdown for the scenarios with (i) 0 EVs and (ii) 75 EVs with respect to base case.

Figure 18. Case study 3b only PV: (0 wind turbines) with no batteries – relative cost breakdown for the scenarios with (i) 0 EVs and (ii) 75 EVs with respect to base case.

7.4 Onsite fraction (OEF) and matching (OEM) of the non-dominated solutions- with batteries (Case 1a, 2a, and 3a)

In this section all the cases 1a, 2a and 3a are shown in Figures 19, 20 and 21. These figures show the onsite fraction (OEF) and onsite matching (OEM) of the non-dominated optimized solutions of the cases 1a, 2a and 3a respectively. Figure 19 shows OEF and OEM of the system with maximum 500 turbines, Figure 20 shows the OEF and OEM of the system with maximum 200 wind turbines and Figure 21 shows the OEF and OEM of the system with 0 wind turbines. The (x-axis) of all the figures shows the configuration number of the optimized solution, these configurations are arranged in the similar pattern and numbering as the Pareto fronts in section 7.1. While the (y-axis) shows the OEF and OEM of each single optimal solution. For comparison within each case (1a, 2a and 3a), all the scenarios are shown where the EVs are 0, 25, 50 and 75.

The on-site energy fraction (OEF) varied between 100% and 1% as shown in Figure 19 for case 1a. This indicates that the wind turbines, photovoltaic and electrical storages are able to meet 100%—1% of the local demand of the system, depending upon the wind turbines capacity, photovoltaic size and annual electricity demand of the community and EVs. The OEF is less when the wind turbines capacities, photovoltaic area and batteries capacities are less on the right side of the Figure 19 (configuration 700); hence the on-site generation of electricity is not enough to meet the demand. It

improved until 100% when the photovoltaic, wind turbines and storage capacities increases towards left side of the Figure 19 (configuration 1), resulting in large on-site electricity generation. The maximum OEF is 100% because of the storages, any mismatch between the generation and consumption is met via the storages. Moreover, the maximum OEM achieved is 50% as shown in Figure 19. This indicates that in the highest performing cases 50% of the on-site generation by renewables sources are used locally while the rest of the 50% is exported to the grid. On the other hand, the OEM is 80% when the renewable energy sources and storage capacities are small, however this resulted in 1% OEF only.

Figure 19. Case study 1a (1-500 wind turbines) with batteries – the onsite fraction (OEF) and onsite matching (OEM).

Figure 20 (case 2a) shows the similar behaviour like Figure 19 (case 1a). The on-site energy fraction (OEF) varied between 100% and 1% as shown in Figure 20 for case 2a. This indicates that wind turbines, photovoltaic and electrical storages are able to meet 100%—1% of the local demand of the system depending on the configuration. Since there are electricity storages, in the cases (configuration 1) where the renewables sources and storage capacities are large the maximum OEM achieved is 60% as shown in Figure 20. On the other hand, the OEM is 80% when the renewable energy sources and storage capacities are small, however this resulted in 1% OEF only. The difference between case 1a (Figure 19) and case 2a (Figure 20) in configuration 1 is that OEM is higher in case 2a. This is because the maximum number of wind turbines are 200 therefore less is exported in this case 2a, compared to case 1a where maximum limit for wind turbines are 500. Large capacities are not always required and optimization is important in order to provide techno-economically better solutions.

Figure 20. Case study 2a (1-200 wind turbines) with batteries – the onsite fraction (OEF) and onsite matching (OEM).

Figure 21 (case 3a) shows the similar behaviour like in Figure 19 (case 1a) and in Figure 20 (case 2a). The on-site energy fraction (OEF) varied between 45% and 1% as shown in Figure 21 for case 3a. This indicates that photovoltaic and electrical storages are able to meet maximum 45% of the local demand of the system when EVs are 0 in configuration 1. The OEF reduced to 35% when EVs are 75 in configuration 1. It shows that in the case where wind turbine is 0, the number of EVs can affect the OEF in this case 3a.

