Joachim Meyer

Solar Electricity Utilization in Finland

An Hourly Comparison of Photovoltaic System Output Data and Simulated Building Electricity Load Profiles

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Tämän insinöörityön tavoitteena on painottaa aurinkosähköjärjestelmän tuottoprofiilin ja rakennuksen käyttöprofiilin tuntikohtaisen yhteensopivuuden tarkastelun tärkeyttä sen kannattavuuden määrittelyssä sekä tarkastella aurinkosähköjärjestelmien mitoitustapoja elinkaarilaskennan avulla. Syy tutkimukselle oli Suomessa koettu epätietoisuus aurinkosähköjärjestelmien tämänhetkisestä kannattavuuden potentiaalista.

Insinöörityö alkaa kirjallisuusselvityksellä, jossa kuvataan aurinkosähköä ilmiönä sekä sen hyödyntämisen edellytyksiä Suomessa. Lisäksi työssä on selvitetty aurinkosähköjärjestelmän kannattavuuteen vaikuttavia tekijöitä sekä määritelty niiden lähtötiedot elinkaarilaskentaa varten. Aurinkosähkön tuntikohtaiset tuottotiedot kerättiin MetroSol-aurinkoenergia-laboratoriosta vuodelta 2014. Kahden eri rakennustyypin sähkönkulutusprofiilia simuloitiin dynaamisella energialaskentasovelluksella FINVAC:in tarkennettuja käyttöprofiileja hyödyntäen. Tämän jälkeen tehtiin sekä tuntikohtaiset että kuukausikohtaiset tarkastelut, joiden pohjalta pohdittiin niiden tarkkuutta. Kannattavuuslaskennan avuksi kehitettiin mitoituksen optimointityökalua sisäisen korkokannan menetelmällä.

Tutkimustuloksista päätellen aurinkosähkön kannattavuuslaskelmia pitäisi ehdottomasti suorittaa tuntikohtaisella tasolla, sillä kuukausikohtaisen tarkastelun tulokset olivat hyvinkin epätarkkoja. Lisäksi todettiin, että investointikustannusten määrittely oli tärkeässä roolissa kannattavuuslaskelmissa. Sisäisen korkokannan optimointityökalua todettiin kelpoiseksi työkaluksi, kunhan lähtötiedot olivat riittävän tarkat. Kohteen profiilien yhteensopivuudesta riippuen optimoitu aurinkosähkönjärjestelmän mitoitus saattoi sallia pienen määrän ylijäämäsähköä, kunhan korvatun ostosähkön hyöty oli suhteessa suurempi.

Avainsanat	aurinkosähkö, elinkaarilaskenta

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The goal of this thesis was to emphasize the importance of comparing photovoltaic (PV) electricity production and building electricity load profiles on an hourly basis in order to assess the feasibility of grid-connected PV systems in Finland. The thesis also examined PV system sizing methods through the use of life-cycle cost (LCC) analysis. The main reason for conducting this study was the perceived lack of knowledge of the PV electricity utilization potential in Finland.

In the theoretical part of the study, solar electricity is reviewed as a science and the utilization potential in Finland is assessed. The main factors of PV system feasibility calculation are further discussed and LCC analysis parameters are determined.

The solar PV electricity production data of 2014 was gathered from the MetroSol laboratory. The electricity load profiles of two building types were simulated using dynamic energy calculation software and improved user profiles from a study conducted by FINVAC. Hourly and monthly comparisons of the profiles were carried out and an internal rate of return (IRR) optimization tool was developed for feasibility calculation.

The study results confirm that PV electricity and building electricity load profiles should be compared on an hourly basis in order to achieve sufficient simulation accuracy. The IRR optimization tool was proven to be useful, as long as the calculation parameters were carefully determined. In some cases, the optimal sizing of a grid-connected PV system in Finland seems to allow a portion of PV electricity to be fed into the grid. However, the benefits of increasing the amount of replaced purchased electricity has to outweigh the negative effects of selling generated PV electricity into the grid.

Keywords	photovoltaic electricity, life-cycle cost analysis

Contents

Abbreviations

AC	Alternating current
A-C	Air-conditioning
AM	Air mass
BIM	Building information model
CAV	Constant Air Volume System
c-Si	Crystalline silicon
DC	Direct current
FIT	Feed-in tariff
HVAC	Heating, ventilation and air-conditioning
IRR	Internal Rate of Return
LCC	Life-cycle cost
LCOE	Levelized cost of energy
NPV	Net present value
O&M	Operation & Maintenance
PBP	Payback period
PV	Photovoltaic
TRY	Test reference year

1 Introduction

Solar energy produced by photovoltaics, long known as one of the most expensive renewable energy technologies, is rapidly becoming a viable source of electricity worldwide. Advancements in photovoltaic (PV) technology, production processes and industry development, as well as government involvement, have contributed to significant cost reductions of photovoltaic systems over the last decade. Many countries have implemented policy mechanisms as a way to “jumpstart” renewable technologies such as solar electricity, often in a quest to meet the climate strategy targets set by international agreements. The steady escalation of electricity market prices has also strengthened the position of photovoltaics as a cost-competitive alternative to fossil fuels. This trend can be assumed to continue in the future, further increasing the value of utilized free solar electricity. [1.]

Micro-scale grid-connected PV systems are on the verge of a breakthrough in many countries with sufficient solar potential and favorable regulatory environments. In Finland, solar electricity is widely considered to be economically unprofitable due to minimal financial incentives from the government. As a general rule, feeding excessively produced PV electricity into the grid without compensation through feed-in tariffs is to be avoided [2]. In other words, the feasibility of a PV system in Finland relies on replacing purchased electricity with produced solar electricity. A building’s electricity load and PV production are, however, inconsistent, making it challenging to avoid excess production. Thus, in order to size an economically feasible PV system, it is necessary to carefully analyse the building’s electricity load and PV production profiles.

This study concentrates on micro-scale grid-connected PV systems, designed primarily to produce electricity for a building’s own use. The data consists of simulated electricity load profiles of two different building types, a kindergarten and a residential building, as well as the measured PV output data for the year 2014, generated by the MetroSol solar energy laboratory in Espoo, Finland. The main focus of this paper is to emphasize the importance of accurately comparing the relation between electricity production and consumption on an hourly basis in order to portray a realistic view of the performance of grid-connected PV systems. This study will also explore photovoltaic system sizing optimization through life-cycle cost (LCC) analysis.

2 Solar Energy

Solar energy is the source of nearly all energy on earth. Plants use the process of photosynthesis to transform solar energy into growth. When this so called biomass breaks down, the embodied energy can be used as fuel for heating and electricity generation purposes. Fossil fuels, such as oil and natural gas, are essentially old plant matter with stored solar energy from millions of years ago. Wind energy is the result of the dynamic process of air movement caused by temperature differences created by the sun's heating effect. Similarly, hydro energy is created when the sun evaporates water that subsequently rains down onto higher ground. Solar energy can also be harnessed directly into thermal energy or electricity by utilizing incident solar radiation i.e. sunlight. The potential of solar energy is enormous, as the amount of energy reaching the surface of the Earth every hour is greater than the annual energy needs of our entire population. [3.]

2.1 Solar radiation

Solar radiation is electromagnetic radiation emitted by the sun. This radiation covers a wide spectrum of wavelengths, of which only a small portion can be picked up by our eyes as visible light (see figure 1). The spectrum of light contains small "packets" of energy, called photons. Each photon has a unique energy value depending on its wavelength. [4.]

