Environmental Aspects of Renewable Energy Sources Utilisation in Finnish Limited Liability Housing Companies

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AALTO UNIVERSITY SCHOOL OF ELECTRICAL ENGINEERING	ABSTRACT OF THE MASTER'S THESIS

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In recent years, increasing efforts are undertaken at both national and international levels in order to prevent further global warming. Electricity and heat production is the largest economic sector causing most of the greenhouse gas emissions in the world, comprising 25% of all emissions. In Finland, one third of all electricity is consumed by households, almost half of which live in residential buildings organised in the form of limited liability housing companies. Hence, in order to succeed in climate stabilisation, it is vital to focus on the largest polluter.

This thesis considers various renewable energy sources and their feasibility for deployment in limited liability housing companies. The impact of renewable energy sources on the environment is evaluated along with a possibility for them to be utilised as an additional power generating system. Moreover, this thesis itemises legal and other factors affecting or limiting small-scale electrical power generation in urban areas. Based on statistical data, the thesis provides a definition for an average Finnish limited liability housing company. Also, its base load as well as PV generation, which was identified as the most convenient for utilisation in urban areas source of renewable energy, were modelled using a developed simulation tool.

Based on the simulation results, reduction of greenhouse gas emissions in the case of solar power generation employment were compared to scenarios without solar power generation. As a result, it was possible to determine the scenarios with the most positive effect on the environment and the highest reduction of greenhouse gas emissions. The results indicate that the so-called green energy solutions may cause even more greenhouse gas emission during their lifecycle than existing large-scale decarbonised electrical power generation units. Thus, Finnish limited liability housing companies should concentrate more on the sources, from which purchased energy is produced, instead of installing small-scale renewable energy power generation units.

Keywords: Renewable energy, hydropower, photovoltaic, wind energy, biomass energy, LLHC, small-scale power generation, load simulator, carbon footprint, environmental impact, greenhouse gas, conventional power generation.

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Viime vuosina sekä kansallisella että kansainvälisellä tasolla on sitouduttu lukuisiin kunnianhimoisiin toimenpiteisiin, joilla pyritään hillitsemään ilmaston lämpenemistä. Sähkön ja lämmön tuotanto on maailman suurin kasvihuonepäästöjä tuottava yksittäinen talouden ala, joka aiheuttaa jopa 25 prosenttia kaikista kasvihuonekaasupäästöistä. Suomessa kolmasosa sähköstä kuluu talouksissa, joista puolet asuu asunto-osakeyhtiön muodossa hallinnoiduissa asuintaloissa. Näin ollen fokusointi suurimpaan saastuttajaan takaisi menestyksen taistelussa ilmaston vakauttamisen puolesta.

Tässä diplomityössä tarkasteltiin lukuisia uusiutuvia energialähteitä ja niiden soveltuvuutta hyödyntämiseen suomalaisissa taloyhtiöissä. Myös analysoitiin uusiutuvien energialähteiden käytön ympäristövaikutuksia ja arvioitiin niiden mahdollisuuksia toimia suomalaisissa taloyhtiöissä sähköenergian lisälähteenä verkkosähkön rinnalla. Lisäksi opinnäytetyössä listattiin lailliset ja muut sähkön pientuotantoon kaupunkimiljöössä vaikuttavat ja sen tuottoa rajoittavat seikat. Tilastollisen datan perusteella määriteltiin keskiverto taloyhtiö, jolle erikseen kehitetyllä simulointityökalulla mallinnettiin sen peruskuorma sekä omien aurinkopaneelien sähkön pientuotanto.

Simulointitulosten perusteella laskettiin taloyhtiön aurinkopaneelien sähköntuoton aiheuttamat kasvihuonekaasupäästöt verrattuna skenaarioihin ilman paikallista aurinkosähkön tuottoa. Lopputuloksena löydettiin skenaarioita, joilla on suurin positiivinen vaikutus ympäristöön sekä kasvihuonekaasujen vähentämiseen. Työn tulokset osoittivat, että niin sanotut vihreät energiaratkaisut saattavat aiheuttaa elinkaarensa aikana jopa enemmän kasvihuonekaasupäästöjä kuin olemassa olevat isot hiilivapaat energiantuotantoyksiköt. Näin ollen suomalaisten taloyhtiöiden pitäisi enemmän keskittyä hankkimansa energian hiilijalanjälkeen, kuin sokeasti investoida uusiutuvaa energiaa hyödyntäviin pienimuotoisiin energiantuotantoyksiköihin.

Avainsanat: Uusiutuva energia, vesivoima, aurinkosähkö, tuulivoima, biomassa, taloyhtiö, As Oy, sähkön pientuotanto, kuormituksen simulointi, hiilijalanjälki, ympäristövaikutus, kasvihuonekaasut, perinteinen sähköntuotanto.

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List of symbols

T_w	Temperature on walls
T_{in}	Indoor temperature
T_{amb}	Ambient temperature
R_c	Thermal resistance of windows
R_w	Thermal resistance of walls
C_i	Thermal capacitance of indoor air
C_w	Thermal capacitance of walls
Q_s	Solar radiation
Q_{in}	Indoor heat
Q_{ac_ht}	Heat extraction by AC or heater
$S(t)$	Thermostat performance
W_{in}	Electrical input
Q_{ht}	Heater capacity
m	Mass
C_p	Specific heat of water
T_{hi}	Upper temperature limit
T_{lo}	Lower temperature limit
η	Efficiency
P	Power

Abbreviations

AC	Air conditioner
BTU	British thermal unit
CHP	Combined heat and power
CW	Cloth-washer
CSP	Concentrating solar power
DW	Dishwasher
EC	Electronically commutated
EG	Electronic grade
EER	Energy efficiency ratio
EU	European Union
GHG	Greenhouse gas
HT	Furnace (heater)
HVAC	Heating, ventilation and air conditioning
LCA	Life cycle assessment
LED	Light emitting diode
LLHC	Limited liability housing company
PCM	Phase change material
PV	Photovoltaic
PVGIS	Photovoltaic geographical information system
SRLS	Smart residential load simulator
UI	User interface
VAT	Value added tax
WH	Water heater

1. Introduction

1.1. Background and motivation

Rapid industrialisation and intensive usage of fossil energy sources over the last hundred years have caused changes in the Earth's climate. The impact of human activities is now so obvious that the international community started setting goals for reducing greenhouse gas (GHG) emissions in order to limit global warming [1]. Similar initiatives are also promoted at both the European Union (EU) and national levels. It is worth mentioning that in 2009, the EU Renewable Energy Directive set a target for the proportion of renewable energy sources in the EU. The directive predicted that at least 20% of total energy consumption should be replaced with renewables by 2020 [2]. Furthermore, the second and more strict version of the abovementioned directive entered into force in 2018, establishing a new ambitious EU goal for 2030 of at least 32% renewable energy sources, with the possibility of revision upwards by 2023 [3]. In Finland, the government has set a target of becoming carbon neutral by 2035 [4]. Thus, Finland will become the first welfare society in the world to achieve carbon neutrality by 2035 and carbon negativity soon thereafter. Therefore, new climate and energy policies at international and national levels are here to stay and guide the further development of societies and their economies.

Electricity and heat production is the largest single economic sector causing most of the GHG emissions in the world, comprising approximately 25% of all emissions [5]. In Finland, households are the major consumer of electricity accounting for 28% of Finland's total annual consumption [6]. Almost 50% of all households live in residential buildings (blocks of flats and terraced houses) organised in the form of limited liability housing companies (LLHC) [7]. Due to the continuing process of urbanisation in Finland, the number of households living in blocks of flats has increased annually by approximately 2%. Statistics reveal that LLHCs cause most of the Finnish GHG emissions. Hence, it is vital to focus on the largest polluter in order to meet high national and international obligations to stabilise the climate.

In recent years, increasing concern over the climate change has forced energy users to switch from fossil fuels to renewable energy sources. However, the process is slow and costly. An increasing number of so-called green energy solutions are slowly but surely expanding their market share. National governments worldwide are accelerating the process of energy sector decarbonisation with the help of taxation, subsidies and new renewable energy sources. Windmills have returned to our landscapes after a hundred year break. Solar panels are now almost 300 times cheaper than just 40 years ago [8]. Nevertheless, decarbonised and renewable energy sources, such as nuclear- and hydropower, have already been available for decades. Finnish LLHCs are now facing a dilemma: Is it worth switching to stand-alone renewable energy generation? Or is it more eco-friendly to start buying energy from suppliers that produce needed energy from renewable and decarbonised sources? Is it reasonable to use photovoltaic (PV) electric energy generation in Finland? Both hydropower and solar power produce zero emissions. However, both require materials, transportation, and their disposal processes cause GHG emissions. Which of these would cause less harm to the climate in terms of GHG emissions? At the moment, these and many other questions remain unanswered.

1.2. Objectives

The purpose of this thesis is to determine the influence on the environment of using various renewable energy sources in Finnish LLHCs. In particular, the thesis will identify the most suitable and efficient renewable energy sources for LLHCs in Finland. This would contribute to Finland's ambitious intention of shifting towards a carbon neutral society.

In order to achieve this goal, the thesis studies various renewable energy sources applicable for usage in LLHCs, defines an average Finnish LLHC, and simulates its energy demand. Based on simulation results, GHG emissions will be computed and compared for different energy sources in order to identify the greenest solution from other green, i.e., decarbonised, energy solutions as well as to verify its suitability for adoption in Finnish LLHCs.

1.3. Thesis outline

The remainder of this thesis is organised as follows. Chapter 2 contains a literature review and theoretical backgrounds of numerous renewable energy sources and their potential in Finland. The same chapter also includes a brief introduction to legal and other issues concerning small-scale electric energy generation in Finnish LLHCs. Chapter 3 defines an average Finnish LLHC and its energy needs. In addition, this chapter also presents a simulation tool, simulation results and their interpretations. Chapter 4 describes the environmental impact of renewable and conventional energy sources needed to cover the energy demand of the average Finnish LLHC. Chapter 5 concludes by suggesting renewable energy sources for minimising the negative effects of LLHC energy usage on the environment in the Finnish context.

2. Renewable energy

There are various definitions of "renewable energy". However, a common interpretation may be squeezed into what is stated below. Renewable energy is a sort of energy obtained from natural environment energy flows that are replenished through recurring processes within a reasonable in a human time scale period of time.

Over the past decades, renewable energy has increased its significance relative to conventional sources of energy, which are fossil and nuclear. Over 60% of newly installed power capacity in the EU runs on renewable power sources. However, more than half of the global renewable power capacity is concentrated in developing countries [9]. Rural areas in Africa and Asia have gotten access to modern appliances without need of construction new expensive grids and other energy infrastructure. Industries involved in renewable energy development are creating millions of new jobs worldwide and cause economic growth in other economic sectors [9].

Despite its great potential, renewable energy usage might impact environment as well. Thus, it has to be investigated more in order to prevent mistakes mankind did with fossil energy sources approximately 150 years ago.

2.1. Renewable energy sources

In contrast to fossil fuels, which are considered to be a finite resource, renewable energy sources will be available as long as surrounding nature remains unchanged. So far as fusion processes in the Sun happen, its radiation will transmit created energy to Earth that will cause wind to blow, water to cycle and synthesis in plants to continue. Therefore, this flow of energy can be transformed into electricity and thus serve the mankind.

It is estimated that existing renewable power capacity worldwide generates and supplies more than 20% of global electrical energy [9]. Due to intentions to improve ecological situation in the world, the role of renewables will only increase. Renewable energy sources utilisation is based on employment of hydropower, solar and wind energy, as well as biomass energy.

2.1.1. Hydropower energy

Water has already performed work for humans for thousands of years. Ancient Greeks used to grind wheat into flour more that 2000 years ago using water wheels [10]. Even in Finland, water used to drive sawmills starting from the 14th century [11]. The evolution of the modern hydropower turbine began in the middle of the 18th century with a publication Architecture Hydraulique written by Bernard Forest, a French hydraulic and military engineer. However, only in the late 19th century hydropower became a source for generating electricity [10]. At the moment, approximately 16% of the global generation of electricity comes from hydroelectric sources. Data by countries varies from 0% in Malta, 25% in Finland to almost 96% in Norway [12].

Figure 1 shows the basic principle of hydropower, which is in using water to drive turbines with kinetic energy of water flow. Turbines are connected to a generator that supplies electricity through a transformer to a grid. Often, a hydropower plant facility contains a dam that is constructed to act as a reservoir. If needed, water can be released in various quantities according to electricity demand or level of water in the reservoir. Furthermore, a separate reservoir can be used as energy storage, i.e. pumped storage. During night periods of low electricity demand, it can be fulfilled with water using electrical power from main turbines. At the moments of peak demand, water from reservoir is released. As a result, a pumped storage provides extra power to the grid. These combinations are highly efficient and allow more flexible balancing of production and consumption of electricity.

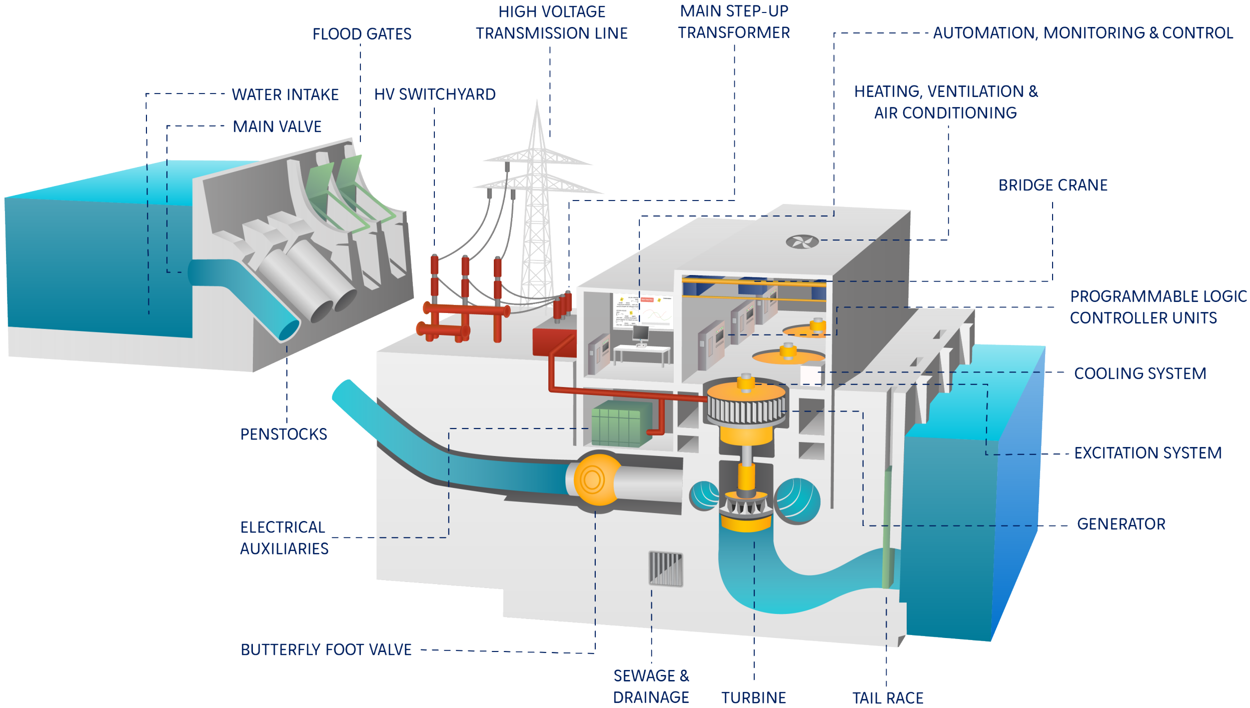


Figure 1. Basic working principle of hydropower plant [50].