Since there are electricity storages but no wind turbines, in the cases (configuration 1) where the renewables sources and storage capacities are large the maximum OEM achieved is 80% as shown in Figure 21. On the other hand, the OEM is 80% when the renewable energy sources and storage capacities are small, however this resulted in 1% OEF only. The difference between case 1a (Figure 19), case 2a (Figure 20) and case 3a (Figure 21) is that the OEM is highest in configuration 1 in case 3a. There is no wind turbine, thus any electricity produced by the photovoltaic is stored in the batteries and used onsite, resulting in less electricity export. However due to the absence of wind turbines the system is only able to meet around 45%-35% of the demand depending on the numbers of EVs. Therefore, the number of wind turbines and EVs can affect the OEF and OEM values.

Figure 21. Case study 3a (0 wind turbines) with batteries – the onsite fraction (OEF) and onsite matching (OEM).

7.5 Onsite fraction (OEF) and matching (OEM) of the non-dominated solutions- with no batteries (Case 1b, 2b, and 3b)

In this section all the cases 1b, 2b and 3b are shown in Figures 22, 23 and 24. These figures show the OEF and OEM of the non-dominated optimized solutions of the cases 1b, 2b and 3b respectively. All these systems have no electrical storage. The OEF and OEM of each single optimal configuration are shown in these figures and arranged in the similar pattern and numbering as the Pareto fronts in section 7.1. These figures are arranged in similar way like in Figure 19, 20 and 21.

The on-site energy fraction (OEF) varied between 90%-70% in configuration 1 and 1% in configuration 2177 as shown in Figure 22 for case 1b. Compared to the case 1a in Figure 19, in case 1b in Figure 22, the OEF is lower i.e. around 90 %. This is due to the fact that there is no electrical storage and all the demand is met via the renewable energy generation with no storage. Therefore during the period when no energy is produced by the wind turbines and photovoltaics, the demand is met via imported electricity. This indicates that to have higher the OEF storage is needed. The OEF also varied in case 1b in Figure 22 (configuration 1) due to the EVs demand; higher the demand from EVs lower is the OEF. The excess demand is met via grid due to non-availability of the batteries.

The OEF is less when the wind turbines capacities and photovoltaic panels area is less on the right side of the Figure 22 (configuration 2177). The on-site generation of electricity is not enough to meet the demand. In the cases (configuration 1) where the renewables sources capacities are large the maximum OEM achieved is 10%-15% as shown in Figure 22. This indicates that in highest performing cases 10%-15% of the on-site generation by the renewables sources is used

605 locally while the rest of the 90%-85% is exported to the grid. Without storage the onsite energy matching can be lower
 606 in the best performing configuration 1 (case 1b, Figure 22). On the other hand, the OEM is 90% when the renewable
 607 energy generation is less, however this resulted in 1% OEF only.

608
 609 *Figure 22. Case study 1b (1-500 wind turbines) with no batteries – the onsite fraction (OEF) and onsite matching (OEM).*

610 Figure 23 (case 2b) shows the similar behaviour like Figure 22 (case 1b). The on-site energy fraction (OEF) varied
 611 between 85%-60% in configuration 1 and 1% in configuration 2288 as shown in Figure 23 for case 2b. This indicates
 612 that the wind turbines and photovoltaic are able to meet 85%—1% of the local demand of the system, depending upon
 613 the wind turbines capacity, photovoltaic size and annual electricity demand of the community and EVs. Since there is
 614 no electricity storage, in the cases (configuration 1) where the renewables sources are large, the maximum OEM
 615 achieved is 20%-30% as shown in Figure 23. On the other hand, the OEM is 90% when the renewable energy sources
 616 capacities are less, however this resulted in 1% OEF only. The difference between case 1b (Figure 22) and case 2b
 617 (Figure 23) in configuration 1 is that the OEM is higher in case 2b. This is because the highest number of wind turbines
 618 are 200 therefore less is exported in this case 2b, compared to case 1b where maximum limit for wind turbines are 500.
 619 As excess electricity from higher wind turbine capacities are exported in large quantity, this result in lower OEM in
 620 case 1b (Figure 22).

Figure 23. Case study 2b (1-200 wind turbines) with no batteries – the onsite fraction (OEF) and onsite matching (OEM).

Figure 24 (case 3b) shows similar behaviour like Figure 22 (case 1b) and Figure 23 (case 2b). The on-site energy fraction (OEF) varied between 26%-16% in configuration 1 and 1% in configuration 4400 as shown in Figure 22 for case 3b. On the other hand OEM varied from 35% to 90% from configuration 1 to 4400.