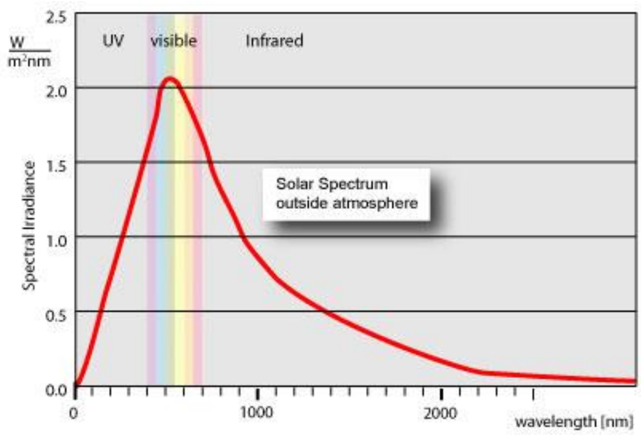

Figure 1. The spectrum of solar radiation outside the Earth's atmosphere. [5]

The intensity of solar radiation, the so called solar constant, is determined by integrating this solar spectrum. It describes the amount of solar energy just outside the Earth's atmosphere, i.e. extraterrestrial solar radiation. The value of the solar constant varies slightly depending on the time of the year and the activity of the sun, but is generally considered to be 1370 W/m^2. [6.]

2.2 Direct, diffuse and reflected irradiance

As solar radiation penetrates the atmosphere of the Earth, it comes into contact with molecules that interact with the photons. A portion of the radiation is absorbed or reflected back into space and the rest is split into diffuse and direct light. As a result, the intensity of the radiation that eventually reaches a surface on Earth is less than the extraterrestrial radiation entering the atmosphere (see figure 3). [6.] The radiation that remains after the interaction with the atmosphere is called solar irradiance and is measured in W/m^2 [7].

The main factors that determine the amount of incident solar irradiance are [6]:

- local conditions; such as clouds, water vapour and pollution
- atmospheric effects; such as absorption, scattering and reflection
- air mass
- landscape (reflective surfaces).

The total incident solar irradiance on a surface, i.e. global solar irradiance, is determined by three solar components; direct, diffuse and reflected irradiance (see figure 2).

$$G_g = G_b + G_d + G_r \quad \text{, where} \tag{1}$$

G_g = Global irradiance, W/m^2

G_b = Direct (Beam) irradiance, W/m^2

G_d = Diffused solar irradiance, W/m^2

G_r = Reflected solar irradiance, W/m^2

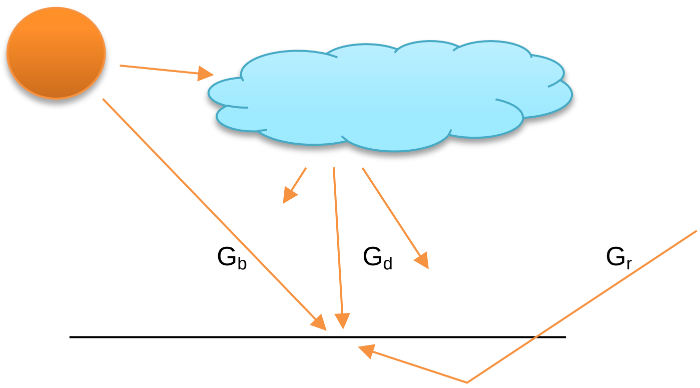

Figure 2. The three components of incident solar irradiance.

Direct irradiance, also called beam irradiance, is sunlight that reaches the surface at a direct path, only being slightly affected by the atmosphere. Diffuse irradiance, on the other hand, indirectly reaches the surface after being scattered by molecules in the atmosphere. Diffuse irradiance comes from many directions simultaneously and, unlike direct radiation, does not cast a shadow. On a sunny day with the sun high in the sky, most of the incident solar irradiance is direct. However, there is always a component of diffuse irradiance since the atmosphere still contains molecules and particles that scatter the solar beams. On a cloudy day the amount of direct irradiance is reduced and most of the incident solar irradiance is in the form of diffuse irradiance. [6.]

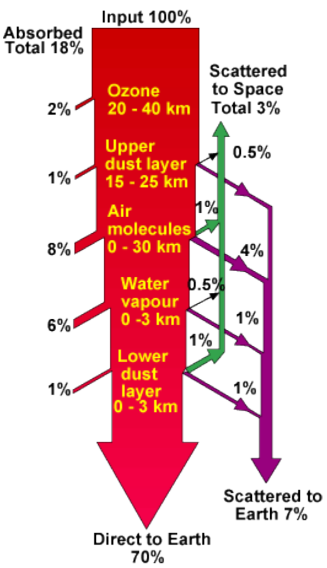

Figure 3. The atmospheric effects on solar radiation in clear sky conditions. [8]

Reflected irradiance is radiation that has reflected off other surfaces, such as the surrounding landscape and constructions. Certain materials and matters reflect more radiation than others. Snow can reflect up to 90% of incident solar radiation, whereas water only reflects 10% (see table 1). [9.]

Table 1. Absorption and reflection of materials. [9]

Material	Absorption %	Reflection %
Snow	10-20	80-90
Water	90	10
Dirt	80	20
Sand	80	20
Grass	70	30
Asphalt	90	10
Concrete	60	40

This phenomenon should be taken into consideration when designing a solar energy plant. In certain situations, PV panels can yield significantly more solar electricity through utilization of highly reflective surfaces.

2.3 Air Mass

As mentioned, the Earth's atmosphere has a reducing impact on the incident solar irradiance. Consequently, the reduction in intensity is relative to the distance that the solar radiation has to travel through the atmosphere (see figure 4). The overall effect the atmosphere has on the incoming solar radiation is determined by the Air Mass (AM) coefficient.

When the sun is in zenith, i.e. directly above the point of reference, the radiation path is normalized to the Earth's surface and the AM coefficient is 1. As the solar angle (θ_z) increases, the solar radiation penetrates a thicker layer of atmosphere and the AM coefficient is increased. [10.]

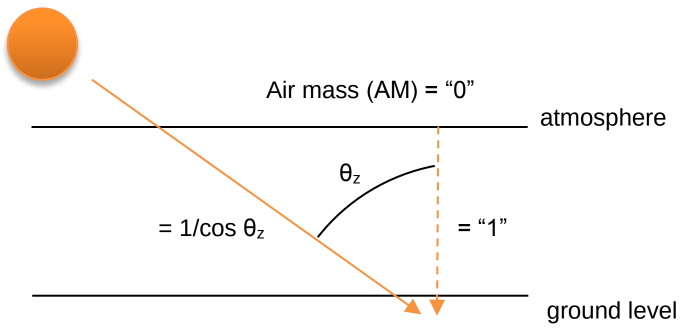

Figure 4. Air mass as a function of the solar radiation path length.

2.4 Position of the sun

As the Earth rotates around the sun and the Earth’s own axis, the position of the sun in the sky at a given location is constantly changing as a function of time. The Earth’s axis of rotation is tilted at a 23.5 degree angle, which in combination with the ecliptic path around the sun causes day length variations. The same phenomenon also determines the seasonal changes in the northern and southern hemisphere (see figure 5). [11.]

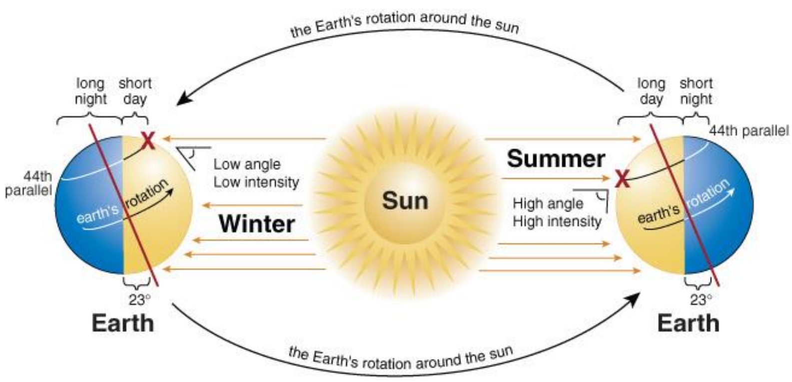

Figure 5. The Earth’s rotates around its own axis and around the sun [12].

As a result, the path on which the sun moves across the sky changes depending on the location and time of year (see figure 6). The solar elevation angle, the angle between the sun’s position in the sky at solar noon and the horizon, is highest at summer solstice and respectively lowest at winter solstice. [13.]