However, hydropower has some disadvantages as well. There are environmental consequences of flooding large areas and damming rivers, among which preventing passage of migratory native fish. A large amount of agricultural lands are excluded from agricultural use. Changed water flow affects other flora and fauna in the region. The initial construction expenses are massive. Although dam may serve up to 100-150 years, allowing generating GHG-free electrical energy, lifetime of electrical equipment is much shorter. Hence, maintenance along with initial construction and renovations are causing GHG emission through relatively large amount of required energy and materials.

According to various scientific research, and taking into account lifetime, geology as well as expected annual electricity production, life cycle GHG emissions of hydropower plants can vary between 0.003 kg(CO_2-equiv)/kWh in mountain areas (Switzerland, Norway) and 0.033 kg(CO_2-equiv)/kWh in flat areas (Finland) [14]-[16].

2.1.2. Solar energy

Solar energy can be captured in forms of electric or thermal energy. Electric energy is obtained either directly from PV solar cells, as presented in Fig. 2, or by heating up fluids with the help of system of mirrors, depicted in Fig. 4. Steamed fluids drive turbines and thus generate electricity. Solar thermal energy is mostly collected by evacuated-tube collectors and utilised in a space and hot water heating. At the moment, approximately 3% of the global generation of electricity comes from solar energy. Data by countries varies from 0,2% in Finland, 7,9% in Germany to the world's leader Honduras with 14% of the total electricity generation [22].

Figure 2. Suvilahti solar power plant in Helsinki [17].

Solar photovoltaic technology is based on semiconducting materials that exhibit photovoltaic effect, which is illustrated in Fig. 3. It allows converting solar radiation into electricity without any other additional energy conversion steps [18]. PV effect is happening in the p-n junction between two types of semiconductor. When a light photon with sufficient energy hits a silicon atom in the boundary between two types of semiconductor, photon energy is transferred to an electron, which can now overcome this boundary. Hence, a flow of photons creates a flow of electrons in an electrical circuit.

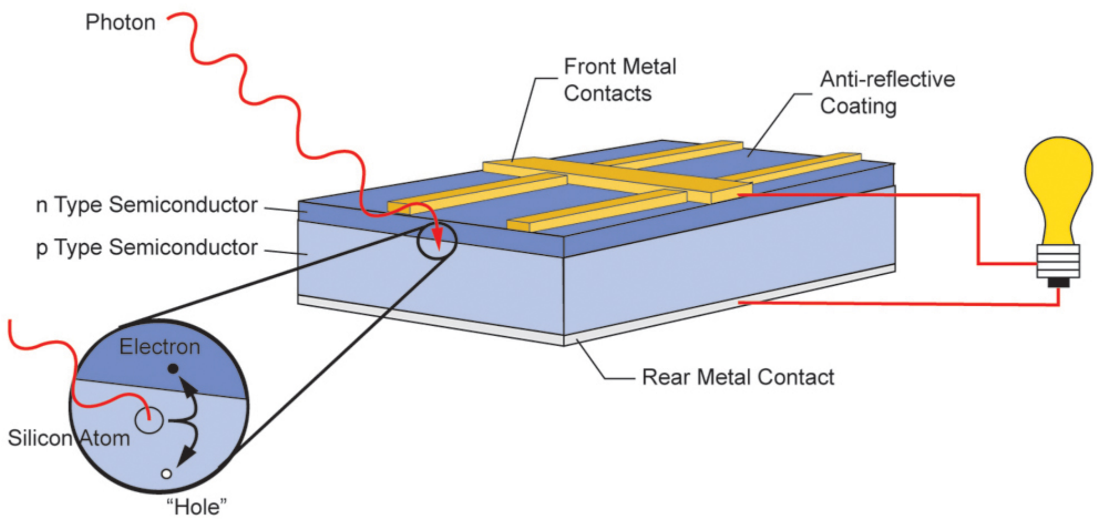


Figure 3. PV effect [19].

Electricity production from PVs does not cause direct GHG emissions in the place of solar electrical power generation. However, PVs' manufacturing process requires massive amount of materials needed to produce PV panels. Hence, mining and usage of toxic materials such as cadmium, various acids, and many other hazardous materials affects the land use, includes risks for the environment as well as produces GHG emissions. It is estimated that cumulative energy and raw materials demand for different stages of the PV panels manufacture process yields from 0,020 to 0,058 kg(CO_2-equiv)/kWh GHG emissions depending on the type of the used PV panel technology [14]-[16].

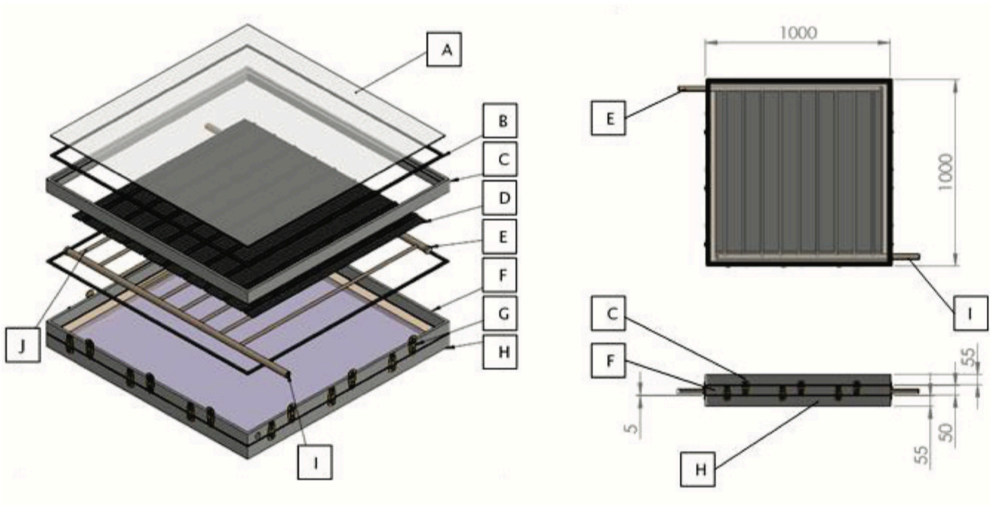
The main working principle of solar thermal electrical power generation is to concentrate sunbeams in order to produce the heat needed to rotate a turbine coupled with a generator, and thus to produce electricity. Such systems consist of two major components: mirrors and a heat receiver. Heat-transfer fluid runs through a receiver and produces steam that converts thermal energy into mechanical one in a turbine. Usually, concentrating solar power (CSP) systems have sun-tracking functionality. It allows constant focusing the sunlight on the receiver during a day. Moreover, solar thermal power plants may also have supplementary fuel system (i.e., oil or gas) that allows electricity generation during low solar activity [20]. Example of CSP (110 MW power plant near Toponah, Nevada, US) is presented in Fig. 4.

Figure 4. Concentrating solar power generation [21].

According to conducted various life cycle assessments (LCA), GHG emissions of CSP electrical power generation are at almost twice lower level comparing to PVs. Life cycle stages (i.e., raw materials extraction, materials production, plant construction, power generation, and plant decommissioning) emit approximately 0,020 kg(CO_2-equiv)/kWh of GHG emissions [23].

Solar thermal collectors absorb sunlight, and thus collect heat, which can be used for heating purposes. Such systems can be often seen in the Southern countries. However, it is also possible to utilise solar thermal energy even in Finland, although with a bit lower efficiency. This technology is not expected to develop into major energy producer. Yet, it works, saves energy that would be otherwise used for heating purposes, and thus prevents GHG emission.

Similar to CSP, solar thermal collectors use liquid circulation and can be divided into two major classes: flat-plate and evacuated-tube collectors. The first ones have flow tubes incorporated into a case with a black glass shelter with low reflectance. It allows sunlight penetrating through the cover, and heating a glycol-containing liquid inside the system of tubes. Figure 5 shows the detailed structure of the flat-plate solar collector. Glycol is used to prevent liquid from freezing. As shown in Fig. 6, due to constant circulation in the system, heat is constantly transferred to the storage, from where it is used for heating purposes, i.e., hot water as well as indoor premises heating [24].



A – glass cover, B – gasket, C – air cavity case, D – absorber plate, E – inlet line pipe, F – plate case, G – lockers, H – PCM cavity, I – outlet line pipe, J – absorber pipes.

Figure 5. Detailed view of the flat-plate solar collector [25].

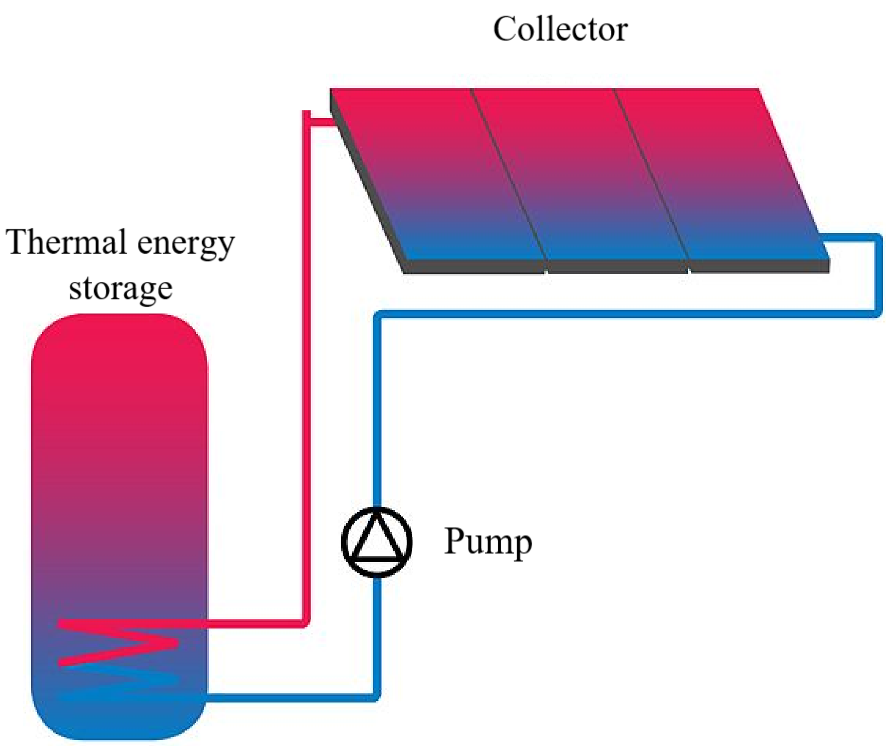


Figure 6. Basic working principle of a solar thermal collector system [24].

Evacuated-tube solar thermal collectors, shown in Fig. 7, differ from the previously described flat-plate solar collectors in efficiency during cold times of the year, and also in price of such systems. Evacuated-tube collectors consist of glass tubes with vacuum in between. This more expensive technique prevents from conductive and convective heat losses and thus allows collecting more solar thermal energy during winters. However, during warm periods, both systems perform equally [24].

Figure 7. Process of installation of evacuated-tube solar thermal collectors. [Courtesy of Kimmo Haimi]

Finally, it is worth to mention that efficiency of solar thermal collectors has already achieved 70% [24]. Meanwhile, efficiency of PVs hasn't even reached 45% during laboratory tests [26]. Efficiency of most of the PV panels available on the market fluctuates around the value of 20%. Hence, installing of solar thermal collectors would benefit its users more than PV panels, since thermal collectors are able to capture almost three times more solar energy comparing to PVs.

2.1.3. Wind energy

Similar to hydropower, people have been utilising wind energy for thousands of years. Applications such as sailing ships, water pumps, grain grinds, and even wood cutting at sawmills were widely used all over the world until the beginning of the 20th century, when transmission lines have spread electricity everywhere. Also, inexpensive and easily transferrable fossil fuels provided higher level of powers for machines, longer distances for ships. Fossils guaranteed better energy availability, since there was no need to wait for wind to blow in order to continue with any activity depending on the wind energy. However, the energy crisis of 1970s forced researchers to develop alternative and renewable sources of energy. That was the time, when wind turbines started to generate electrical energy in the large scale. Later, environmental concerns have only speeded up this process [27].

Nowadays, approximately 6% of the global electricity demand can be covered with wind power capacities [28]. World's absolute maximum of wind energy penetration is registered in Denmark. According to the Danish national transmission system operator for electricity and gas ENERGINET, in 2019 wind power has exceeded 47% of the total electricity generation. In Finland, corresponding value has reached only 7% [29].

Figure 8. Wind turbine in North Ostrobothnia province, Finland [29].

Electrical energy is produced by a wind turbine, an example of which is depicted in Fig. 8. Wind turbines consist of three key elements: a tower, a rotor, and a nacelle, which is a part between the tower and the rotor containing a gear box, a generator as well as a control unit, and monitoring equipment, as shown in Fig. 9. Wind, which contains kinetic energy due to the mass of moving air, strikes blades, and thus produces mechanical energy in the shaft. Furthermore, this mechanical energy is converted into electricity by an electrical generator. Not all 100% of kinetic energy of moving air is converted into electricity, since the air is not still after it strikes the blades of the rotor. However, max 59% of kinetic energy of moving air can be theoretically converted into electrical power [30], [31].