Overall study shows that the wind turbines and the storages are crucial to have higher technical performance of the community sized energy system in the Nordic conditions. If the EVs are integrated in the community, then the importance of the PV becomes evident.

Figure 24. Case study 3b (0 wind turbines) with no batteries – the onsite fraction (OEF) and onsite matching (OEM).

7.6 Net zero energy community (nZEC) analysis (Case 2)

Optimal points from cases 2a and case 2b (cases with maximum 200 wind turbines, with and without batteries, from Figures 7 and 11 respectively), are selected to further analyse the performance of the community on net zero energy community (nZEC) level. Figure 25 shows the exported vs imported electricity of the net zero energy community graph.

635 In addition to the exported and imported electricity extreme points also shows the OEF and OEM respectively. It is
 636 observed that cases with the batteries performed better, by lowering the imported and exported electricity compared to
 637 the cases without batteries. The blue and purple points in Figure 25 are close to the nZEC balance line and also close to
 638 the zero imported electricity point. On the other hand, the red and green points in Figure 25 are away from the nZEC
 639 balance line and also away from the zero imported electricity point. Without the batteries (red and green points in
 640 Figure 25), the system has high exported electricity, which is being sold to the grid, with no significant advantage.
 641 However, system with batteries (blue and purple in Figure 25) has lower exported and imported electricity since the
 642 system is able to utilize onsite generated electricity effectively. The OEM and OEF of the end points (blue and purple)
 643 with batteries are higher compared to the system without batteries (red and green points) in Figure 25.
 644

645
 646 *Figure 25. Imported/exported site energy diagram for cases 2a (1-200 wind turbines, with batteries) and 2b (1-200 wind turbines,*
 647 *without batteries) with corresponding OEF and OEM values.*

648 **8 Discussion**

649 The analyses are made with realistic existing price data. The results could differ if price development changed. For
650 example, lithium-ion battery prices have declined for years but lithium prices steadily rise [71] while lithium demand
651 increases [72]. At some phase, this could influence prices of lithium-ion batteries.

652 Effect of EV deployment can affect the performance of the energy system. It is expected in the future that with the
653 increase in the deployment of the EVs, the impact on the present grids would be significant. Therefore it is important to
654 consider such scenario in the future. While proposing such renewable based community system, it is assumed that
655 household would consider buying EVs. The study is performed to consider such scenario and to observe the effect on
656 the system. It is found that in various scenarios with different number of EVs, the performance of the system is affected.
657 With higher number of EVs the number and size of the renewable energy component also increased. Moreover, in some
658 cases, where the wind turbines and photovoltaic panels are unable to meet the demand, the imported electricity
659 increased. So it is essential to design such communities in a proactive manner.

660 Williams et al. [73] argue that while there are numerous definitions for zero energy buildings, the progress in terms of
661 numbers of buildings built has been small and random. The number of realized zero energy districts is even smaller.
662 This study showed that it is basically possible to build a net zero energy districts in Nordic conditions, heavily relying
663 on variable renewable energy (VRE) if batteries energy storage is part of the system concept. However, this requires
664 major investments. This may indicate that positive energy blocks based on VREs are realistic in northern Europe. As
665 shown in Figure. 25, the cases with higher VRE integration are able to reach positive energy districts, where the annual
666 exported energy is higher than the imported energy. Solutions with batteries will reduce the imported energy and
667 increase the matched energy onsite and can reach zero or positive energy community levels when more integration of
668 renewable takes place. However, solutions without batteries can still be positive energy communities but require higher
669 amounts of imported energy.

670 Land use is also a significant issue in the community, larger the land needed to construct such system, large can be the
671 cost. In the present study, it is assumed that the wind turbines are small 3kW turbines. The results showed that higher
672 performance can be achieved by having large number of wind turbines. It is found that 1.5 MW-0.6 MW turbine power
673 is needed to reach 0 imported electricity. Therefore, it is important to identify the available land space where all the
674 smaller units of wind turbines can be installed or a single large wind turbine is enough. With smaller capacities of
675 multiple wind turbines, the reliability of the system would improve. On the other hand, with single large turbine, the
676 reliability issue can arise.