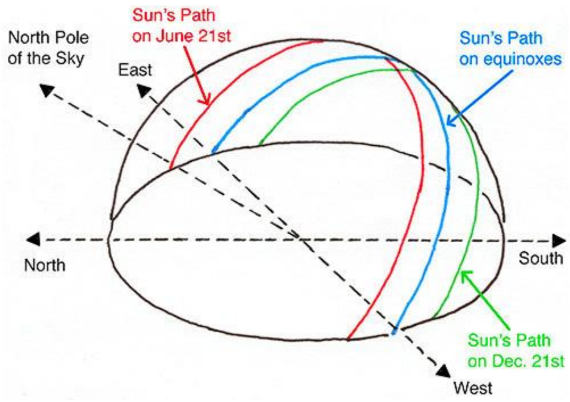

Figure 6. The sun's path changes throughout the year. [14]

In the northern hemisphere, the sun is located in the south when it reaches the highest point in the sky. In the southern hemisphere, the highest point is reaches when the sun is located in the north.

3 PV Technology

Solar PV electricity is an emerging technology with undisputed advantages compared to its fossil alternatives. Solar electricity is a free, non-polluting, renewable and practically inexhaustible source of energy. PV devices are quiet, reliable and long lasting, thanks to their simple construction with no or few moving parts. [3.] Furthermore, PV devices require minimal maintenance and are expected to produce a stable yield for more than 25 years of operation [15]. Perhaps the most attractive feature of PV systems is the increased energy self-sufficiency; independently generated PV electricity offers financial protection against fluctuations in market electricity prices.

The production of solar panels requires some energy, but with the technical improvements in manufacturing, today's PV systems only need between two and five years to produce the amount of energy used in the manufacturing of components. [15.]

On the down side, PV electricity production is dependent on weather conditions and is therefore not able to supply a steady delivery of electricity. It is possible to store generated PV electricity in batteries for later use and thus even out the fluctuations in production capacity, but battery technologies are far from being cost-efficient enough.

They are mainly used in situations where self-sustainability is prioritized on the expense of economic feasibility.

3.1 Global PV Market Outlook

Industry experts have differing opinions about the future of solar PV technology. Some expect an arrival of a “solar age” that will revolutionize the way power systems work, others foresee an end to the steady decline of PV system costs leading to a burst of the “solar bubble”. [1.]

The price of PV modules has been on a steady decrease since the introduction of the technology. The historic trend shows that PV module prices have decreased by 20% for each duplication of the total amount of modules produced worldwide. [1.] In many countries, solar PV electricity has reached grid parity, i.e. the cost of solar PV electricity is equal to the cost of electricity produced by traditional technologies.

The main factors that drive the solar PV market are [16]:

- concerns about energy security
- climate change
- energy prices
- cost of carbon
- increased demand of electricity
- replacement of existing electricity generation capacity.

The solar PV market is still a highly volatile sector, but even the most conservative long-term forecasts suggest that solar PV will be among the dominating electricity resources once the fossil fuel reserves are exhausted. [1.]

3.2 Solar panels

Solar panels are capable of converting sunlight into direct current (DC) electricity via the photovoltaic process. When the photons from the sun reach the solar panel material with properties of a semiconductor, electrons in the material are freed and channeled into an electric current. This current is then either used to power electric devices or fed into the grid. [17.]

A solar panel consists of several small, commonly 156 x 156 mm, solar cells connected in series and/or in parallel. The most common material used in solar cells is crystalline silicon (c-Si). Crystalline silicon cells are available as monocrystalline or polycrystalline, depending in the manufacturing process used (see figure 7). Monocrystalline cells are thin slices of a single silicon crystal, whereas polycrystalline cells contain of mix of silicon crystals.

Monocrystalline cells convert sunlight into electricity more efficiently than polycrystalline cells, but polycrystalline cells are cheaper to manufacture. Both cells are about as cost-efficient, but the cheaper price of polycrystalline cells has made them slightly more common on the market. [18.]

Figure 7. Mono- and polycrystalline cells. [18]

The total solar panel voltage is the sum of the voltage of each solar cell connected in series. The total electric current is the sum of the current of each solar cell connected in parallel. By altering the setup, it is possible to achieve the desired voltage and electric current of a solar panel. [19.]

The DC electricity produced by the solar panels can be used by devices that run on DC electricity. These appliances are often used in off-grid households. Alternatively, by the use of an inverter, the produced DC electricity can be converted into alternating current (AC) electricity. This is necessary in grid-connected buildings as the electric equipment will run on AC electricity provided by the electric grid. [19.]

3.3 PV System orientation

The sun's position in the sky changes constantly throughout the day and varies depending on the time of the year. The maximum amount of global irradiation is harnessed when the sun's rays hit the surface at an angle perpendicular to the surface normal. As the angle of incidence increases, less incident solar irradiation will reach the surface and therefore a larger area is required to receive the same solar energy as the cross section of the sunbeam (see figure 8). [5.]

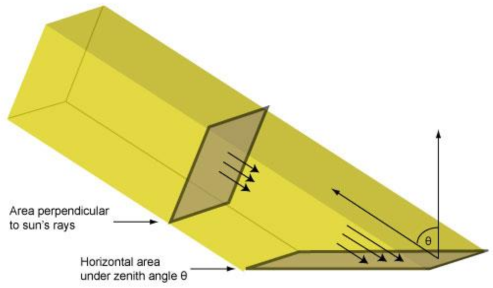

Figure 8. A perpendicular angle between the receiving surface and the incident solar irradiation is ideal for PV electricity production. [5]

In other words, for maximum PV generation it is desirable to orientate a PV system so that it can receive as much solar irradiation over the course of a year as possible. The sun constantly moves in the sky and so the angle of incidence changes. For fixed systems, this means finding the optimal compromised panel tilt angle for the given location. By altering the tilt angle, it is also possible to optimize the PV system performance for seasonal production (see figure 9). For example, a steep panel tilt angle improves the harnessing of low winter-time solar angle irradiation while a shallow panel tilt angle shifts the peak of PV electricity generation towards the summer months.

Figure 9. Solar panel installation tilt angles optimized for seasonal PV generation. [20]

Alternatively, a tracking system can be used to ensure that the panel surface is always facing the sun, maximizing the utilization of direct solar irradiation. In locations with a high amount of direct irradiation, the use of tracking systems can greatly improve the performance of a panel array. On the downside, a tracking system is more expensive than a fixed system and higher operation & maintenance (O&M) costs can be expected. [21.]

3.4 PV Electricity Generation Conditions in Southern Finland

A general misconception is that Finland is not suitable for solar electricity harnessing due to lack of solar irradiation, but the annual amount of global solar irradiation in Finland seems to suggest the opposite. In fact, as figure 10 shows, the yearly global solar irradiation in Southern Finland is close to that of Northern Germany, where solar electricity has successfully been implemented as an integral part of the area’s electricity production. [22.]