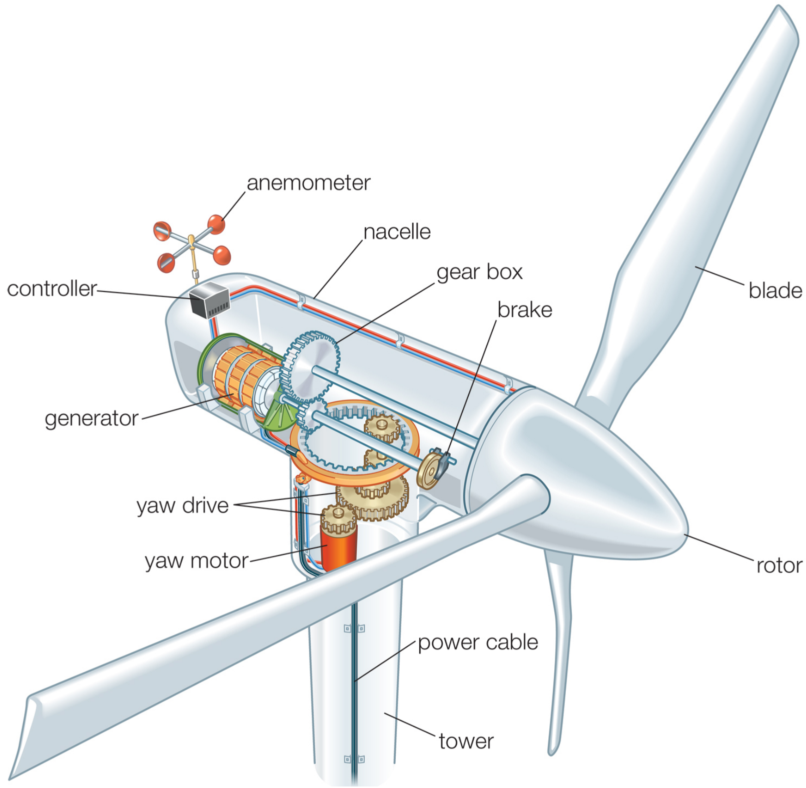


Figure 9. Mechanical construction of a wind turbine [45].

By its nature, wind is an intermittent phenomenon, and thus wind energy integration into existing power system is challenging, since a high quality wind power forecast is almost impossible to perform [30]. However, wind is sustainable and will never run out. Another problems wind power generation may cause are visual and noise pollution. Often, wind turbines are seen as a constant blot on the landscape that can be also heard even hundreds meters away depending on the wind direction. That is why local communities reject new wind farms in Finland. Nevertheless, public acceptance is slowly but steadily changing. Turbine windmills are one of the most effective solutions in reducing global GHG emissions.

Nothing comes for free. Wind energy is not an exception. In order to harvest infinitely renewable energy of wind, a large amount of raw materials have to be extracted, transported, processed and recycled after wind turbine decommission. It costs, demands energy, and thus causes GHG emissions. According to conducted studies, life cycle GHG emissions or wind power electrical generation can be averaged to 0,010 kg(CO_2-equiv)/kWh [14]-[16].

2.1.4. Biomass energy

Although firewood is a well known and was used by humans for thousands of years renewable source of energy, usage of biomass in much larger industrial scale became widespread only a few decades ago. Biomass is a general name for various sorts of energy containing products: forestry, agricultural, and municipal residues, along with crops grown specially as a fuel. Biomass energy is available in three states: solid (e.g., wood chips or straw, which are depicted in Fig. 10), liquid (e.g., vegetable oils and animal slurries that can be converted to biogas), and gaseous (e.g., biogas). Biomass is either employed for generating electricity and heat through combustion, or converted into liquid/gaseous fuels, which can be stored for later use in transportation, heat and power generation [9]. However, more than 90% of the biomass is used for heating purposes, and thus power generation is just a complimentary. Biomass energy share has increased to 19% worldwide, and reached 36% in Finland [36], [37].

Figure 10. Wood chips at the yard of CHP biomass power plant in Kerava, Finland.

Biomass is widespread in Nordic region due to developed forest industry and large wooded areas. That is why forestry residues are widely available at competitive prices in Finland and Sweden, where biomass is mostly utilised in highly efficient combined heat and power (CHP) plants [9]. A modern boiler technology provides efficiencies higher than 95%. Biomass boilers are designed for a specific type of biomass residues [33]. The general structure of a CHP biomass power plant is depicted in Fig. 11. Wood chips combustion allows obtaining heat needed for producing high pressure steam that rotate the turbine, coupled with a power plant generator. The passed steam from the turbine enters a heat exchanger of a district heating system. Thus, both heat and power are produced at one single unit.

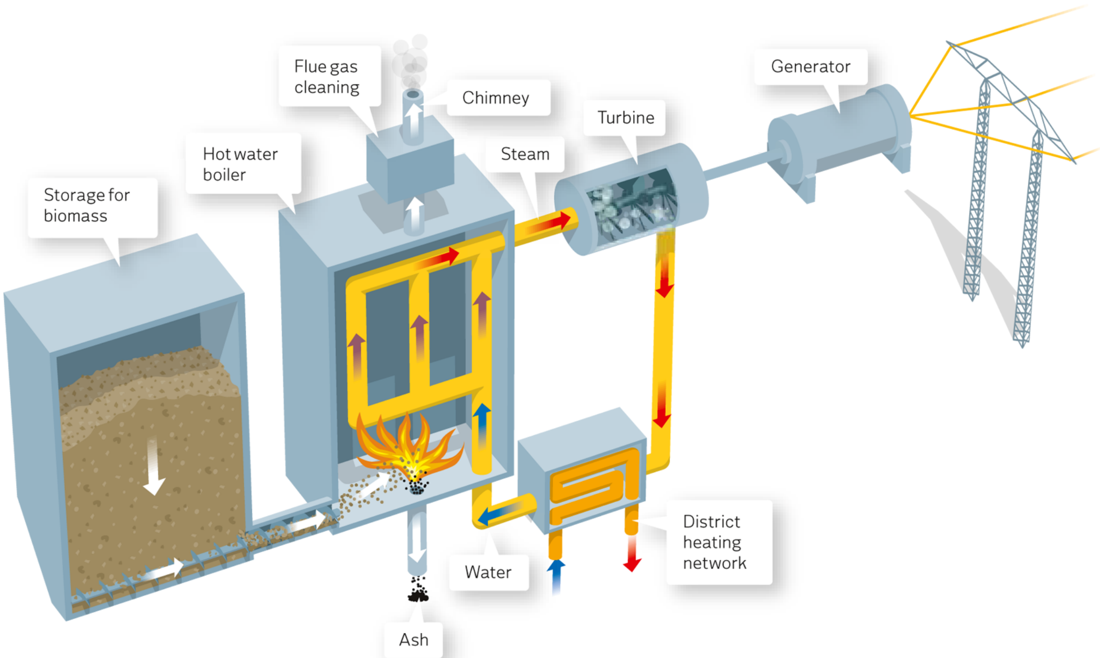


Figure 11. CHP biomass power plant working principle [51].

Fossil gasoline and diesel can be mixed or even totally replaced with liquid biofuels, which are obtained from biomass. From sugar containing plants it is possible to produce ethanol, which can be added to fossil fuels. In Finland, gasoline already contains 10% of ethanol. In Brazil, a corresponding value is 30%. Biodiesel is derived from animal or vegetable oils and even recycled cooking grease. Liquid biofuels can be utilised not only in transportation, but also for producing renewable and GHG-free heat and electrical energy in rural areas.

Another widespread form of biomass energy is biogas, which is obtained in a result of anaerobic breakdown of organic matter. This process takes approximately three weeks. Biogas by 98% consists of methane and rest 2% is carbon dioxide. Biogas reactors, on top of which spherical gas holders are located, are displayed in Fig. 12. In Finland, during last decade capacities of reactors that produce biogas has tripled [34]. Thus, biogas becomes an alternative for natural gas, which is used in CHP plants as well as industrial processes, since it can be delivered to consumers through a pipeline network or in a liquefied form. Often, biogas is also used for fuelling municipal vehicles.

Figure 12. Jepuan Biokaasu Oy biogas plant, Finland [52].

Biomass is perceived as a carbon neutral source of energy on the assumption that GHG emissions from biomass combustion are absorbed by the growth of the next generation of plants, creating neutrality that sees no new carbon created [32]. Production of biogas follows the same logic, since methane itself is a GHG, and would be anyway produced in nature during the process of organic matter breakdown. Hence, organised gradual process of biomass termination causes no harm to environment. However, life cycle GHG emissions of biomass energy power plants and biomass transportation can vary between 0,026 and 0,062 kg(CO_2-equiv)/kWh. In general, forestry as well as agricultural residues treatment leads to smaller, and obtaining ethanol for biofuels causes higher values of GHG emission from the abovementioned range [15], [32], [35].

2.2. PV electrical energy generation potential in Finland

Among various types of renewable energy sources mentioned in the previous subchapter, PVs are the most convenient for deployment in LLHCs. Solar panels can be easily located on the roofs of the existing buildings and any other types of additional premises such as garages or storages. Moreover, electrical energy produced by rooftop PV power stations can be utilised by multiple technical systems of the building, since pumps, heaters, elevators as well as air-conditioning units run on electricity. In most of the cases, installation of solar panels does not require any permission from city or energy authorities. In contrast to PVs, installation of portable wind turbines or geothermal heat pumps requires numerous approvals from local administrations. These installations have an influence on highly regulated urban landscape or underground spaces, which might be according to a local underground master plan reserved or already in use. As a result, PVs were chosen as the most suitable and promising renewable source of energy for LLHCs in Finland and thus will be examined further in this thesis.

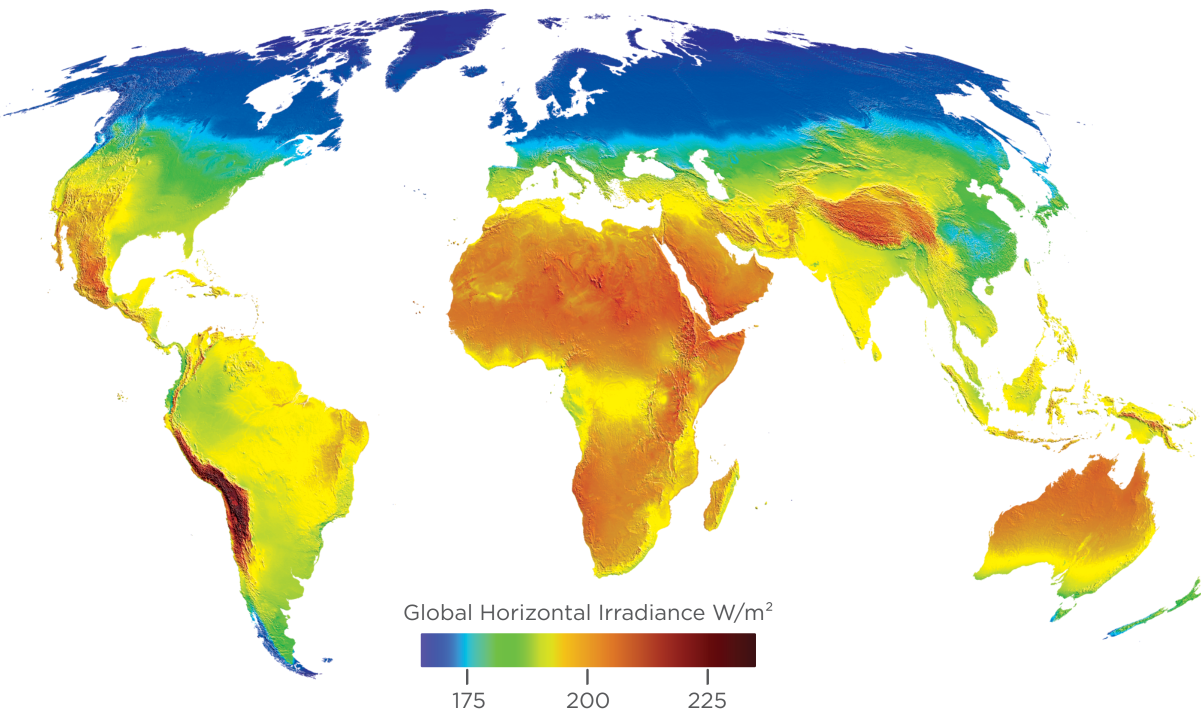


Figure 13. Global solar resource map [53].

Solar irradiance is not evenly distributed around the globe. As shown in Fig. 13, areas closer to the equator receive more solar radiation compared to higher latitudes next to the poles of the planet. However, it is possible to generate solar power with higher or lower efficiency in the every corner of the Earth. Hence, Finland is also suitable for solar power generation, even though it is located in the cold Northern Europe, where daylight availability during winters is poor. Nevertheless, cold weather conditions turn into advantage in terms of PV panel efficiency, which increases with reducing the ambient temperature [38], [40]. The same phenomenon can be tracked in other semiconductors as well. Thus, the overall potential of solar power generation in Finland is high.

It is possible to cover annual electricity consumption of Finland (81 TWh) with just 30 to 30 kilometres PV area [40], [41]. However, a significant seasonal storage would be required, due to a varying amount of solar radiation during a calendar year. Figure 14 illustrates that an average daily irradiation to Southern Finland is 2,47 kWh, which is 901,55kWh over a year [40]. Global annual irradiation in Finland and Germany differs by only 10%. However, Germany obtains 7,9% of its electricity from PVs, when Finland only 0,2% [22]. The gap is massive and forecasts a rapid growth of solar power generation in the nearest future. Taking into account constantly decreasing prices of PVs, Finland is now on the verge of PV breakthrough.