677 The costs of EVs are not considered. In Trafi's (Finnish Transport Safety Agency) car comparison service [74], the
678 consumers may compare properties of different electric and other cars sold in Finland. The cheapest and smallest full
679 EVs cost around €25 000 and the most expensive ones over €165 000. According to some recent estimates [75], the
680 price of driving is roughly the same with different kinds of cars in Finland if about 30 000 km is driven annually and the
681 car is not replaced during the first five years. If annual driving amount is smaller, then traditional cars become much
682 cheaper.

683 The average net living area of a new Finnish single-family house is 165 m² and the average building cost is 2010 €/m²
684 (in total 332 000 €) when all work has been done by professionals [76]. In addition, the plot typically costs around
685 €50 000 but the price may be multiple in the most wanted areas [76]. Some municipalities also rent plots. The average
686 costs of technical systems, including installation, are €16 320 for heating (4.9% of the total building cost), €12 460 for
687 water and sewage (3.8% of the total building cost), €8 900 for ventilation (2.7% of the total building cost), and €14 850
688 for electricity (4.5% of the total building cost) [77]. The size of the studied houses is smaller (100 m²). Based on the
689 previous cost data [76,77], the building cost for such a house could be around €200 000 and the cost of heating and
690 ventilation systems about €25 000. The investment costs for the studied zero import energy systems are around 1186
691 €/m² which are 83% higher than this estimate for energy systems in a typical house. This indicates that the prices of
692 new energy systems still need to reduce in order to be widely deployed and somehow equivalent to the ratio of 1.

693 9 Conclusions

694 A novel renewable district heating and electrical systems based on simulation models are proposed. The integrated
695 system includes both the centralized solar thermal district heating network and renewable (wind and photovoltaic) based
696 electrical system. The study is performed using dynamic simulation software (TRNSYS). In addition, a multi-objective
697 building optimizer is integrated into the model, which used Non-dominated Sorting Genetic Algorithm (NSGA-II). The
698 following is a brief summary of the key findings:

- 699 • The renewable-based community sized energy systems performed better in the studied Finnish conditions,
700 compared to the reference community with no photovoltaic, wind turbines and stationary storages.
- 701 • The cases with 200 wind turbines and electrical storages outperform the cases without the turbines and
702 electrical storage.

- With 200 wind turbines, storages and 75 EVs (case 2a), the imported energy changed from 87 kWh/m²/yr to 1.9 kWh/m²/yr and the life cycle price from 536 €/m² to 1190 €/m². The onsite energy fraction (OEF) changed from 1% to 97% and the onsite energy matching (OEM) changed from 76% to 62%, respectively.
- With 200 turbines, no storage and 75 EVs (case 2b), the imported energy changed from 87 kWh/m²/yr to 36 kWh/m²/yr and the life cycle price from 534 €/m² to 764 €/m². The onsite energy fraction (OEF) changed from 1% to 58% and the onsite energy matching (OEM) changed from 90% to 27% respectively.
- With no wind turbine, no storage and 75 EVs (case 3b), the imported energy changed from 88 kWh/m²/yr to 74 kWh/m²/yr and the life cycle price from 534 €/m² to 585 €/m². The onsite energy fraction (OEF) changed from 1% to 16% and the onsite energy matching (OEM) changed from 90% to 34% respectively.
- Generally in all the systems, investments are first made in the wind turbines and after that PV and storages in order to improve the performance of the system. However, only in the case with 75 EVs, investments are made in the photovoltaics and wind turbines initially to improve the performance of the optimized solutions.
- In the systems without the storage, systems are not able to reach zero imported electricity. The storages not only reduced the imported electricity but also reduced the exported electricity.
- The batteries assisted in reaching net zero energy community (nZEC) levels compared to the community without the batteries.
- Higher numbers of EVs affect the performance of the system and this need to be considered for the design of the energy networks for the future.
- It is important to optimize the systems by aiming to maximize the onsite-energy fraction and onsite-energy matching.