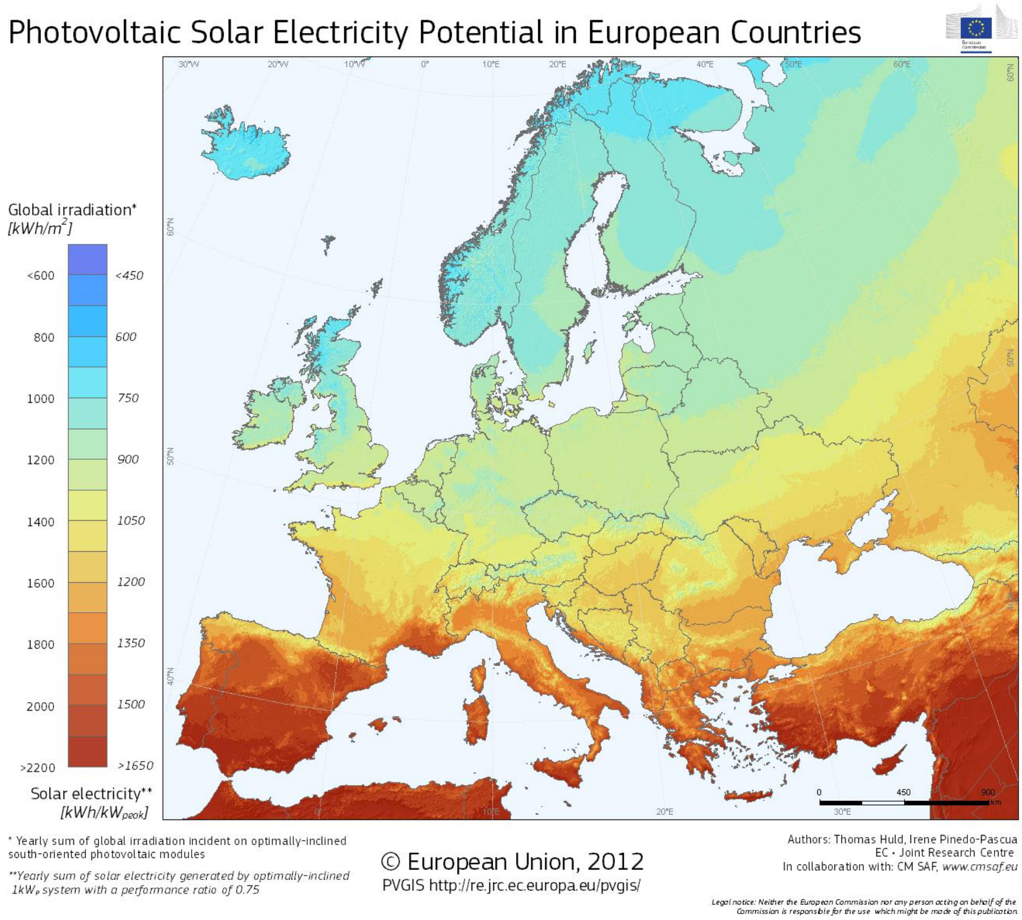

Figure 10. Yearly solar irradiation in Europe. Helsinki receives around 1000 kWh/m2 on a horizontal surface. [23]

However, at the latitude of 60° N, the seasonal changes in daylight conditions in Southern Finland have a significant impact on available solar irradiation. PV electricity production is heavily concentrated towards the summer months, whilst wintertime production is non-existent (see figure 11). This imbalance makes utilization of PV electricity challenging and often results in undesired excess production in the summer when the electricity consumption in buildings generally is decreased.

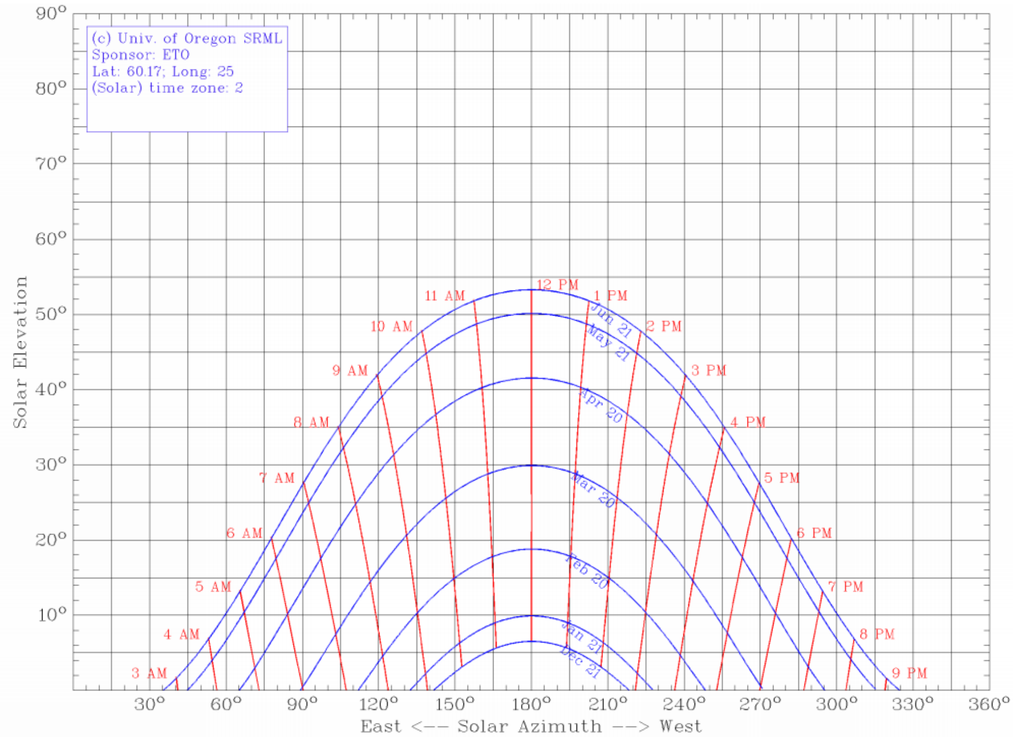

Figure 11. Solar altitude curves at 60° N latitude. The solar altitude angle, the angle between the sun and the horizon, varies between 6,5° on December 21st and 53.5° on June 21st . [24]

In Southern Finland, about half of the yearly solar irradiation is diffused. This doesn't necessarily affect the performance of the photovoltaic panels themselves, but discourages the use of tracking systems. [22.] Also, tracking systems consist of moving parts, which are prone to mechanical failure in harsh arctic environments.

From a solar irradiation perspective, Southern Finland has potential for solar electricity utilization. However, with the severe seasonal changes, the solar conditions do not allow for a steady production of solar energy throughout the year. For grid-connected building integrated PV systems, a surplus of PV electricity will easily be generated in the summer and forcefully fed into the grid, while the system will be unable to significantly contribute to energy savings for the remaining part of the year. These characteristics emphasize the importance of matching PV generation to the building's electricity needs on an hourly basis.

3.5 Sizing methods

The Finnish state owned Motiva Oy, a consultant company that provides information on energy resource efficiency for both the public and private sector, states that PV systems in Finland are generally sized based on one of the following objectives [25]:

- Base electricity consumption load
- Peak electricity consumption load (summertime)
- Average consumption load (summertime)
- Annual consumption (net zero energy goal)
- Electricity self-sufficiency
- Full utilization of available non-shaded roof or wall surface area
- Available financial resources.

Of these sizing methods, the most common ones are base load sizing, average summertime load sizing and peak load sizing. Figure 12 (translated) illustrates how these load levels are determined by analyzing the daily electricity consumption.

Figure 12 Sizing methods based on the building's electricity consumption. [25]

Base load sizing dimensions the PV system according to the building's base electricity consumption load to ensure that the PV system will not produce electricity in excess at any time [26]. This is based on the assumption that feeding electricity into the grid is unprofitable without incentives and should therefore be avoided.

Peak load sizing dimensions the PV system according to the building's peak electricity consumption load in order to cover all the electricity needs with generated PV electricity. However, a large portion of the generated PV electricity is produced in excess and consequently fed into the grid. Peak load sizing in Finland is seldom a feasible option and is generally used for increasing the level of self-sufficiency. [27.]

Average summertime load sizing aims to cover a balanced portion of the electricity consumption in the summer, when solar electricity is available. It is an attempt to find a compromise between PV electricity utilization and excessively produced PV electricity. [27.]

3.6 Solar Energy Incentives

The PV market is tied to the price of fossil fuels, mainly crude oil. As long as the investment costs of PV systems are too high to compete with conventional fossil technologies, there is a lack of internal market pressure to bring forth this alternative energy source. Thus, the PV market growth is heavily dependent on regulatory frameworks in the form of incentive mechanisms. [16.]

These incentive mechanisms stimulate PV market growth by making PV investments feasible in a situation where PV technology in itself is still not cost-efficient enough. Common ways to subsidize PV markets are by the use of feed-in tariffs and investment support.

3.6.1 Feed-in Tariffs

A feed-in tariff (FIT) system is a governmentally implemented policy mechanism aiming to accelerate renewable energy technology deployment in a region. A FIT program typically guarantees that customers will receive a set price for the generated electricity they provide to the grid. The specified rates can be well above the retail price of electricity, as in the German model. [28.] These purchase agreements are designed to drive market growth by making renewable energy investments cost-efficient for developers. A FIT is often offered as a long-term contract, usually from 10 to 25 years. The payment levels can also be designed to decline during the contract period to encourage technological development. Depending on the policy goals, these payment levels can be differentiated by technology type, project size, resource quality, and project location. [29.]