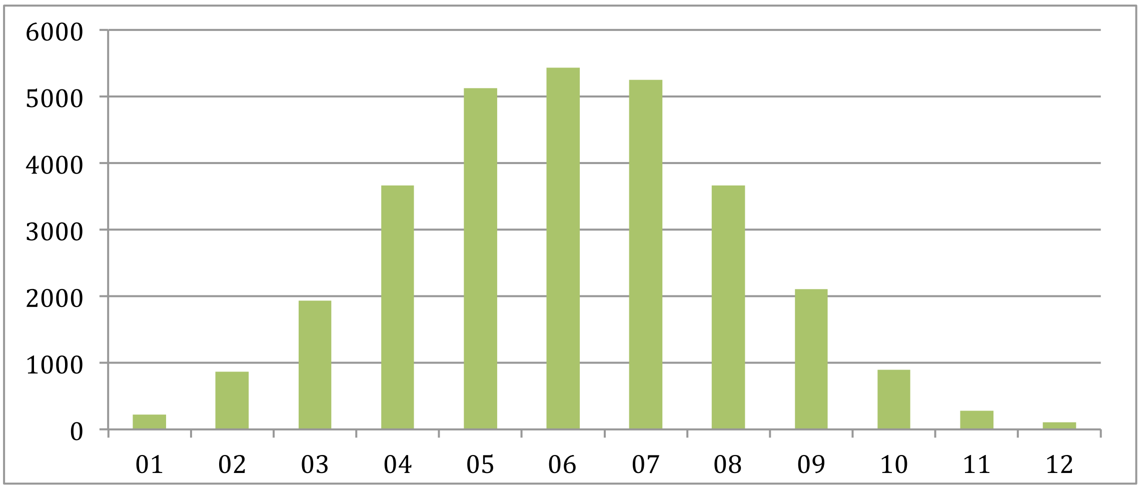


Figure 14. Average daily irradiation energy to Southern Finland (Wh/m^2, month) [40].

One of the reasons for more advanced level of PV power generation in Germany is in feed-in tariff system, which was first applied already in 1990 [42]. Special feed-in tariffs for surplus electricity generation allowed reducing the payback time of PVs, and thus making them more attractive for German LLHCs. In Finland in the beginning of 2020, there is not any feed-in tariff system for PV power generation. Therefore, a solar power generation is still in its infancy stage in Finland in comparison to Germany not due to the actual difference in irradiation, but due to the governmental energy policy of the last decades. Figure 15 illustrates examples of solar radiation in certain European cities and definitely proves high potential of PV electrical energy generation in Finland.

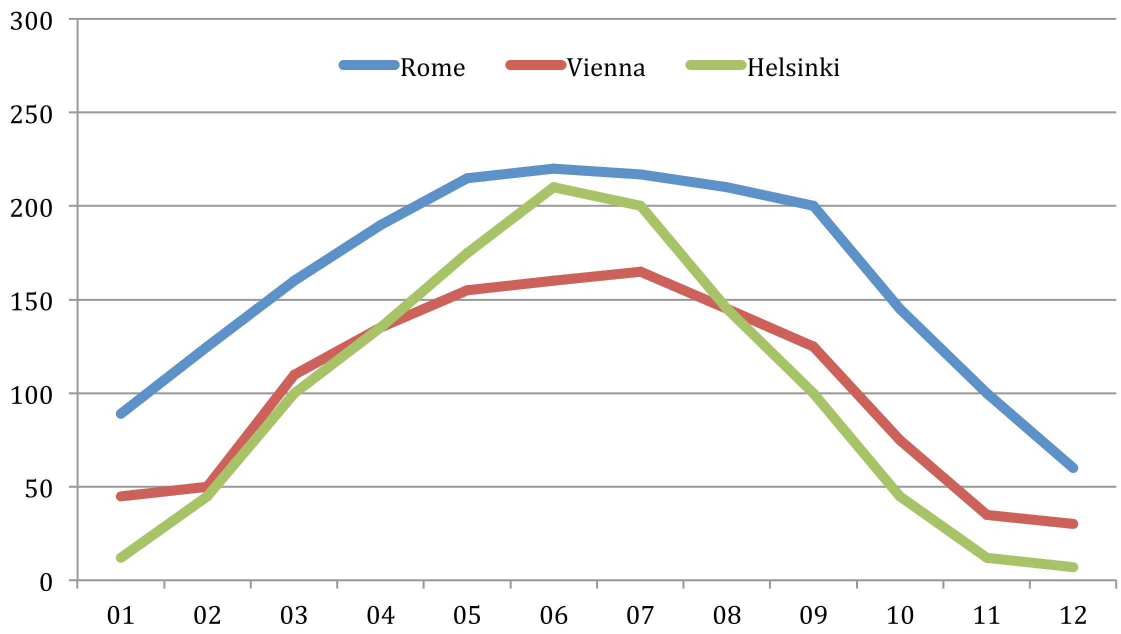


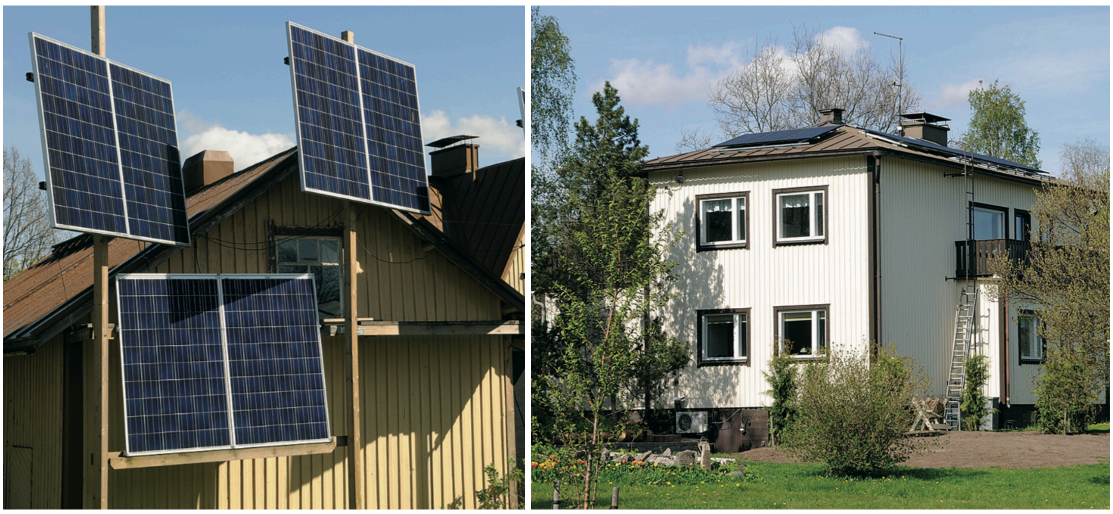
Figure 15. Examples of solar radiation in European cities (kWh/m^2, month) [40].

In Finland, most of the buildings are residential buildings with the total residential area of 273420000 m^2. Rough evaluation would give a total roof area of 244890000 m^2. If one fourth of the total roof area faces the South, and at least 60% of it can be utilised for PVs, then potential electricity harvest of solar panels would be around 3 TWh a year. This is almost 4% of the total electricity consumption in Finland. Furthermore, solar power generation can be increased by covering roof areas of commercial and public buildings, as well as walls facing the South with PVs [40].

2.3. Legal and other issues of small-scale PV electrical energy generation in Finland

Finnish legislation defines the maximum power for microgeneration installation at the level of 100kW with annual electricity generation of 800 MWh. In Finland, such small-scale PV electrical energy generation used for covering one's own electricity demand is not charged with any tax. Hence, it is completely tax free to generate electricity for LLHC's own needs as well as selling the surplus to the grid within the previously defined limits [43]. However, the amount of electricity exported to the grid cannot exceed the amount of imported from the grid electricity. If the export-import balance is positive, the electric power producer is obligated to pay an income tax. Any tax as well as its administration affects the payback time of PV panels, and thus making them less attractive to LLHCs.

Figure 16 shows a PV installation in urban areas in Finland. PV panels can be installed without any restrictions on the top of roofs if they do not generate inconvenience to neighbours and cause no major changes to the architecture of the building itself or general view on the street. Installations on the top of historic buildings are not prohibited either. However, historic status of the building sets certain limitations. Thus, the local historic preservation board has to study the case and approve/reject PV installation application. Nevertheless, practice shows that historic preservation and energy efficiency can go hand in hand.



(a) (b)

Figure 16. Inappropriate (a) and decent (b) installation of PV panels in urban area [54].

Prior to installation of solar panels, it is also necessary to negotiate with a local grid company terms and conditions for electricity surplus supply to the grid. Usually, all the surplus generation is purchased at Nord Pool spot price, examples of which are provided in Fig. 17. However, it is worth to mention at this point that PV electricity should be utilised in LLHC in full measure. Possible electricity export to the grid would significantly affect the payback time of PVs. It is due to a dramatic difference in prices of purchased and sold electricity. When importing electricity from the grid, the electric energy unit price also includes service fees, transmission tariff, electricity tax and value added tax (VAT) on top of the Nord Pool spot price. Thus, the final price of imported from the grid electricity would be 3-4 times higher than the compensation obtained from the grid company for surplus electric power delivered to the grid.

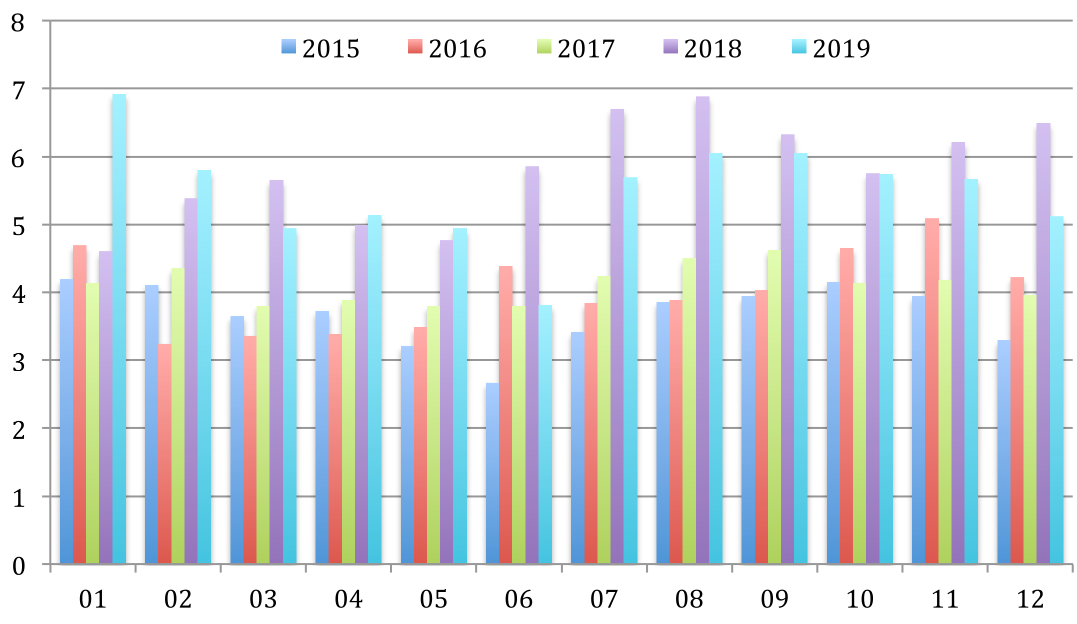


Figure 17. Nord Pool statistics of average monthly electrical energy spot prices (c/kWh).

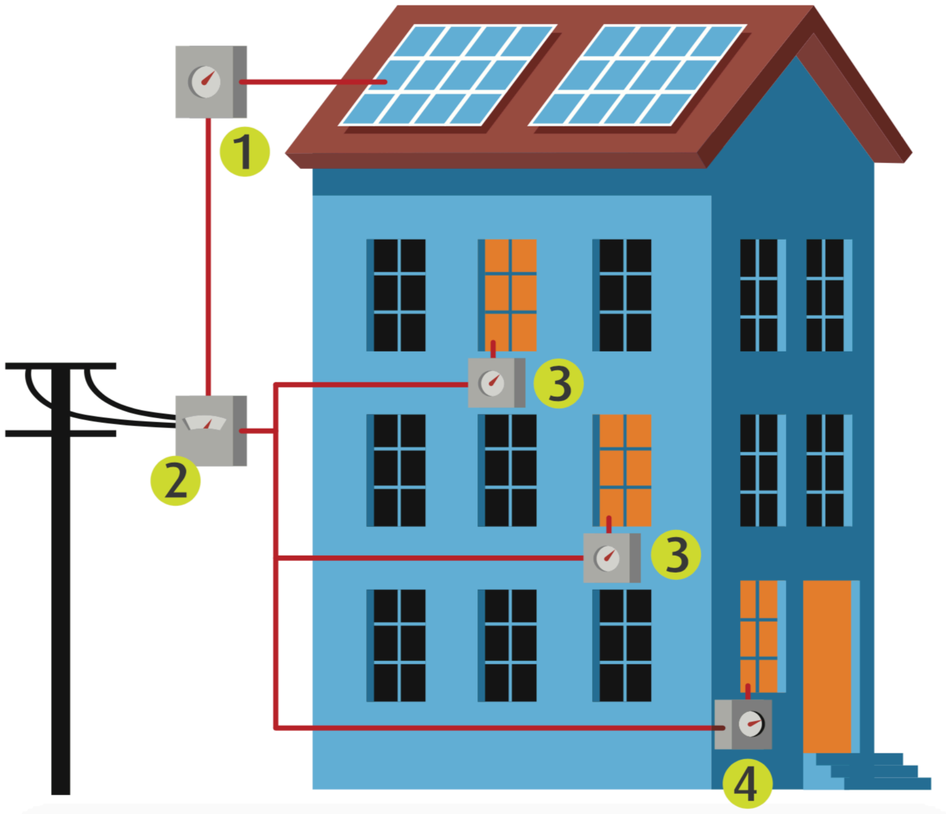
As it can be observed from Fig. 14 and Fig. 15, solar radiation in Southern Finland is at its maximum level during daytime periods in summer. At these particular moments, energy demand in LLHC is minimal, since most of residents are at work or on vacation, use of hot water is down to zero, and there is no need to light corridors and stare-cases since it is bright outside. This is challenging for solar power utilisation in LLHC during periods of maximum generation of power.

One of the solutions to the abovementioned problem is in employment of generated solar power not only for common LLHC needs (e.g., ventilation, heating, water pumping, lighting), but also in residential apartments. Unfortunately, local grid company electricity meters form a barrier for the proposed scenario.