This research can be useful in further recommending the society towards building such renewable communities in the Nordic climatic regions of the world. The study also revealed that the systems should address both the heating and electrical demand of the community. Moreover, the optimization of such systems, controls and integration of various demand and generation are some of the important aspects towards reaching the goals. These energy systems can be made technically and financially better by promoting self-consumption. The self-consumption can be increased by integrating seasonal storage and batteries. Experimental validation is required in the future and this study would provide basic calculations. It is expected that the prices of the thermal collectors, wind turbines, batteries and photovoltaics, would reduce in near future. This would assist in making such systems feasible compared to the traditional energy systems.

733

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740 References

741

- 742 [1] European Commission. Transforming the European Energy System through Innovation. 2016.
743 doi:10.2833/45248.
- 744 [2] IEA. Energy Technology Perspectives 2016. Towards Sustainable Urban Energy Systems. Paris: OECD
745 Publishing; 2015. doi:10.1787/energy_tech-2014-en.
- 746 [3] European Commission. Energy Roadmap 2050. 2011. doi:10.1017/CBO9781107415324.004.
- 747 [4] European Commission. An EU Strategy on Heating and Cooling. 2016. doi:10.1017/CBO9781107415324.004.
- 748 [5] European Commission. Proposal for a directive of the European Parliament and of the Council on the
749 promotion of the use of energy from renewable sources (recast). COM(2016) 767 final/2. 2017.
- 750 [6] OECD/IEA. Technology Roadmap: Energy storage. 2014. doi:10.1007/SpringerReference_7300.
- 751 [7] Collier U. Renewable Heat. IEA; 2018.
- 752 [8] Butera FM. Zero-energy buildings: the challenges. Adv Build Energy Res 2013;7:51–65.
753 doi:10.1080/17512549.2012.756430.
- 754 [9] Rodriguez-Ubinas E, Rodriguez S, Voss K, Todorovic MS. Energy efficiency evaluation of zero energy houses.
755 Energy Build 2014;83:23–35. doi:10.1016/j.enbuild.2014.06.019.
- 756 [10] Paiho S, Pulakka S, Knuuti A. Life-cycle cost analyses of heat pump concepts for Finnish new nearly zero

energy residential buildings. *Energy Build* 2017;396–402. doi:10.1016/j.enbuild.2017.06.034.

[11] Takase K, Kawashima N, Sato K, Ohnuma Y. Practice of net Positive Energy House in the Suburb of Tokyo. *Energy Procedia* 2017;143:112–8. doi:10.1016/j.egypro.2017.12.657.

[12] Couty P, Lalou MJ, Cuony P, Cotture S, Saade V. Positive energy building with PV facade production and electrical storage designed by the Swiss team for the U.S. Department of Energy Solar Decathlon 2017. *Energy Procedia* 2017;122:919–24. doi:10.1016/j.egypro.2017.07.410.

[13] Alajmi A, Rodríguez S, Sailor D. Transforming a passive house into a net-zero energy house: a case study in the Pacific Northwest of the U.S. *Energy Convers Manag* 2018;172:39–49. doi:10.1016/J.ENCONMAN.2018.06.107.

[14] Yildirim N, Bilir L. Evaluation of a hybrid system for a nearly zero energy greenhouse. *Energy Convers Manag* 2017;148:1278–90. doi:10.1016/J.ENCONMAN.2017.06.068.

[15] Sameti M, Haghighat F. Integration of distributed energy storage into net-zero energy district systems: Optimum design and operation. *Energy* 2018;153:575–91. doi:10.1016/j.energy.2018.04.064.

[16] Aghamolaei R, Shamsi MH, Tahsildoost M. A Review of District-scale Energy Performance Analysis : Outlook towards Holistic Urban Frameworks. *Sustain Cities Soc* 2018;98:1–30. doi:10.1016/j.scs.2018.05.048.

[17] Koutra S, Ioakimidis CS, Gallas M-A, Becue V. Towards the Development of a Net-Zero Energy District Evaluation Approach: A Review of Sustainable Approaches and Assessment Tools. *Sustain Cities Soc* 2018;39:784–800. doi:10.1016/j.scs.2018.03.011.

[18] Bartholmes J. Smart Cities and Communities SCC1 - 2018 2017:24.

[19] Walker S, Labeodan T, Maassen W, Zeiler W. A review study of the current research on energy hub for energy positive neighborhoods. *Energy Procedia* 2017;122:727–32. doi:10.1016/j.egypro.2017.07.387.