The production tax incentive is another performance-based policy tool, which contributes to enable renewable energy investments to become profitable. Tax incentives offer tax reliefs on the generated PV electricity that the producer feeds into the grid. [28.]

Net metering tariffs, on the other hand, enable customers to “use the electricity they generate in excess of their consumption at certain times to offset their use of electricity from the grid at other times.” These tariffs are especially designed to encourage distributed renewable energy generation and they differ from other FITs in one key aspect: the value of the excessively generated PV electricity is tied to the current electricity consumer price, whereas other tariff incentives are not following the development of the energy market. [28.]

3.6.2 Investment Support

Governments can also encourage the development of new renewable capacity by granting subsidies for purchasing renewable generation equipment. This support mechanism aims to enhance the profitability of early-stage investments, as well as minimalize the risks associated with the introduction of new technology.

This is currently the only subsidy available for solar electricity in Finland. The Centres for Economic Development, Transport and the Environment (ELY-centre) can grant a maximum of 30% of the acceptable investment costs for solar projects undertaken by companies, communities and other organisations [30].

4 Life-cycle Cost Analysis

LCC analysis is a method for assessing whether an investment is economically feasible over the duration of its life-cycle. It takes into account the initial investment costs, as well as the costs of owning and disposing a building services system. It is especially useful when comparing different building upgrade options with the same performance requirements but different cost structures. [31.] Depending on financial objectives, there is a range of suitable LCC methods to be used for project evaluation. The most commonly used methods for PV investment analysis is net present value (NPV) analysis, period payback (PBP) analysis and the analysis of the investment's internal rate of return (IRR).

In a **NPV analysis**, all the life-cycle profits and expenses at set times are discounted to a present value using a pre-set discount rate. The investment is considered to be feasible if the sum of the calculated present value is positive. In this case, all the discounted net profits of the investment, including the residual value, is greater than the total investment cost. [32.]

The present value of future payments and revenues is calculated using the following discount formula [33]:

$$\mathrm{PV} = \frac{\mathrm{FV}}{(1+\mathrm{i})^{\mathrm{n}}} \quad \text{, where} \tag{2}$$

$\mathrm{PV} = \text{Present value}$

$\mathrm{FV} = \text{Future value}$

$\mathrm{i} = \text{discount factor}$

$\mathrm{n} = \text{year}$

When all the project costs are identified by year and amount, and discounted to present value, the total LCC is calculated using the following formula [31]:

$$\mathrm{LCC} = \mathrm{I} + \mathrm{R}_{\mathrm{repl}} - \mathrm{R}_{\mathrm{res}} + \mathrm{E} + \mathrm{OM\&R} \quad \text{, where} \tag{3}$$

$\mathrm{LCC} =$ Life–cycle cost in present value

$\mathrm{I} =$ present value investment costs

$\mathrm{R}_{\mathrm{repl}} =$ present value of replacement costs

$\mathrm{R}_{\mathrm{res}} =$ present value of residual value

$\mathrm{E} =$ present value of energy costs

$\mathrm{OM\&R} =$ present value of operating, maintenance and repair costs

A **PBP analysis** measures the amount of time it takes for the total cost of a system upgrade to be recovered due to lower operating costs. [34.] The method does not take into account the monetary benefits acquired after the recovery timeline, and therefore does not illustrate the overall life-cycle feasibility of the investment. Since a PV system has a long service period with accumulating savings, the PBP method is not suitable for assessing the feasibility of PV projects.

IRR calculation is a method that measures the overall profitability of a project. It determines the discount rate needed to make a project profitable during its service period. In other words, the internal rate of return of an investment is the discount rate at which the net present value costs equal the net present value benefits. [35.]

The IRR is calculated using the following formula:

$$\mathrm{IRR} = \frac{(\mathrm{NPV}_{\mathrm{returns}} - \mathrm{NPV}_{\mathrm{costs}})}{\mathrm{NPV}_{\mathrm{costs}}} \quad \text{, where} \tag{4}$$

$\mathrm{IRR} =$ Internal rate of return

$\mathrm{NPV}_{\mathrm{returns}} =$ Net present value of total life–cycle returns

$\mathrm{NPV}_{\mathrm{costs}} =$ Net present value of total life–cycle costs

A PV installation is often a stand-alone system with the sole objective of accumulating savings by replacing purchased electricity over an extended period of time. A PV installation can also be considered a low-risk investment with monetary benefits, at the same time providing a form of insurance against escalating future electricity prices. It is therefore appropriate to focus on the overall profitability of PV systems by evaluating the possible IRR in different energy market development scenarios.

The future always involves uncertainty and the same goes for calculation models trying to predict it. By conducting a **sensitivity analysis**, we can identify the impact of uncertain input values on the overall feasibility evaluation. A sensitivity analysis points out which uncertainty factors have the greatest influence on the evaluation results and should therefore be carefully and critically assessed. It is a great tool for testing different scenarios of future development of unknown factors. [31.]

5 Methods of Investigation

In this study, the measured PV production data and simulated building electricity load profiles are compared on an hourly and monthly basis. The results are then analyzed and the required level of data accuracy for LCC analysis purposes is determined. The study results will also be used in the development of a PV system sizing tool.

The solar electricity yield of the MetroSol solar energy laboratory is collected in an hourly format, creating 8760 data points corresponding to each hour of the year. The production data is then made scalable by establishing the ratio of hourly produced solar electricity to rated array peak capacity. This is known as the performance factor (kWh/kW_p) of a PV system.

The electricity load profile of a kindergarten and a residential building are simulated using the dynamic simulation software RIUSKA. The user profiles are based on a report made by The Finnish Association of HVAC Societies, FINVAC. The PV production profile and building electricity load profiles are then compared on an hourly and monthly basis. The aim of the comparison is to point out the importance of analysing the profiles with appropriate precision. An LCC analysis will further explore methods of PV system sizing optimization and evaluate potential weaknesses involved in simulations with speculative LCC parameters.

6 PV Production and Building Electricity Load Profile Data

The collected PV electricity production data and the simulated load profiles of the kindergarten and the residential building are presented and analyzed in this section of the paper.

6.1 MetroSol Solar Energy Laboratory

The MetroSol Solar Energy Laboratory is a micro-scale solar energy production plant situated on the rooftop of the Metropolia University campus building in Espoo, Finland. The solar energy laboratory is designed for educational and developmental purposes and serves as a test platform for solar energy studies. With a high degree of configurability and equipped with accurate measuring equipment, the laboratory is ideal for studying the performance of solar energy installations in various weather conditions.

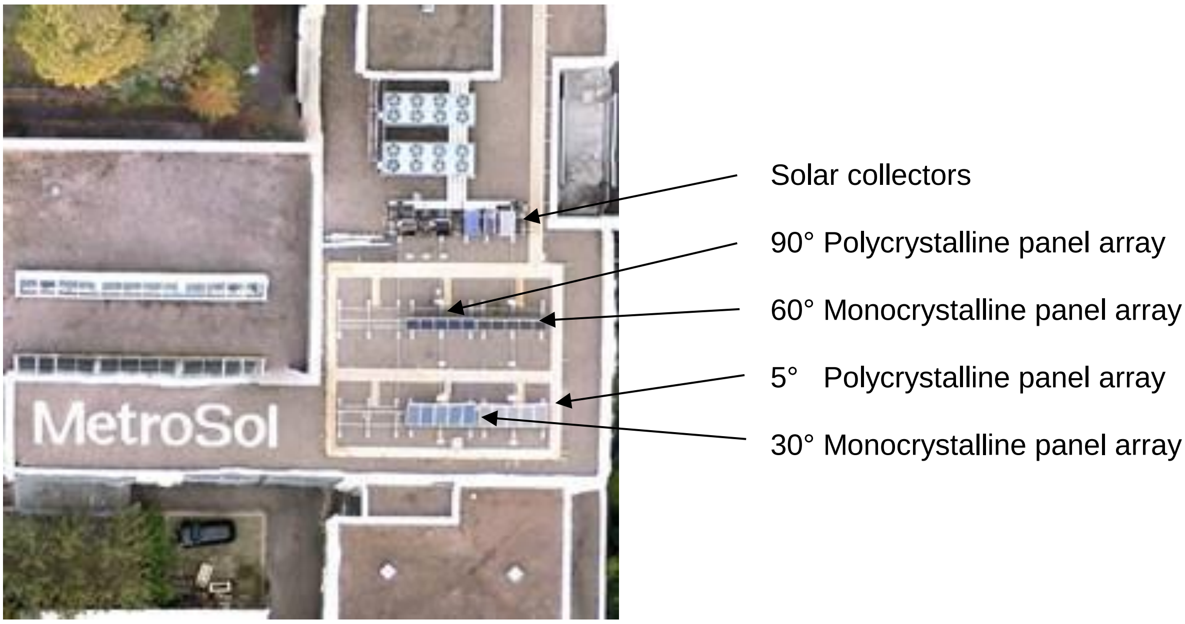

Figure 13. Google Earth picture of the MetroSol PV System installation. [36]