Electricity distribution in LLHC has a star topology, where each user (e.g., a residential apartment or a LLHC itself) is connected to a central power unit throughout an electricity meter owned and administrated by a local grid company. The central power unit is supplied by a local grid. Such structure of LLHC electric power network is defined by Finnish legislation, stating that each user of electricity has a right to freely choose electricity supplier [44]. That is why each user is provided with an individual electricity meter. Every time electricity is transmitted from one user to another within the same LLHC electricity distribution network, electrical power is considered to be exported to the grid (and thus owned by a grid company), and then sold to another user according to an actual pricelist. Hence, existing legislation as well as LLHC electricity distribution network structure does not promote full-scale PV power generation utilisation in LLHC.

In fact, it is possible to exclude individual electricity meters from LLHC electricity distribution network, yet it demands unanimous consent of all stakeholders (i.e., owners of the LLHC) [44]. In such case, there will be only one owned by a local grid company electricity meter at the enter point to the LLHC inner grid. Such solution would facilitate unlimited flows of electrical energy inside of the LLHC electrical network. Thus, solar power generation will be fully employed by the LLHC itself as well as by all the residents. Therefore, there will be no more need to export electricity surplus to the grid, when power generation is at maximum level. Despite higher level of solar power generation deployment, it will be necessary to create its own electricity meter system within the LLHC. It would allow to charge electricity consumed by residents, when LLHC's own power generation will not cover the total power demand. Figure 18 shows the utilisation of LLHC owned electricity meters. Installation and administration of the abovementioned smart electricity meter system would cause extra expenses, and thus prologue the payback time of the installed

PV power generation system. An example of the proposed smart electricity meter system is displayed in the figure below: 1, 3 and 4 represent smart electricity meters owned by LLHC; 2 is a main electricity meter owned and administrated by the local grid company.



1,3 and 4 – smart electricity meters (LLHC); 2 – main electricity meter (local grid operator)

Figure 18. Utilisation of LLHC owned smart electricity meters [54].

According to the facts mentioned in this subchapter, solar power generation in Finland in urban areas can become more widespread in the nearest future, due to the absence of visible legal or any other obstacles to that. It would reduce the amount of electrical energy LLHC have to purchase for its own needs. Consequently, an environmental impact caused by LLHC energy consumption will be reduced. Of course, it would be a right step towards carbon neutral society, for which Finland along with other developed countries is aiming.

3. Load simulation

3.1. Defining of an average limited liability housing company in Finland

Currently, there are a bit more than 3 million dwellings in Finland, and their amount is constantly growing by almost 30 thousand annually [46]. As mentioned earlier, 50% of all dwellings are apartments in blocks of flats and terraced houses [7]. It is estimated that there are in total more than 50 thousand blocks of flats in Finland, which were built in the period 1880-2000. A vast amount of them are built in the Helsinki Metropolitan Area and have 3-4 storeys [47]. As Fig. 19 depicts, the majority of dwellings are located in the buildings constructed in the 60-80s of the 20th century. Thus, it allows to perform the first relevant assumptions about an average LLHC: it is a 4-storey building, completed in the 70s, it is located in Helsinki and consists of approximately 30 apartments. Usually, blocks of flats built in that period of the 20th century have 2-3 apartments on the floor in the staircase. Hence, an average LLHC would have 4 staircases with 2 apartments on each of 4 floors, giving us all together 32 apartments in an average residential building, an example of which is shown in Fig. 20.

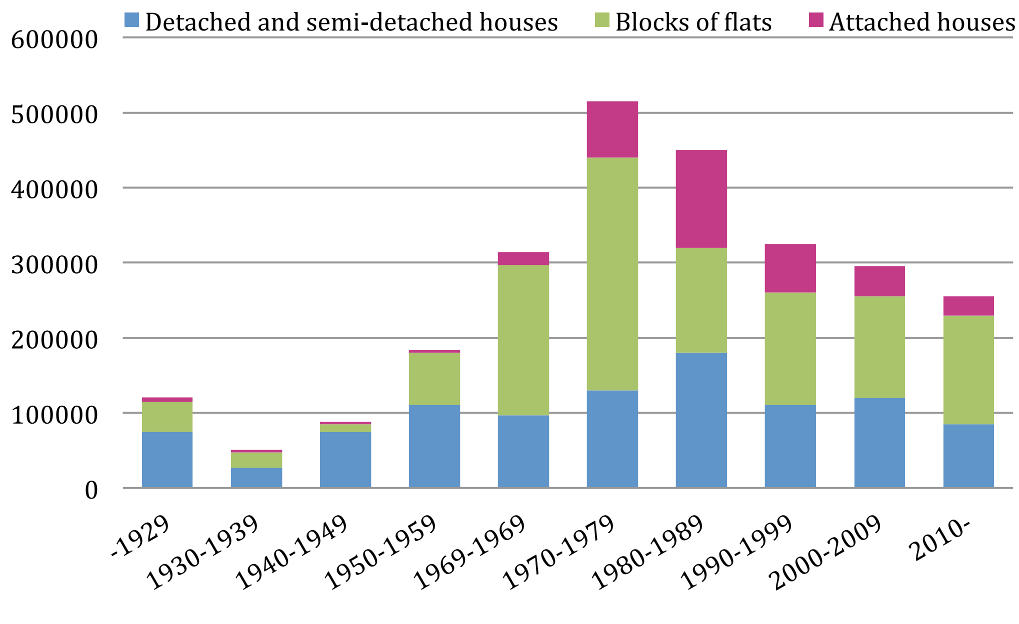


Figure 19. Household-dwelling units by building type and completion decade [48].

Figure 20. An average residential building completed in 70s.

Since the average LLHC is now defined on the basis of available statistics, it is now relevant to provide assumptions about the loads in the building that would demand electric power.

Typically, blocks of flats completed in the 70s are connected to a district heating system and have quite minimal level of technical equipment, which have to be powered by electricity. District heating is used to provide domestic hot water to residents all year round as well as for heating indoor premises during winters. For this reason, a special heat exchanger, as shown in Fig. 21, is installed in the technical premises on the ground floor. Electrical energy is needed for running various pumps as well as controlling general work of all systems of the heat exchanger in order to alarm in case of any technical failure. Any unexpected pauses in the work of pumps during heating season may cause freezing of liquids in the pipes of the building heating system and thus cause large as well as expensive damages. Therefore, approximately 1 kW of electric power would be constantly needed during heating periods, and 0,5 kW when only hot water is delivered to residential apartments.

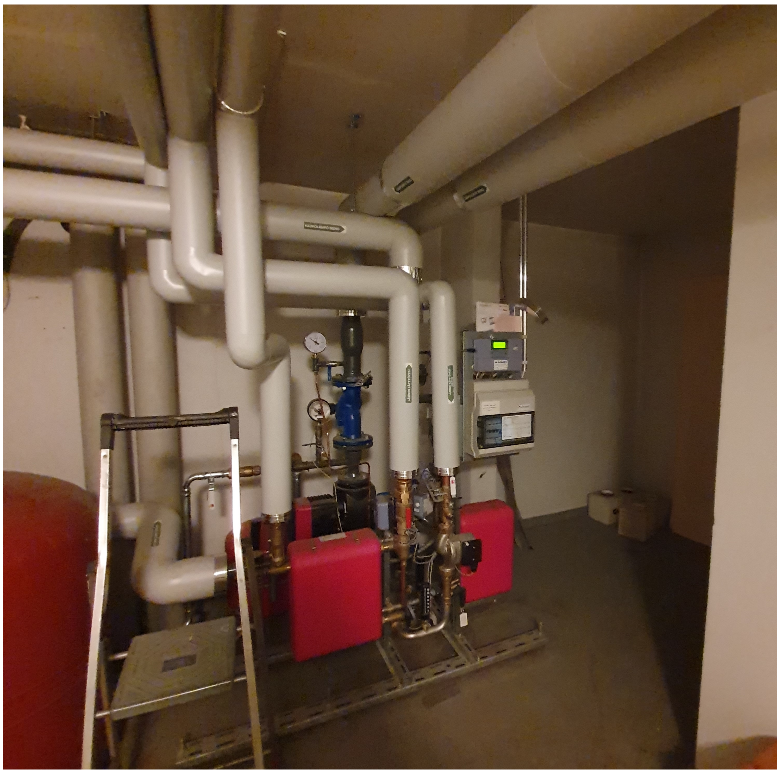


Figure 21. District heating system heat exchanger unit in the typical residential building completed in 70s.

Each staircase of the previously defined average LLHC includes an elevator, which is powered by an electric machine. A typical residential building elevator motor would consume approximately 3 kW of electric power when in use.

Nowadays, ground floor corridor as well as staircase lighting do not require much power due to advanced LED technologies. However, power of 0,1kW would be a proper estimate for single staircase lighting power consumption. For outdoor lighting during nights, an estimate of 0,5 kW would be adequate.

Finally, another technical system in residential buildings, which is powered by grid electricity, is ventilation. The most common form of ventilation for dwellings completed in the 70s is mechanical exhaust ventilation, where the used air is removed from dwellings by a rooftop ventilator, depicted in Fig. 22, and replacement air comes from air inlet valves. Mechanical ventilation is considered to be better for ensuring a proper air exchange during all seasons than natural ventilation. In most of the cases, mechanical ventilator is installed on top of the ventilation channels, coming from a stack of apartment units. Thus, one stack of residential apartments requires only one single ventilator (i.e., an electronically commutated (EC) motor) that runs 24/7 consuming approximately 0,5kW of electric power. In addition, a separate ventilator is placed on top of each staircase. Then, a total amount of ventilators needed for one staircase of the average LLHC would be 3. In addition, a couple of separate ventilators would provide ventilation to ground floor technical premises. That would result in 14 ventilators for the whole residential building, with a total power consumption of 7kW.

Figure 22. Example of a typical mechanical exhaust ventilation rooftop unit.

Of course, there might be also other types of loads along with corresponding powers. Moreover, the electrification of parking slots is completely excluded from the calculation assumptions due to the nature of car heaters usage, which are most often operated during dark winter mornings, when rooftop PV generation would be equal to zero. Thus, the assumptions are made to represent the most general and basic loads that would be definitely found from any resident building completed in 70s.

The relevant information about discussed in this subchapter loads of the average LLHC is listed in Tab. 1, which presents usage of the assumed loads during a summer period on a 24-h horizon.

Load type	Power, kW	Duration of use, min	Remarks
Heat exchanger	0,5	1440	Constant load 24/7
Elevator unit	3	1	One ride travel time
Staircase lighting	0,1	5	Staircase motion detection sensors used
Outdoor lighting	0,5	240	Night-time
Ventilation	7	1440	Constant load 24/7

Table 1. Specifications of LLHC loads.

3.2. Smart Residential Load Simulator (SRLS)

Combining smart grids with renewable energy sources can be beneficial for both economics and environment. Moreover, it would allow to improve efficiency of smart grids, providing better employment of existing assets, reducing dependence on imported energy as well as enhancing power quality and thus resulting in creating a market force containing substantial economic value [49]. In order to accelerate the growth of the smart grids' sector, their advantages have to become more obvious to all stakeholders involved, especially households, which cause almost 30% of Finnish GHG emissions and thus are considered to be the largest polluter [6].

Peak demand reduction along with energy consumption optimisation has been in scope of researchers for quite a while. In fact, a simple scheduling of some appliances may reduce energy costs and total emissions without a major impact on comfort of the costumers. Scheduling can be also combined with paying closer attention to the influence of spot prices of energy. Therefore, a complex linear programming model can be developed in order to minimise costs of energy and maximise the level of comfort of residents.

There are various approaches in designing appliance-level load models for load management purposes. They can be based on the previously collected statistical data to predict the load-shape of the demand. On the other hand, such simulators can be created for modelling certain systems only (e.g., HVAC, lighting), or for modelling the impact of abovementrioned systems on a thermal energy demand in residential buildings. Nevertheless, none of the existing tools or developed approaches takes into account other appliances installed and used in dwellings. Moreover, some of the existing simulators are not user-friendly at all [49].

Consequently, there is a clear need for simulators with a user-friendly user interface (UI) allowing understanding how appliances interact with each other with respect to energy consumption [49]. For this reason a Smart Residential Load Simulator was designed by a group of researchers at the University of Waterloo, Canada.

The proposed SRLS can facilitate studying, demonstrating and evaluating of numerous energy management strategies for residential buildings. Its user-friendly graphical interface enables simulation of optimal on/off decisions of appliances that can be often seen in residential buildings in Canada. Residential energy profiles are studied on a 24-h horizon, and local renewable energy generation (e.g., battery energy storage, PV and wind generation) is also considered [49]. The developed simulator is a relevant example of MATLAB-based program representing the most important loads along with sources of energy. It will be studied properly in this thesis in order to be used as an example for a similar model for the energy demand simulation of the previously defined average Finnish LLHC.

3.2.1. User interface

Figure 23 shows the SRLS complete graphical UI, which contains individual windows for house appliances that can be simulated either separately or as a group.

Characteristics of the residents (i.e., number, age as well as occupation) have an influence on the relevant appliance models, for instance the residential building thermal model and hot water consumption, and thus can also be modified and modelled. User-defined inputs, such as ambient temperature (has a crucial impact on energy consumption), price of electrical energy (facilitates real-time pricing), play a vital role in consumption of energy and its price for the households, and therefore are also considered in the simulation tool.

Figure 23. SRLS graphical UI [49].

The simulation results window is presented in the Fig. 24. As can be observed, the depicted results include consumption along with local generation by appliances and energy sources. Moreover, energy consumption as well as generation profiles can be plotted individually for each type of load and source of energy. Some of the model inputs, such as charge and discharge profiles of the energy accumulating battery storage, can be also illustrated. Furthermore, tables containing relevant data on energy consumption/generation along with costs of consumed/generated electrical energy are detailed. In conclusion, natural gas data can be also added to the results plot if it was chosen as a primary source of energy for the residential house furnace.