[20] Ala-Juusela M, Crosbie T, Hukkalainen M. Defining and operationalising the concept of an energy positive neighbourhood. *Energy Convers Manag* 2016;125:133–40. doi:10.1016/j.enconman.2016.05.052.

[21] Tian Z, Zhang S, Deng J, Fan J, Huang J, Kong W, et al. Large-scale solar district heating plants in Danish smart thermal grid: Developments and recent trends. *Energy Convers Manag* 2019;189:67–80. doi:10.1016/J.ENCONMAN.2019.03.071.

- 783 [22] Wu W, Skye HM. Net-zero nation: HVAC and PV systems for residential net-zero energy buildings across the
784 United States. *Energy Convers Manag* 2018;177:605–28. doi:10.1016/J.ENCONMAN.2018.09.084.
- 785 [23] Ma W, Xue X, Liu G. Techno-economic evaluation for hybrid renewable energy system: Application and
786 merits. *Energy* 2018;159:385–409. doi:10.1016/J.ENERGY.2018.06.101.
- 787 [24] Flynn C, Sirén K. Influence of location and design on the performance of a solar district heating system
788 equipped with borehole seasonal storage. *Renew Energy* 2015;81:377–88. doi:10.1016/j.renene.2015.03.036.
- 789 [25] Kiviluoma J, Meibom P. Influence of wind power, plug-in electric vehicles, and heat storages on power system
790 investments. *Energy* 2010;35:1244–55. doi:10.1016/j.energy.2009.11.004.
- 791 [26] Das M, Singh MAK, Biswas A. Techno-economic optimization of an off-grid hybrid renewable energy system
792 using metaheuristic optimization approaches – Case of a radio transmitter station in India. *Energy Convers*
793 *Manag* 2019;185:339–52. doi:10.1016/J.ENCONMAN.2019.01.107.
- 794 [27] Zhang W, Maleki A, Rosen MA, Liu J. Sizing a stand-alone solar-wind-hydrogen energy system using weather
795 forecasting and a hybrid search optimization algorithm. *Energy Convers Manag* 2019;180:609–21.
796 doi:10.1016/J.ENCONMAN.2018.08.102.
- 797 [28] Hirvonen J, Sirén K. A novel fully electrified solar heating system with a high renewable fraction - Optimal
798 designs for a high latitude community. *Renew Energy* 2018;127:298–309. doi:10.1016/j.renene.2018.04.028.
- 799 [29] Hirvonen J. Towards zero energy communities: Increasing local and renewable energy utilization in buildings
800 through shared energy generation and storage. Aalto University, School of Engineering, 2017.
- 801 [30] Paiho S, Hoang H, Hukkalainen M. Energy and emission analyses of solar assisted local energy solutions with
802 seasonal heat storage in a Finnish case district. *Renew Energy* 2017;107:147–55.
803 doi:10.1016/j.renene.2017.02.003.
- 804 [31] Marczinkowski HM, Østergaard PA. Residential versus communal combination of photovoltaic and battery in
805 smart energy systems. *Energy* 2018;152:466–75. doi:10.1016/J.ENERGY.2018.03.153.
- 806 [32] Rehman H ur, Hirvonen J, Kosonen R, Sirén K. Computational comparison of a novel decentralized
807 photovoltaic district heating system against three optimized solar district systems. *Energy Convers Manag*
808 2019;191:39–54. doi:10.1016/J.ENCONMAN.2019.04.017.