The MetroSol Solar Energy Laboratory consists of 20 solar panels with 4 inverters, 6 solar collectors and a 1200 liter storage tank. The PV panel arrays are installed in two rows facing south. Located on the rooftop of a three-storey building and at a distance from surrounding buildings, there is minimal shading from surrounding objects. Only self-shading, i.e. panels being shaded by other panels, is a concern (see figure 13).

The MetroSol PV system is divided into 4 arrays of both monocrystalline and polycrystalline solar panels. Each of the four panel arrays consists of 5 solar panels connected in series and an inverter that converts the DC electricity produced by the panels into AC electricity. The total output of the system is 4900 W_p.

Polycrystalline solar panels:

Installation angles:	5 and 30 degrees
Panel model:	5 x INNOTECH SOLAR EcoPlus 240W
Nominal output / panel:	240 W_p
Panel array output:	1.2 kW_p
Panel array area:	8.25 m^2

Monocrystalline solar panels:

Installation angles in 2014:	60 and 90 degrees
Panel model:	5 x SolarWATT M250-60 AC 05
Nominal output / panel:	250 W_p
Panel array output:	1.25 kW_p
Panel array area:	8.3 m^2

The laboratory is equipped with measuring equipment, such as pyranometers, that measure the intensity of the incident solar irradiance (W/m^2) from a field of view of 180 degrees. A Vaisala WTX520- weather station measures the wind speed and direction, outside air temperature, relative humidity, air pressure levels and precipitation conditions on site.

The PV yield and weather data of the MetroSol Solar energy laboratory is uploaded in real-time to the SunnyPortal online server though a wireless internet connection. The recorded data enables accurate analysing of the PV system performance in different weather conditions throughout the entire service period of the system.

6.2 PV System Output Profiles

For this study, the hourly PV electricity yield data of all panel arrays was collected for the entire year 2014. Table 2 presents the monthly electricity yield of each panel array. The performance factor is between 580 and 820 kWh/kW$_p$, which is slightly below the local average potential for such PV system.

Table 2. MetroSol PV System total electricity yield for year 2014 [kWh/kW$_p$].

	05 deg	30 deg	60 deg	90 deg	System
January	1.9	2.6	10.0	9.5	24.0
February	7.9	6.2	9.3	7.4	30.8
March	48.8	49.5	70.3	61.4	230.1
April	102.1	104.0	96.5	72.5	375.1
May	109.4	110.9	87.8	67.7	375.8
June	101.9	118.5	83.1	59.1	362.6
July	134.0	166.9	109.4	90.7	501.1
August	96.2	125.6	92.7	81.7	396.2
September	64.8	99.2	82.2	87.5	333.7
October	15.8	28.5	27.9	32.4	104.5
November	1.6	3.7	5.8	6.7	17.8
December	0.7	2.3	1.6	2.2	6.8
Year total	**685.1**	**818.0**	**676.6**	**578.8**	**2758.4**

The optimal tilt angle in Espoo is between 35 and 45 degrees, but PV arrays installed at 30 and 60 degree tilt angles produce almost the same amount of electricity [37]. In the MetroSol laboratory, the panel array installed with a 30 degree tilt angle produced more energy compared to the other panel arrays. This was to be expected, as the 30 degree angle is able to harness the biggest amount of summertime solar irradiance. However, the 60 degree tilt angle panel array did not produce as much as could be have been expected. A closer look at a sunny day in September (see figure 14) clearly shows that the 60 degree tilt angle panel array suffers from self-shading. Before 2 pm the 60 degree tilt angle generates the highest amount of electricity out of all the panel arrays, in line with the fact that the 60 degree tilt angle is the most advantageous for the solar path in September, when the maximum solar elevation is around 30 degrees. At 3 pm, the curve graph of the panel array is cut down to roughly 75% of its potential. After 4 pm the generation curve is restored to its expected trend path.

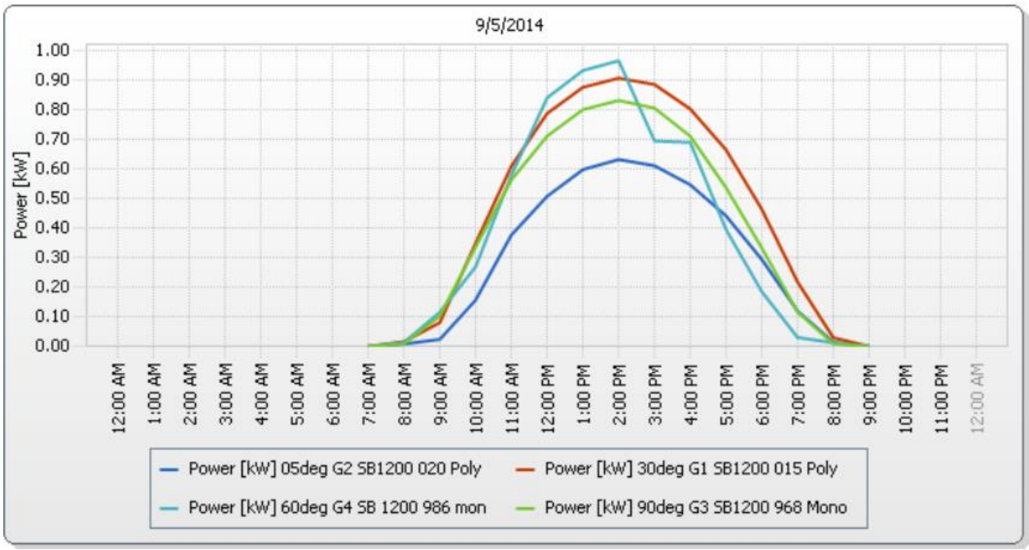

Figure 14. The production of the 30 degree tilt angle panel array suffers from self-shading in the afternoon. [38]

The self-shading is caused by the 90 degree tilt angle panel array installed to the west of the 60 degree tilt angle array. The two arrays are too close together. However, the problem could be fixed by altering the tilt angles or by increasing the distance between the arrays.

To put the yield data of 2014 into perspective, it is compared to a yield profile simulated with the PVGis (Photovoltaic Geographical Information System) photovoltaic energy calculator (see figure 15). The PVGis calculator is a tool for estimating the yearly electricity generation potential of defined PV systems. The calculator's solar irradiation profile is based on historical irradiation statistics and is well suited as a test reference year (TRY) profile for simulation use. [39.]