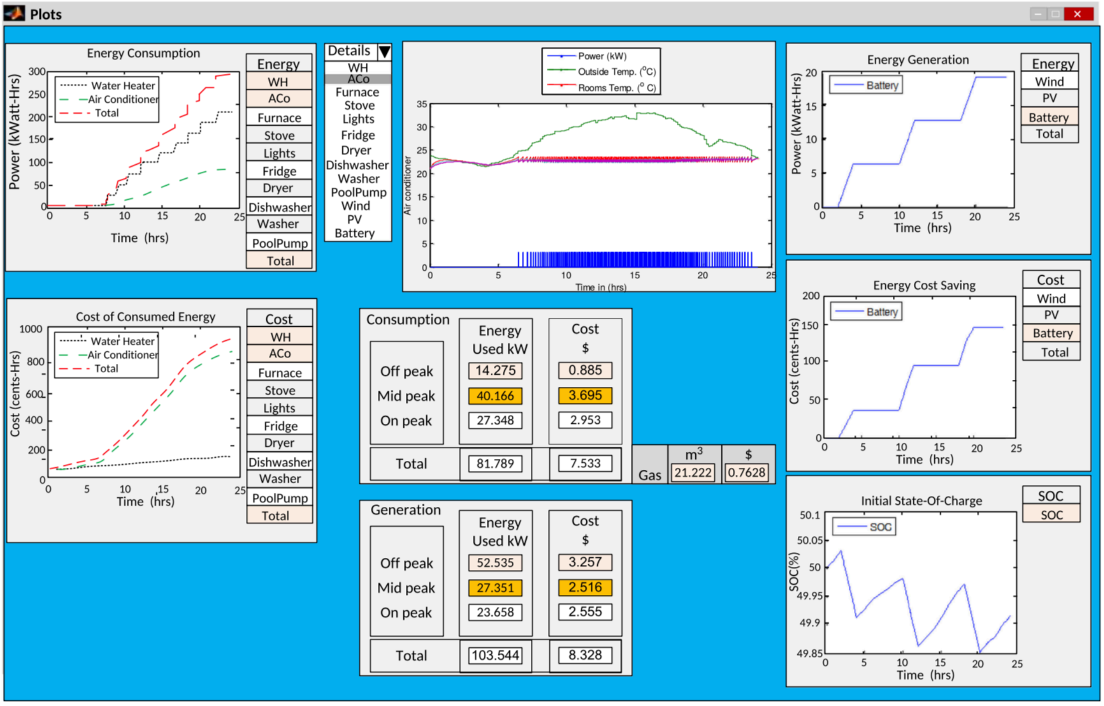


Figure 24. Results of the simulation [49].

The following subchapter provides explanations for the models of household appliances employed in the simulator as well as sources of energy.

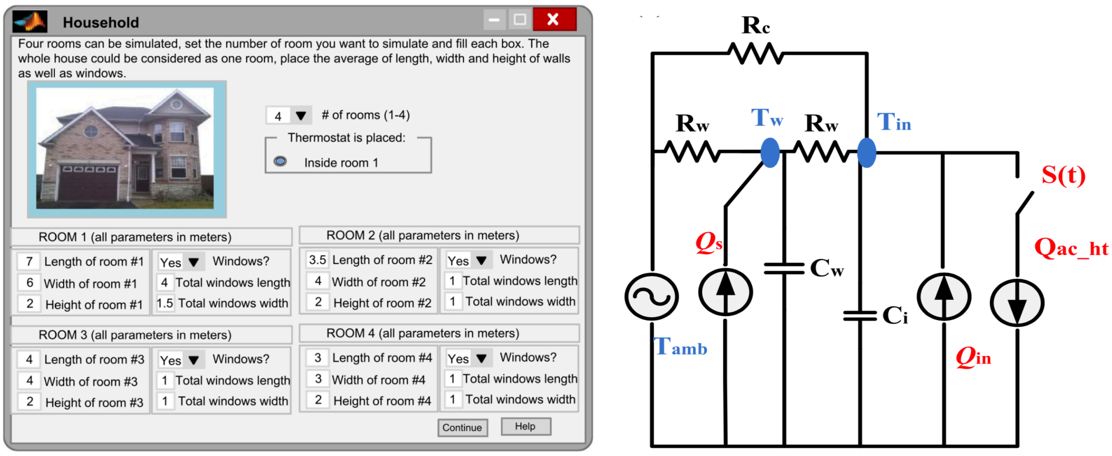
3.2.2. Models for appliances

Thermal performance of the residential building is affected by the properties of the materials, from which it is constructed. Walls with windows, a roof and a floor can be modelled in thermal circuit model using their values of central thermal conductivity. The number of rooms, their geometry as well as the location of the thermostat also influences the total energy consumption of the house. Due to the abovementioned reasons, a graphical interface of the household model is organised as depicted in Fig. 25 (a).

A thermal circuit model of one single room is shown in Fig. 25 (b). In addition to the ambient temperature T_{amb} includes also capacitance of the walls C_w and indoor air C_i, thermal resistance of windows R_c and walls R_w, and the furnace or AC system thermal source Q_{ac_ht}. This model enables computing of the temperatures of the room T_{in} as well as walls T_w. The set of equations below represent the dynamics of the temperature, which can be also obtained from the thermal circuit model of a room:

$$\frac{dT_w}{dt} = \frac{Q_s}{T_w} + \frac{T_{amb}}{R_w C_w} + \frac{T_{in}}{R_w C_w} - \frac{2T_w}{R_w C_w}$$
$$\frac{dT_{in}}{dt} = \frac{(Q_{in} - Q_{ac_{ht}})S(t)}{C_i} - \frac{T_{in}}{C_i}\left(\frac{1}{R_w} + \frac{1}{R_c}\right) - \frac{T_w}{R_w C_i} \tag{1}$$

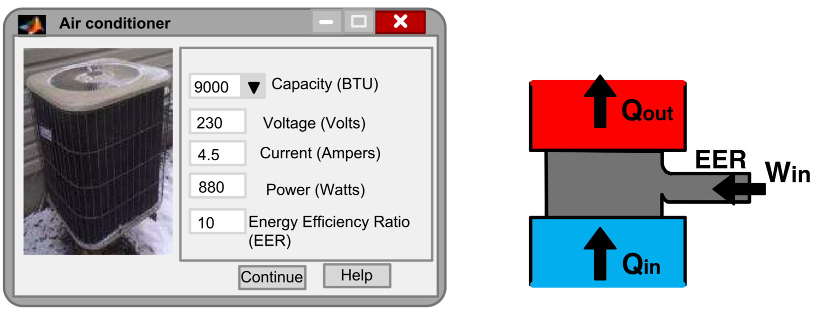
where $S(t)$ is a binary variable describing the state of the heating/cooling device [49].



(a) (b)

Figure 25. Graphical interface (a) and room thermal circuit model (b) [49].

Often, the cooling capacity of an AC is specified in terms of British thermal units (BTU). It is the amount of energy required by AC equipment to regulate humidity and the temperature of the indoor air in the building [49]. Moreover, it is also possible to define other characteristics of the AC model as shown in Fig. 26(a).



(a) (b)

Figure 26. Graphical interface (a) and Carnot machine representation (b) of AC [49].

The heat-flow diagram in Fig. 26(b) represents the model of an AC. Energy efficiency ratio (EER) defines the cooling effect provided by the AC as follows:

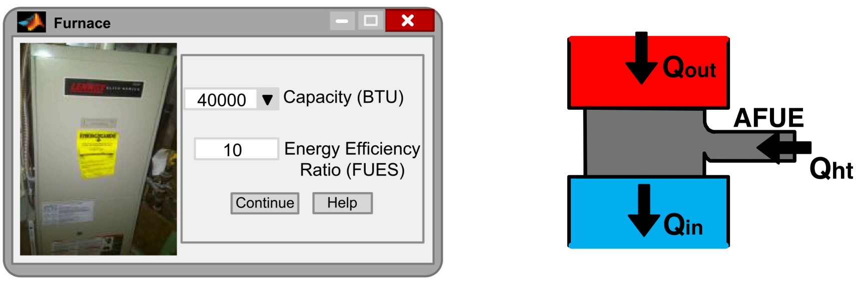
$$EER = 3{,}412\frac{Q_{in}}{W_{in}} = 3{,}412\frac{Q_{in}}{(Q_{out} - Q_{in})} \tag{2}$$

where Q_{out} is the amount of energy needed to extract the surplus Q_{in}, and W_{in} stands for required electrical energy to perform this work [49].

The utilisation of gas furnaces (HT) is rather widespread method for heating the indoor air in the houses all over North America. Natural gas is used as a primary source of energy. The SRLS simulation tool furnace graphical interface is presented in the Fig. 27 (a). The Carnot machine representation of HT is depicted in Fig. 27(b), where AFUE stands for the annual fuel utilisation efficiency. The thermal model of the furnace can be computed using the following equation:

$$AFUE = 3{,}412\frac{Q_{in}}{Q_{ht}} = 3{,}412\frac{Q_{in}}{(Q_{in} - Q_{out})} \tag{3}$$

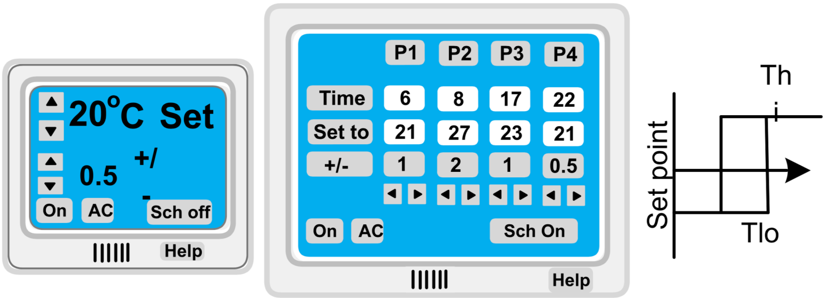
where Q_{ht} represents the HT capacity, and Q_{in} represents the indoor air heat [49].



(a) (b)

Figure 27. Graphical interface (a) and Carnot machine representation (b) of HT [49].

Programmable thermostats are employed whenever AC and HT are utilised in the household. Such thermostats allow to adjust the temperature of indoor air at different periods of the day and according to user preferences. Moreover, the desired temperatures can be scheduled in advance according to the rhythm of life of tenants.

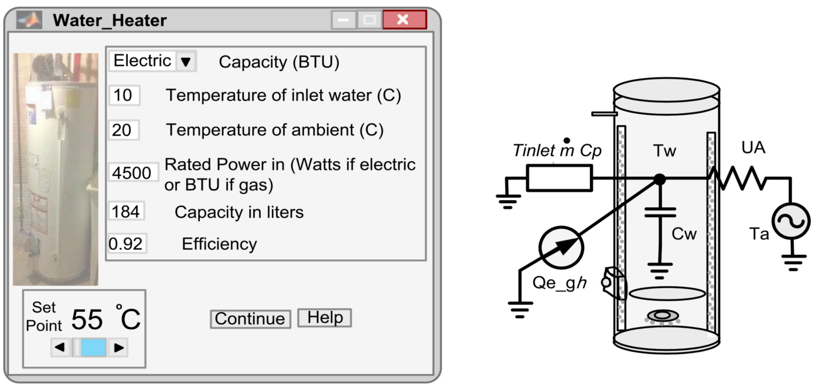


(a) (b) (c)

Figure 28. Graphical interfaces of non-programmable (a) as well as programmable (b) thermostats. Thermostat delay representation (c) [49].

The SRLS simulation tool considers both conventional and programmable thermostats, shown in Fig. 28 (a) and Fig. 28 (b). A programmable thermostat in addition to desired temperatures allows to specify periods of time along with temperature fluctuations in the residential building. The thermostat model, presented in Fig. 28(c), illustrates its basic working principle, showing that thermostat maintains the house temperature within the set upper and lower limits of the temperature.

Cylindrical storage tank water heater (WH) covered by thermally insulated metal sheets is the most common WH type used worldwide. The SRLS simulation tool combines both gas and electric WH models. The WH graphical interface, shown in Fig. 29 (a), recognises a few user inputs, such as inlet water and ambient temperatures, rated power in Watts (electricity) or BTU (natural gas) as well as WH tank capacity and estimated efficiency.



(a) (b)

Figure 29. Graphical interface (a) and thermal circuit model (b) of the WH model [49].

The WH thermal model can be considered as a classical thermal model already discussed in the thesis. Figure 29(b) represents the WH model thermal circuit that consists of the mass of water m, heat conducting characteristics of insulation materials C_w (UA), specific heat of water C_p and input power Q_{e_gh}. The WH energy flows implemented in the model can be represented by the following equation:

$$\frac{dT_w}{dt} = \frac{mC_p}{C_w} T_{inlet} + \frac{UA}{C_w} T_{amb} - \frac{UA + mC_p}{C_w} + Q_{e_gh}\eta \qquad (4)$$

where T_w is the tank wall temperature, T_{amp} is the ambient temperature, T_{inlet} is the temperature of running water and η is the efficiency of the WH [49].

The SRLS allows to define periods of time and intensity of the stove utilisation, as shown in Fig. 30. Thus, a straightforward multiplication of time and power would produce the value of electrical energy consumed during a day.

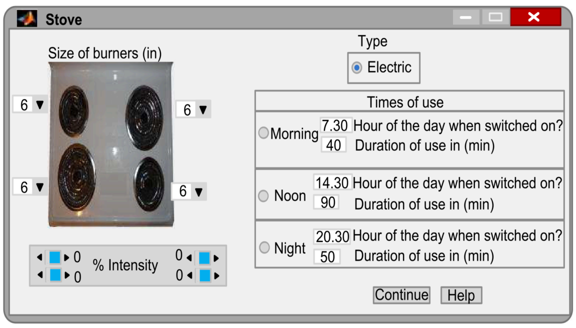


Figure 30. Graphical interface for the model of stove [49].

Although lighting nowadays is not a major consumer of electricity in residential buildings, it is also considered in the SRLS in order to build as precise simulation model as possible. Lighting system graphical interface, which is depicted in Fig. 31, includes information about the type and number of light bulbs, electric power of the light sources as well as duration of their daily use. On the basis of the abovementioned quantities, a total energy consumption can be readily computed.

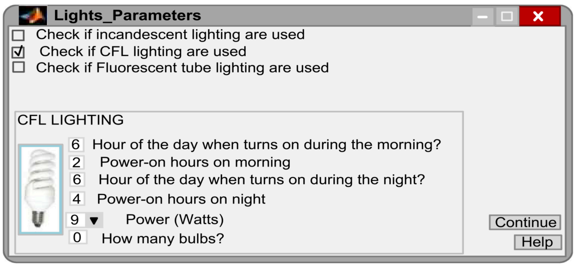


Figure 31. Graphical interface for lights parameters [49].

The main features of the refrigerator can be defined in its graphical interface, as shown in Fig. 32. The thermal circuit model is similar to the previously described appliances and thus is modelled in a similar way.