- [33] Kosai S. Dynamic vulnerability in standalone hybrid renewable energy system. *Energy Convers Manag* 2019;180:258–68. doi:10.1016/J.ENCONMAN.2018.10.087.
- [34] Liu J, Chen X, Cao S, Yang H. Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings. *Energy Convers Manag* 2019;187:103–21. doi:10.1016/J.ENCONMAN.2019.02.080.
- [35] Huang Z, Xie Z, Zhang C, Chan SH, Milewski J, Xie Y, et al. Modeling and multi-objective optimization of a stand-alone PV-hydrogen-retired EV battery hybrid energy system. *Energy Convers Manag* 2019;181:80–92. doi:10.1016/J.ENCONMAN.2018.11.079.
- [36] IEA International Energy Agency. Global EV Outlook 2017: Two million and counting. 2017. doi:10.1787/9789264278882-en.
- [37] Guo C, Chan CC. Analysis method and utilization mechanism of the overall value of EV charging. *Energy Convers Manag* 2015;89:420–6. doi:10.1016/J.ENCONMAN.2014.10.016.
- [38] Statistics Finland. First registrations of motor vehicles. On-Line Stat 2018. http://www.tilastokeskus.fi/til/merek/index_en.html (accessed July 12, 2018).
- [39] sähköinenliikenne.fi. Suomen julkiset latauspisteet 2017. <http://www.sahkoinenliikenne.fi/suomen-julkiset-latauspisteet> (accessed March 17, 2017).
- [40] Ministry of Economic Affairs and Employment. Government report on the National Energy and Climate Strategy for 2030 2017:121.
- [41] Paiho S, Saastamoinen H, Hakkarainen E, Similä L, Pasonen R, Ikäheimo J, et al. Increasing flexibility of Finnish energy systems—A review of potential technologies and means. *Sustain Cities Soc* 2018;43:509–23. doi:10.1016/j.scs.2018.09.015.
- [42] García-Olivares A, Solé J, Osychenko O. Transportation in a 100% renewable energy system. *Energy Convers Manag* 2018;158:266–85. doi:10.1016/J.ENCONMAN.2017.12.053.
- [43] IEA SHC. Net Zero Energy Solar Buildings 2017. <http://task40.iea-shc.org/> (accessed January 10, 2019).
- [44] Cao S. Comparison of the energy and environmental impact by integrating a H2 vehicle and an electric vehicle into a zero-energy building. *Energy Convers Manag* 2016;123:153–73.

- doi:10.1016/J.ENCONMAN.2016.06.033.
- [45] Cao S, Klein K, Herkel S, Sirén K. Approaches to enhance the energy performance of a zero-energy building integrated with a commercial-scale hydrogen fueled zero-energy vehicle under Finnish and German conditions. *Energy Convers Manag* 2017;142:153–75. doi:10.1016/J.ENCONMAN.2017.03.037.
- [46] Kılış Ş. A net-zero building application and its role in exergy-aware local energy strategies for sustainability. *Energy Convers Manag* 2012;63:208–17. doi:10.1016/J.ENCONMAN.2012.02.029.
- [47] Deng S, Dalibard A, Martin M, Eicker U. Energy supply concepts for zero energy residential buildings in humid and dry climate. *Energy Convers Manag* 2011;52:2455–60. doi:10.1016/J.ENCONMAN.2010.12.054.
- [48] Rehman H ur, Hirvonen J, Sirén K. A long-term performance analysis of three different configurations for community-sized solar heating systems in high latitudes. *Renew Energy* 2017;113:479–93. doi:10.1016/j.renene.2017.06.017.
- [49] Rehman H ur, Hirvonen J, Sirén K. Influence of technical failures on the performance of an optimized community-size solar heating system in Nordic conditions. *J Clean Prod* 2017;175:624–40. doi:10.1016/j.jclepro.2017.12.088.
- [50] Noel L, Papu Carrone A, Jensen AF, Zarazua de Rubens G, Kester J, Sovacool BK. Willingness to pay for electric vehicles and vehicle-to-grid applications: A Nordic choice experiment. *Energy Econ* 2019;78:525–34. doi:10.1016/J.ENERCO.2018.12.014.
- [51] Alanne K, Liimatainen H. Design implications of the electrification of passenger vehicle stock on renewable energy integration in Finnish apartment buildings. *Sustain Cities Soc* 2019;47:101507. doi:10.1016/J.SCS.2019.101507.
- [52] Regan R. NREL solar cost benchmarks, 2010-2017 2018. <https://solartribune.com/residential-solar-cost-trends/nrel-solar-cost-benchmarks-2010-2017/> (accessed May 13, 2019).
- [53] Hannoschöck N. What is the average efficiency of gas water heat exchanger? 2016. https://www.researchgate.net/post/What_is_the_average_efficiency_of_gas_water_heat_exchange (accessed November 9, 2018).
- [54] Solar Energy Laboratory U of W-M. TRNSYS—a transient systems simulation program, Version 17.1, 2009–

2012 2012. <http://sel.me.wisc.edu/trnsys> (accessed November 9, 2012).