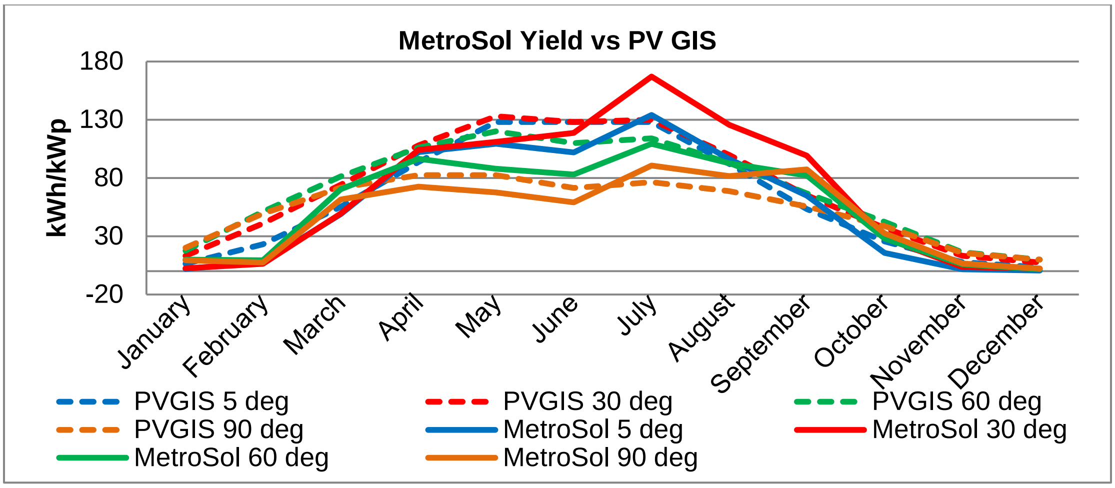

Figure 15. PV electricity production data from MetroSol in 2014 with comparable simulated production estimates of a similar setup.

As shown in figure 16, the MetroSol PV plant heavily underperformed up until June, after which the yield was far greater than average for the late summer and fall months. This was due to the irregular weather conditions in southern Finland in 2014. The first half of the year was cold and rainy with significant cloud cover for extended periods of time. The late summer on the contrary was very sunny. The late months of 2014 (October - December) were also cloudier than usual.

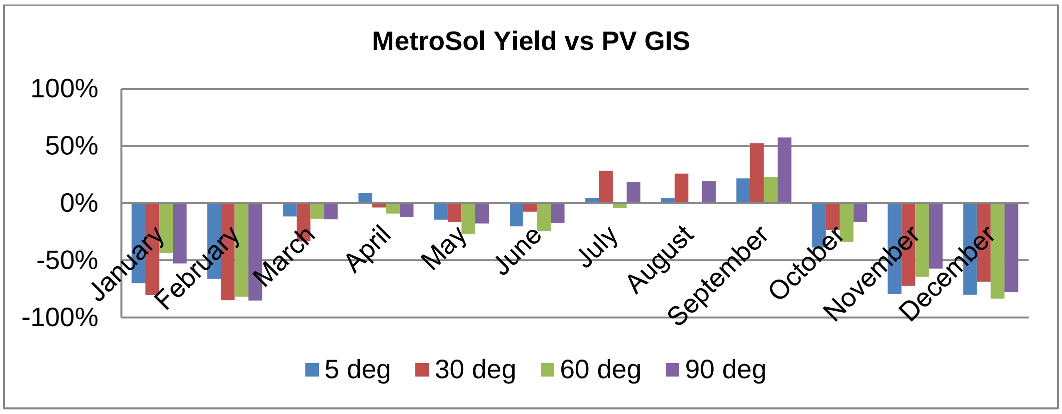

Figure 16. MetroSol PV yield for year 2014 compared to simulated PVGIS data [%].

Table 3 illustrates the difference between the monthly generated yield of the MetroSol PV plant and the simulated PV data of PVGis. During the winter months the PV plant produced up to 80% less electricity than the average potential. In September, the 30 and 90 degree tilt angle arrays produced over 50% more than the average potential, whereas the 60 degree tilt angle only produced 23% more than the average potential. The same situation can be observed in May, June and July.

Table 3. MetroSol PV yield for year 2014 compared to simulated PVGIS data [%]. Positive values represent months when the MetroSol PV plant outperformed the average potential of such a system.

	05 deg	30 deg	60 deg	90 deg	System
January	-70%	-80%	-43%	-53%	-58%
February	-66%	-85%	-82%	-85%	-81%
March	-12%	-33%	-14%	-14%	-19%
April	9%	-4%	-9%	-12%	-4%
May	-15%	-17%	-27%	-18%	-19%
June	-20%	-7%	-24%	-17%	-17%
July	5%	28%	-4%	19%	12%
August	5%	26%	0%	19%	12%
September	22%	52%	23%	57%	39%
October	-39%	-23%	-34%	-16%	-27%
November	-80%	-72%	-64%	-57%	-66%
December	-80%	-69%	-83%	-78%	-78%
Year total	**-8%**	**-4%**	**-18%**	**-10%**	**-10%**

It is clear that the PV electricity generation data from the MetroSol laboratory is not suitable for neither dimensioning nor feasibility calculation purposes. The data could, however, be corrected to achieve a fairly realistic PV generation profile. The goal of this study is to analyse the yield and load profiles on an hourly versus monthly basis without taking a stand on the feasibility of PV systems in Finland, and, therefore, this correction is not necessary. For dimensioning and feasibility purposes, it is more suitable to use PV electricity generation profiles based on average historical irradiation records.

6.3 Electricity Load Profile Simulation

Electricity is used for various purposes in a building. HVAC equipment, such as ventilation fans, circulation pumps, heating coils and air-conditioning units designed to provide a controlled indoor environment and produce sufficient building services for the residents, require electricity to operate. Building users, on the other hand, need electricity for lighting and technical appliances.

A building electricity load profile is created by estimating the use of electricity in a building on an hourly basis. In order to perform accurate dynamic building energy simulations, it is very important to establish accurate and realistic electricity load profiles. These profiles help to achieve a balance between energy supply and demand, and serve as a platform for feasibility studies of technical improvements. [40.]

Hourly electricity loads can be determined by the user profile of a building. A user profile consists of hourly load factors, i.e. a percentage factor of the maximum estimated load, unique for the space and the type of activity conducted in it. User profiles are needed to accurately determine the user schedules of different building types, taking seasonal factors such as weekends and holidays into account. [40.]

The electricity loads of a building can vary greatly in a relatively short period of time, from base load to momentary peaks. Base load is a term used to describe the average minimum electricity load when the building is not being used, e.g. at night and during holidays. The peaks are caused by an increased presence of people requiring lighting, sufficient ventilation and electricity for their technical appliances.

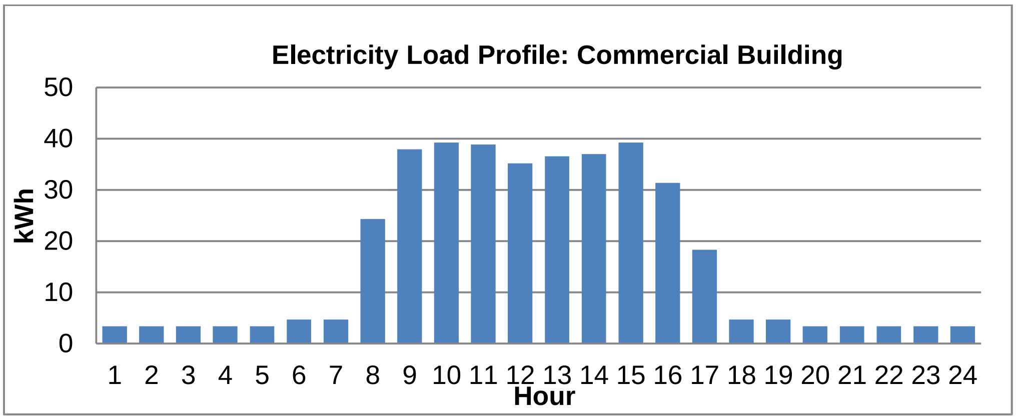

Figure 17. Simulated electricity load profile of a commercial building.

Different building types have different load profile characteristics. A commercial building (see figure 17) has a load profile where the electricity use is high during business hours.