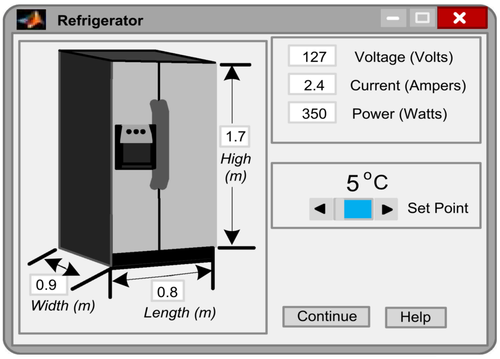
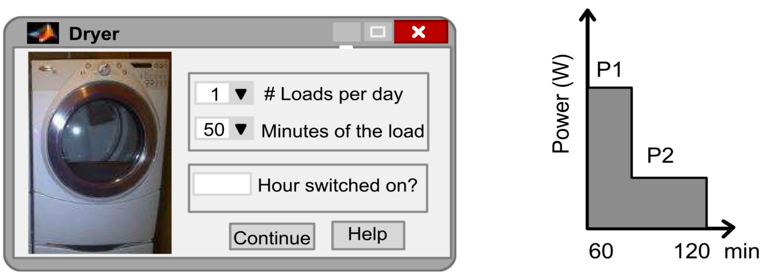


Figure 32. Graphical interface for refrigerator [49].

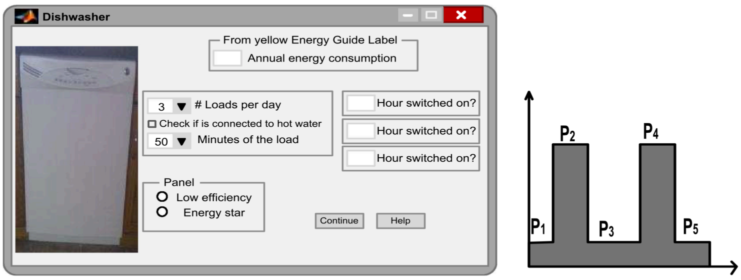
Since electrical dryers consume enormous amounts of energy, they are also considered in the SRLS. Figure 33(a) depicts a graphical interface, where it is possible to select the amount of daily loads and their durations. Figure 33(b) explains the power consumption pattern, where powers P1 and P2 are 2kW and 0,5kW respectively during the typical times of the drying programmes predefined by the manufacturer.



(a) (b)

Figure 33. Graphical interface (a) along with power consumption cycles (b) for dryer model [49].

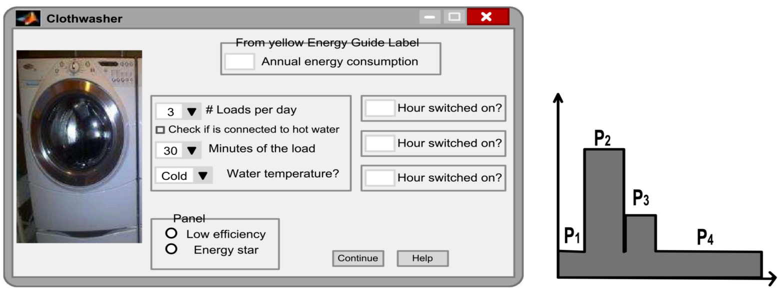
Approximately two-thirds of the electricity, which is consumed by a dishwasher (DW), is used for heating purposes during various washing and drying cycles. Although DW is responsible for a rather small share of the total energy consumption in the residential building, high peaks it draws, as shown in Fig. 34(b), during relatively short periods of time makes this appliance relevant for peak demand management [49]. Hence, DW is also considered in the SRLS. Figure 34(a) shows a grahical interface as well as basic options (i.e., user inputs) of a typical dishwasher.



(a) (b)

Figure 34. Graphical interface (a) along with power consumption cycle (b) for dishwasher [49].

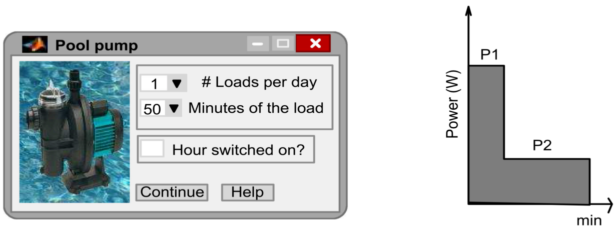
A cloth-washer (CW) utilises electricity mainly for two processes: water heating as well as driving the drum motor. Similarly to DW, a CW graphical interface, shown in Fig. 35(a), allows to input some basic data such as the amount of loads, duration of use as well as efficiency of the motor and water temperature. Power consumption cycles of CW are shown in Fig. 35(b), where powers P1 along with P4 represent filling and draining the rinse water, P2 stands for heating the water during the main phase of the washing programme and P3 – spinning the washer drum.



(a) (b)

Figure 35. Graphical interface (a) along with power consumption cycles (b) for cloth-washer [49].

Due to the popularity of swimming pools in residential buildings in North America, a pool pump was also considered in the SRLS. A pool pump graphical interphase, shown in Fig. 36(a), provides the user with an opportunity to define the amount of daily loads and their durations. Often, pool pumps in addition to just filtering the water also heat it up. Thus, working cycles as well as electrical power demand depend very much on how often the pool is used, its geometry and volume. However, a typical pool power consumption demand, as shown in Fig. 36(b), would include a higher value of power P1 (heating along with water filtering) and much lower value of electric power P2 (only water filtering), which would constantly alternate.

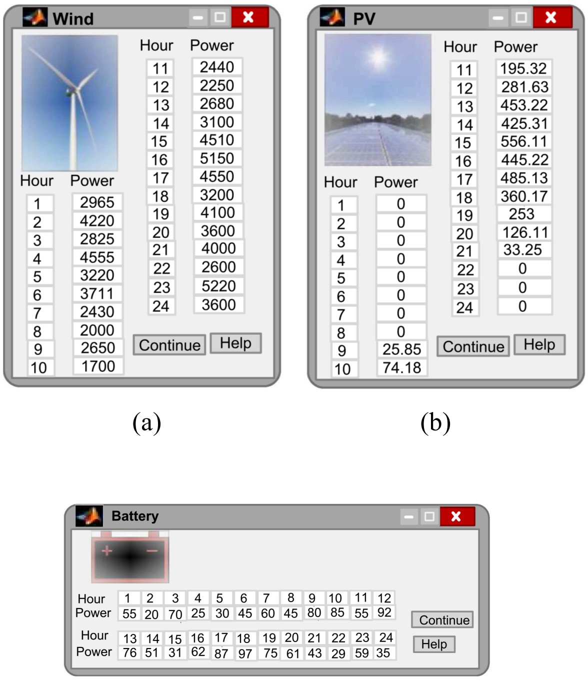


(a) (b)

Figure 36. Graphical interface (a) along with power consumption cycle (b) for pool pump [49].

A part of the residential house electricity demand can be covered with local power generation. Hence, PVs and portable wind turbines are considered in the SRLS. Electricity production of such local power generation sources is impossible to adjust to actual demands due to the nature of processes in the atmosphere. Therefore, a model of battery energy storage is integrated into the simulation tool, providing an opportunity to store the generation surplus from the periods of low demand and release it when demand drastically increases. Interfaces of abovementioned energy generation and storage systems are depicted in Fig. 37.

In SRLS simulation tool, it is possible to apply various scenarios for wind and solar power generation by modifying the values of generated power in the graphical interfaces, where the user can define different hourly profile outputs and thus to test various energy management approaches. The total sum of these power supply sources feed the residential house loads, but the possible power generation surplus is exported to the grid in case battery storage is fully charged.



(a) (b)

(c)

Figure 37. Graphical interfaces for defining profiles of local power generation and storage: a portable wind turbine (a), PVs (b) and a battery storage (c) [49].

3.3. Simulation results

This section explains the process of development of a simulation model of residential building, using the SRLS and based on the assumptions about the loads of an average LLHC. This model describes power demands of each load, presented in Tab. 1, according to the level of its utilisation during various periods of time on a 24-h horizon. These periods are rush hours (7-8 and 16-17), quiet hours (21-5) and the rest hours of the day are considered to be semi-quiet. The results of the simulation in Fig. 38 show that all 4 elevators are in rather intensive use during morning and afternoon rush hours, causing 3 kW peaks. Higher peaks of 6 and 9 kW are registered when more than one elevator is in simultaneous use. Also, the level of indoor staircase lighting utilisation is higher at evenings and mornings, causing 0,1 kW peaks, which last for 5 minutes due to to the time settings of indoor lighting. Moreover, a constant 0,5 kW load of the heat exchanger is depicted along with outdoor night lighting (0,5 kW). Finally, the ventilation system, which is running on a constant basis and is consuming 7 kW of electric power, is also presented in Fig. 38.

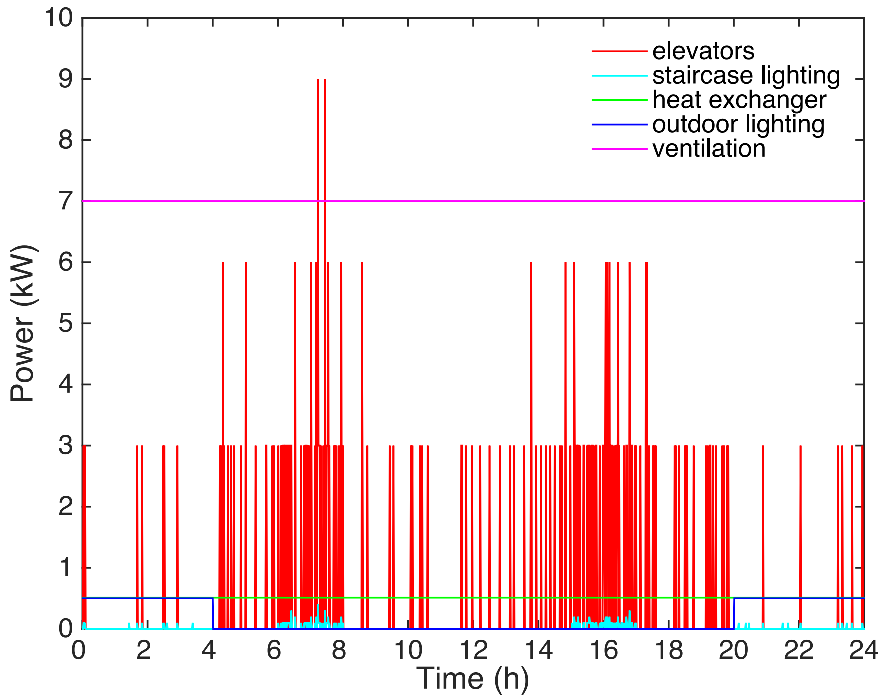


Figure 38. Simulation results of LLHC loads.

A part of the LLHC electricity demand can be covered with local power generation. Since PVs were previously defined as the most convenient source of GHG-free locally generated energy, which can be employed without any restrictions, solar panels are also considered in the model.

Based on the general perception, the rated power of a solar power plant, which is used in the Finnish LLHC, should not exceed the rate of a base load by more than 10%. It is due to intention to shorten a payback time of PVs by reducing the amount of the surplus, which is exported to the grid. The price difference between imported and exported electricity may exceed 300%. Hence, the main task of PVs in the Finnish context is to reduce the amount of expensive import of electricity that would save the money of the LLHC and reduce its GHG emissions. In fact, selling the surplus to the grid improves the energy performance of the building, and thus promotes its energy class. However, in case of exporting too much of the surplus, the payback time of PVs may exceed their lifetime, which would make the investment unacceptable in the eyes of the owners of the LLHC. Thus, it is relevant to adjust the rated power of a solar power plant to the base load of the LLHC.

A sum of all loads of the LLHC would result in the total power demand, which is depicted in Fig. 39. According to the LLHC power demand curve, the value of the base load may be estimated at 7,5 kW. Hence, an appropriate rated power of the solar power plant would be approximately 8 kW. One of the options for a single solar panel might be SHARP ND-AK275 with an approximate maximum power output of 200W in Southern Finland [55]. In order to generate needed 8 kW, an array of 40 solar panels has to be installed on the LLHC rooftop. In order to simulate PV generation, a Photovoltaic Geographical Information System (PVGIS) was utilised. Power generation of 40 SHARP ND-AK275 solar panels in June is depicted in Fig. 39. Thus, a PV generation of an average LLHC, which is located in the Helsinki Metropolitan Area, is simulated according to the value of the base load, in order to minimise the payback time and cut the reasonable amount of GHG emissions of the LLHC.

Power demand and PV generation data may be split into three major parts, as presented in Fig. 39: a part of the needed electric energy is generated locally; a surplus of the local generation is exported to the grid; and imported energy, which is purchased from the grid at the moments when local generation is not able to meet the LLHC power demand. These three parts are shown in Fig. 40. Simulation resulted in the electric power balance of the LLHC on a 24-h horizon in June as follows:

- Import – 129 kWh;
- PV generation that is employed locally – 56 kWh;
- Surplus export to the grid – 1 kWh;
- The total power demand of the LLHC – 185 kWh.

Based on the obtained results, a properly selected rate power of a solar power station will be enough to cover approximately a third of the total power demand during summer periods. Of course, during winters local PV generation will cover less then 5% of the demand. Furthermore, snow and clouds may reduce local generation down to 0%. Nevertheless, most of the time PVs will generate a considerable amount of electricity, and thus will not only reduce monthly payments of an average LLHC but also cut its GHG emissions. The next chapter of the thesis will provide an analysis of an effect on environment caused by employment of PVs in an average LLHC.