[55] Finnish Meteorological Institute. Weather and Climate in Finland 2010. <http://en.ilmatieteenlaitos.fi/> (accessed November 9, 2018).

[56] Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. *Energy Build* 2013;56:189–203. doi:10.1016/j.enbuild.2012.08.023.

[57] Hamdy M, Hasan A, Siren K. Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings. *Build Environ* 2011;46:109–23. doi:10.1097/WNF.0000000000000198.

[58] Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans Evol Comput* 2002;6:182–97.

[59] Palonen M, Hamdy M, Hasan A. MOBO A new software for multi objective building performance optimization. 13th Conf. Int. Build. Perform. Simul. Assoc. Chambéry, Fr., 2013.

[60] Palonen M, Hasan A. MOBO Beta 0.3b Manual Version 1.4 2017. <https://www.researchgate.net/publication/273307166> (accessed November 9, 2018).

[61] Hirvonen J, ur Rehman H, Sirén K. Techno-economic optimization and analysis of a high latitude solar district heating system with seasonal storage, considering different community sizes. *Sol Energy* 2018;162:472–88. doi:10.1016/J.SOLENER.2018.01.052.

[62] Nord Pool. FI-Elspot prices 2016. <https://www.nordpoolgroup.com/Market-data1/Dayahead/Area-Prices/FI/Hourly/?view=table> (accessed November 9, 2018).

[63] Cao S, Hasan A, Sirén K. On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections. *Energy Build* 2013;64:423–38. doi:10.1016/j.enbuild.2013.05.030.

[64] FinnWind. TUULE C - pientuulivoimala n.d.:4.

[65] Finnwind. Lataustuulivoimala, 1500W/48V, 12m masto 2018. <https://finnwind.fi/tuote/lataustuulivoimala-1500w-48v-12m-masto/> (accessed May 15, 2018).

[66] GREENoneTEC Solarindustrie GmbH. Large-size Collectors. 2018.

886 [67] CIT Energy Management AB. SUNSTORE 4. WP5 - European level concept study. Feasibility/simulation
887 studies. n.d.

888 [68] AXITEC Solar. AXI Power n.d. <https://www.axitecsolar.com/en/solar-modules.html> (accessed November 10,
889 2018).

890 [69] Kalamees T, Jylhä K, Tietäväinen H, Jokisalo J, Ilomets S, Hyvönen R, et al. Development of weighting factors
891 for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. *Energy*
892 *Build* 2012;47:53–60. doi:10.1016/J.ENBUILD.2011.11.031.

893 [70] Vassileva I, Campillo J. Adoption barriers for electric vehicles: Experiences from early adopters in Sweden.
894 *Energy* 2017;120:632–41. doi:10.1016/j.energy.2016.11.119.

895 [71] IHS Markit. Prices stabilize as supply and demand for Li-ion batteries begin to balance. 2018.

896 [72] Hocking M, Kan J, Young P, Terry C, Begleiter D. Welcome to the Lithium-ion Age Global. 2016.

897 [73] Williams J, Mitchell R, Raicic V, Vellei M, Mustard G, Wismayer A, et al. Less is more: A review of low
898 energy standards and the urgent need for an international universal zero energy standard. *J Build Eng*
899 2016;6:65–74. doi:10.1016/j.job.2016.02.007.

900 [74] Trafi. Car Comparison Service 2018. <http://autovertaamo.trafi.fi/?lang=en> (accessed July 11, 2018).

901 [75] Trafi. Ajamisen hinta 2018. https://www.trafi.fi/oleedellakavija/ajamisen_hinta (accessed July 11, 2018).

902 [76] Pientaloteollisuus PTT ry. Omakotitalon rakentamiskustannukset 2018 2018.
903 <http://www.pientaloteollisuus.fi/fin/rakentajalle/keskimaarainen-omakotitalo/kustannukset/> (accessed July 10,
904 2018).

905 [77] Rakentajan Tietopalvelu RTI. Valintaopas omakotirakentajalle 2018-2019 2018:194.

906

907