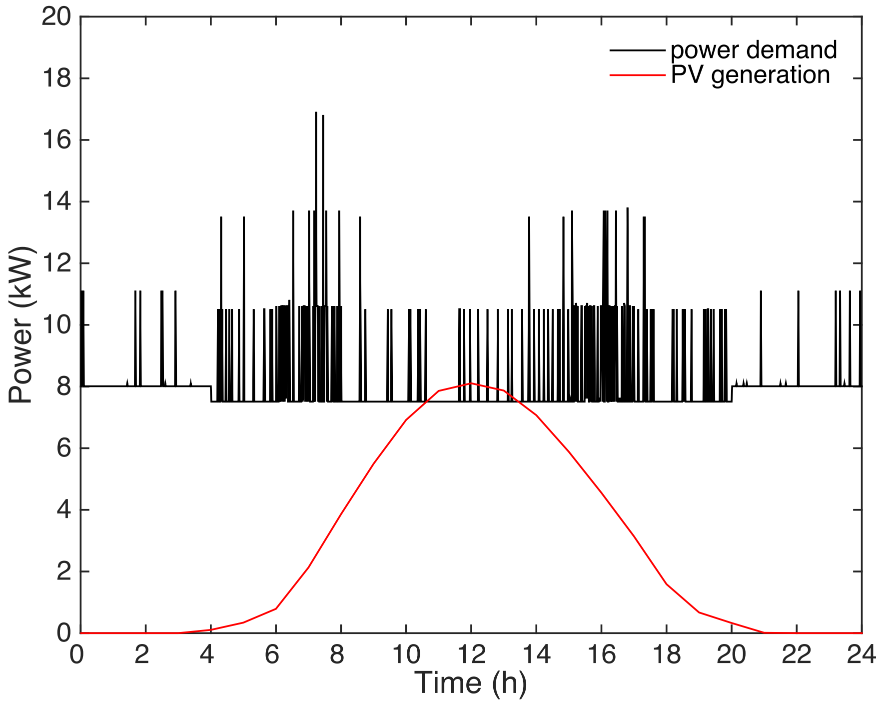


Figure 39. Total power demand of LLHC and PV generation.

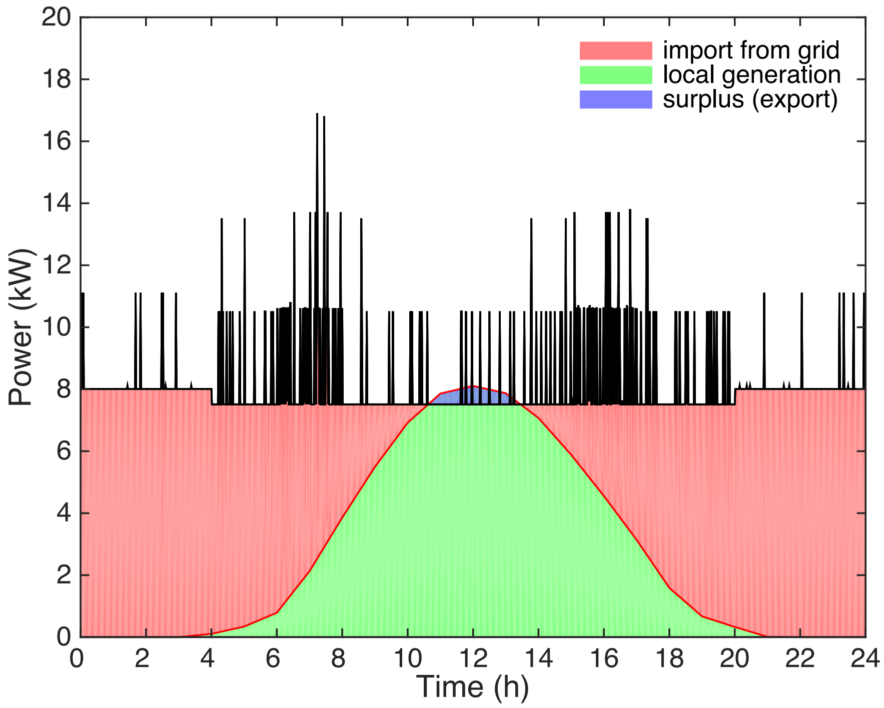


Figure 40. Electric power balance.

4. Environmental aspects

4.1. PV electrical energy generation carbon footprint

Often, PV electrical energy generation is advertised as green and GHG-free method for obtaining electricity. However, such statements should be questioned. Generating of electricity by PVs does not cause any direct GHG emissions in the solar power plant location. Nevertheless, the manufacturing process of solar panels involves a large amount of raw materials, which have to be extracted from a natural environment, processed in order to become applicable for further manufacturing process. Then, multiple steps in a complex manufacturing process, which also include usage of various toxic and hazardous materials as well as acids, require energy and transportation. Completed solar panels have to be transported to the places of their usage, where panels will operate for approximately 30 years. Later, decommission and recycling obligate to use more energy. A part of the abovementioned processes involve usage of fossils. Hence, it is relevant to define and explain what is the actual carbon footprint of PV electrical energy generation.

Everything starts with quartz reduction of silica sand. The process involves multiple reduction agents along with electricity. Usually, this process is organised in places where cheap electricity is available. As a result, metallurgical grade silicon is obtained, which is converted to electronic grade (EG) silicon in the Siemens process. Electronic grade silicon is later purified in a corrosive bed. The EG-silicon is melted, and a slowly growing crystal is extracted from the melting-pot. The crystalline columns are sawn into wafers of $300\mu m$ thickness. This particular process involves usage of electricity, a large amount of water and various working materials, such as stainless steel saw-blades, argon gas, acids as well as hard coal as proxy for graphite. Afterwards, wafers are endowed with phosphorus, and front and rear contacts of a crystalline solar cell are printed. Completed solar cells are formed in arrays and joined under pressure and heat in a sandwich-block, which rare and front covers are made from glass, aluminium and polyvinyl fluoride film. After adding an aluminium frame and a connection box, panels are tested and packed [14].

All the abovementioned processes result in GHG emissions, which can be divided by assumed operational lifetime of solar panels (30 years) and expected produced amount of electricity. Thus, the entire process of manufacture as well as decommission and recycling yield in average 0,039 kg(CO_2-equiv)/kWh of GHG emissions, which is far from 0 as advertisements usually state [14]-[16].

4.2. Environmental impact of renewable energy sources of an average limited liability housing company in Finland

In order to quantify positive effects caused by employment of renewable energy power generation, it is necessary to define a starting point for comparison. Electricity demand of an average LLHC in June was previously simulated on a 24-h horizon. Based on the simulation results, the total power demand would be 185 kWh. In order to compute the GHG emissions the abovementioned electricity production would cause, it is relevant to determine an energy source and method that was used for power generation, since for example coal-fired and nuclear power plants would cause in average 1,115 and 0,010 kg(CO_2-equiv)/kWh of GHG emissions respectively, which is an enormous variation [16]. However, a usage of an average value of GHG emissions caused by a production of 1 kWh of electric energy in Finland would be acceptable. Thus, a value of 0,158 kg(CO_2-equiv)/kWh will be used in further calculations [56].

In case when an average LLHC will not use an additional power generation of PVs, which where previously defined as the most convenient for deployment in LLHCs, a total GHG emissions caused by electricity generation needed to cover a demand of LLHC in June on a 24-h horizon may be computed as follows:

$$185\ kWh * 0{,}158\ kg(CO_2\text{-}equiv)/kWh = 29{,}23\ kg(CO_2\text{-}equiv)$$

If a part of the electrical energy import is replaced with local solar power generation, the total GHG emission of an average LLHC in June on a 24-h horizon can be computed as follows:

$$129\ kWh * 0{,}158\ kg(CO_2\text{-}equiv)/kWh + 56\ kWh * 0{,}039\ kg(CO_2\text{-}equiv)/kWh = 22{,}57\ kg(CO_2\text{-}equiv)$$

Based on the calculation results, the utilisation of PVs in an average LLHC would reduce GHG emissions during one day in June by approximately 23%, which would have significantly positive effects on the environment in a long-term perspective and in a scale of the whole country.

4.3. Conventional power plants electrical energy generation carbon footprint

This subchapter considers energy sources that are utilised to generate electrical energy in Finland: coal, natural gas, nuclear power generation, large-scale wind and hydropower. Moreover, their GHG emission for generating the amount of energy needed to cover a 24-h demand in June of an average LLHC will be computed.

During last decades, coal-fired power plants and CHPs have been reducing their generation due to environmental policy. In Finland, coal consumption in energy sector is now 47% lower than just 20 years ago. Moreover, the most dramatic decrease was registered in 2019, when the total consumption has dropped by 25% in compare to 2018 [57]. It goes in line with the future carbon neutrality of Finland [4]. In addition, the usage of coal in energy sector will be totally prohibited in Finland starting from the first of May 2029 [58]. As a result, it is expected that GHG emissions caused by coal-fired power plants will be decreasing further until they reach 0 at some point. However, at the moment average GHG emissions of the coal-fired electrical power generation can be estimated to 1,115 kg(CO_2-equiv)/kWh [14]. Hence, the total GHG emissions caused by generating of 185 kWh needed for 24-h consumption in June in the average LLHC is 206,29 kg(CO_2-equiv). In case of employment of PVs – 146,02 kg(CO_2-equiv).

Natural gas has a rather small share of approximately 5% of Finnish total energy consumption [59]. In contrast to coal, this particular fossil fuel has a lower level of GHG emission, which can be estimated to 0,738 kg(CO_2-equiv)/kWh, and its products of burning do not contain nitrogen oxides, which are considered to be precursors to smog [14]. Often, natural gas is used in energy sector as an additional fuel that is employed at the moments of peak demand or when natural gas prices promote its wide utilisation for electric energy and heat production. In order to provide power to an average LLHC during 24 hours in June, the usage of natural gas would result in 136,53 kg(CO_2-equiv) of GHG emissions. Partial employment of PVs would reduce GHG emissions to 97,39 kg(CO_2-equiv).

Nuclear power generation has been facing a lot of criticism, and public attitudes towards nuclear energy have changed drastically after the latest nuclear accident in Fukushima, Japan. However, nuclear power plants are an important tool in the promoting of carbon neutrality and reducing global GHG emissions due to extremely low level of waste and other emissions of the whole nuclear power chain, which is mining, milling as well as uranium enrichment, fuel fabrication, construction and decommissioning phases of power plants after relatively long period of exploitation [16]. In Finland, approximately 25% of the consumed in 2018 electricity was generated at 4 existing reactors in Loviisa and Eurajoki [6]. A cumulative GHG emissions of nuclear power generation can be estimated to 0,010 kg(CO_2-equiv)/kWh, which is less than any other known decarbonised source of energy would emit [14]. Thus, the total GHG emissions caused by generating of 185 kWh needed for 24-h consumption in June in the average LLHC would be only 1,85 kg(CO_2-equiv). In case of employment of PVs – 3,47 kg(CO_2-equiv).

	Mix of sources (FI, average)	**Coal**	**Natural gas**	**Nuclear power**	**Wind power**	**Hydropower**
Energy source GHG emissions, kg(CO_2-equiv)/kWh	0,158	1,115	0,738	0,010	0,010	0,033
Energy source total emissions to cover a LLHC 24h demand in June, kg(CO_2-equiv)	29,23	206,29	136,53	1,85	1,85	6,105
Energy source generation + PVs to cover a LLHC 24h demand in June, kg(CO_2-equiv)	22,57	146,02	97,39	3,47	3,47	6,441

Table 2. Overview of GHG emissions for different energy utilisation scenarios.

Large-scale wind and hydropower electrical power generation was considered previously in this thesis. The results of their GHG emissions along with the results of other sources of energy, which were discussed in this chapter, are presented in Tab. 2.

5. Conclusions

The main focus of this thesis work was the environment. The significance of adopting further steps towards climate stabilisation is not questionable anymore. There are many ways to succeed. Nevertheless, only a complex approach involving simultaneous steps in all economic sectors may lead to a desired result. In Finland, the housing sector is considered to be the largest polluter. Due to this reason, LLHCs were chosen as a target of analysis in this research. In order to reduce their GHG emissions, it is relevant not only to consume energy in an efficient manner, but also to generate it with the minimum impact on the environment. Common methods for the reduction of GHG emissions include also LLHCs' own additional electrical power generation, which is presented in urban areas worldwide mostly by PVs and small-scale wind turbines. However, these methods may not be universal for all countries. Moreover, methods and steps towards a reduction of GHG emissions should also consider available energy sources and existing energy balance. Thus, it was relevant to research how globally accepted solutions would work in the Finnish context.

In this thesis, various existing sources of energy with different levels of GHG emissions were considered. In order to understand how energy consumption affects the total GHG emissions of LLHCs, an average Finnish LLHC along with its loads were defined based on the available statistical data. Then, electricity consumption on a 24-h horizon of an average LLHC was modelled. Finnish legislation and regulations were explored in order to obtain information about sorts of additional local energy generation units, which may be utilised in an average LLHC. As a result, PVs were determined as the only convenient renewable source of electrical energy generation that can be deployed almost without any restrictions in Finnish urban areas. In addition, PVs are also customer perceived as GHG-free sources of electrical energy, although they are not.

In order to quantify positive environmental effects caused by employment of PVs, their power generation was modelled on a 24-h horizon in June, as shown in Fig. 39. Based on the simulation results, the amount of electrical energy imported from the grid has dropped by almost 30%. The next step was to evaluate the abovementioned drop in terms of GHG emission. Therefore, multiple scenarios of utilisation of energy, which is imported from the grid and thus generated from different sources, were considered. The results are presented in Tab. 2. Based on the results, a level of positive effect from deployment of PVs depends on the sources of electrical energy, which are replaced by PVs. The most promising results were noticed, when electrical energy produced from fossil fuels was at least partly replaced with PVs. In cases of nuclear energy, wind and hydropower, GHG emissions of an average LLHC have increased, which is opposite to original intention to decrease GHG emissions of residential buildings. This is due to the lifecycle GHG emissions of PVs, which exceed large-scale decarbonised power generation units that already exist in Finland.

In Finland, approximately 41% of consumed electrical energy is already produced from renewable sources. Moreover, a share of renewables is constantly growing [59]. It is due to effective and consistent environmental and tax policies of numerous Finnish governments during last decades. Energy market receives annually new portions of decarbonised electricity, which is produced in cost-effective and sustainable manner. As simulation results and further computations showed, purchasing of electrical energy from producers, which deploy decarbonised or renewable energy sources, would result in much lower level of GHG emissions compared to small-scale rooftop PV installations. Hence, Finnish LLHCs should concentrate more on the sources, from which purchased energy is produced, instead of installing small-scale renewable energy power generation units. Nevertheless, the only positive scenario for small-scale PV power generation units involves replacement of electrical energy generated from fossil fuels. However by the end of 2020s, combustion of fossil fuels in Finnish energy sector will be prohibited, and thus positive environmental effect of PVs will be completely eliminated. Moreover based on the research results, it seems that solar panels will become an environmental burden, from which our planet should be protected and avoided. Of course, future studies will bring more clarification and provide a better knowledge in this field.

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