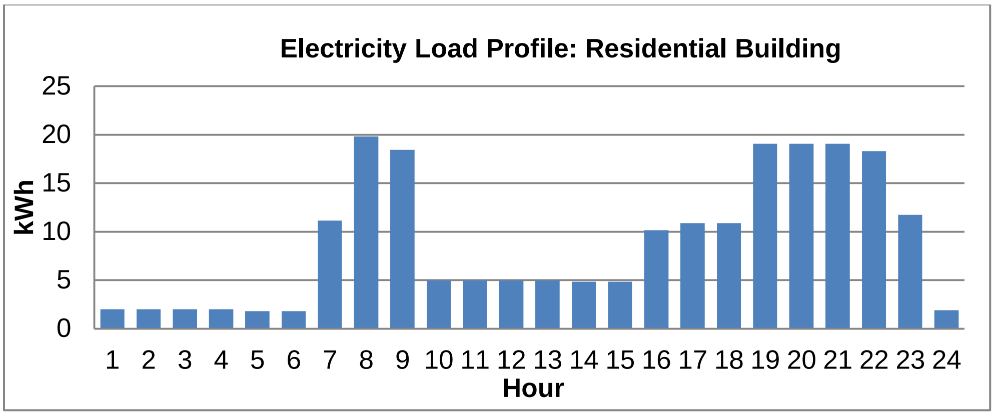

Figure 18. Simulated electricity load profile of a residential building.

A residential building load profile (see figure 18) usually consists of two peaks, in the morning and the evening, when the residents are at home. During the day the electricity use is reduced as the residents are at work. [40.]

6.4 Building Electricity Load Profiles

The following building electricity load profiles are simulated using the RIUSKA energy simulation software. The BIM models used in the simulations represent typical buildings of respective building types. The initial profile data used in these simulations is based on a rapport created as the result of a survey conducted by The Finnish Association of HVAC Societies FINVAC. The survey project, initiated by the Finnish Ministry of Environment, aims to provide improved user profile data especially for simulating the cooling needs in various building spaces.

RIUSKA is a dynamic energy simulation software developed by the Finnish engineering consulting firm Granlund Oy. It is based on the internationally acclaimed DOE 2.1E building energy analysis software. The software utilizes an imported building information model (BIM) to calculate a building's thermal conditions and energy consumption on an hourly basis. [41.]

RIUSKA is a useful tool for examining the energy efficiency of different HVAC solutions in existing buildings or design projects. It shows how different HVAC systems, energy costs, insulation, windows, geographical orientation, local climate etc. will affect the building's energy efficiency and indoor climate. [41.] RIUSKA is approved as a dynamic energy simulation tool for BREEAM, the world's foremost environmental assessment method and rating system for buildings [42].

Case 1: Kindergarten

The daily schedules of lighting, equipment consumption and user presence of the kindergarten are shown in table 4. The table also presents the daily operation cycles of the building's air-conditioning (A-C) units, as well as the electricity consumption of auxiliary building services devices.

Table 4. Electricity load profile specifications of the kindergarten. [40]

Space	Load	W/m2	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Entrance	Lighting	18.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Class room	Lighting	18.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.0	0.5	0.5	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.0	0.5	0.5	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hall	Lighting	18.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Staff room	Lighting	18.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dining room	Lighting	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kitchen	Lighting	18.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	56000 W (1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	4 persons	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bathroom	Lighting	18.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Locker room	Lighting	18.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	37.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.5	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

HVAC equipment

A-C Unit	Type	η, heat recovery	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Primary	CAV (2	50%	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
Kitchen	CAV (3	60%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Bathrroms	CAV (2	79%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

hot water circulation pump [W]	80
Heating auxiliary devices [W]	370

(1 1100 W constant load (refridgeration etc.)

(2 Night ventilation: 3 °C offset, minimum 21 °C

(3 Always on

Building electricity load profiles of the kindergarten is presented on a daily, weekly and yearly basis in figure 19.

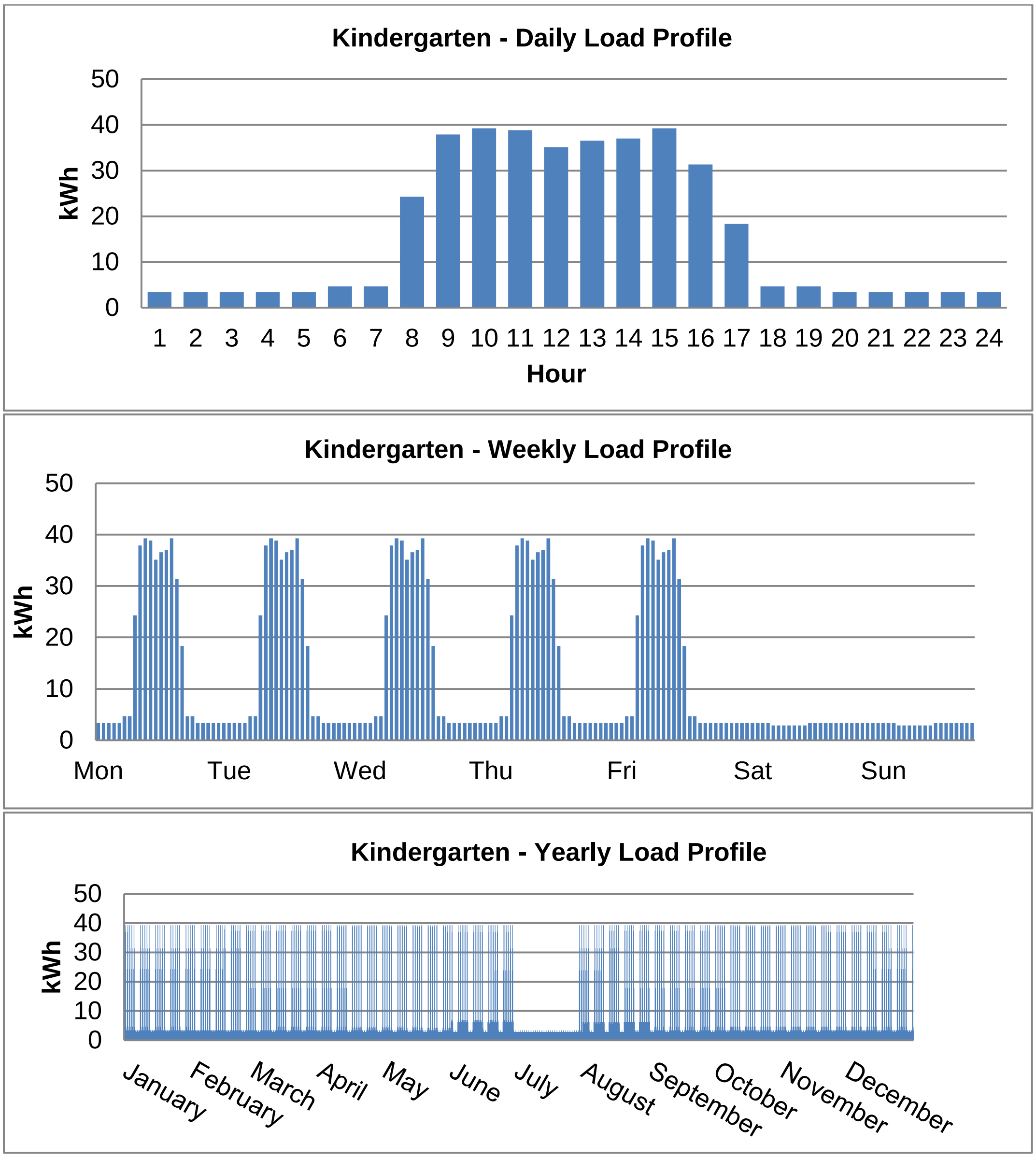

Figure 19. Electricity load profiles of the Kindergarten.

As the yearly load profile indicates, the kindergarten is not in operation in July due to summer holidays.

Case 2: Residential Building

The daily schedules of lighting, equipment consumption and user presence of the residential building are shown in table 5. The table also presents the daily operation cycles of the building's A-C units, as well as the electricity consumption of auxiliary building services devices.

Table 5. Electricity load profile specifications of the residential building. [40]

Space	Load	W/m2	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Entrance	Lighting	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0
	Equipment	4.0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0
Apartment (living room + kitchen + entrance)	Lighting	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0.5	1.0	1.0	1.0	1.0	0.5	0.0
	Equipment	14.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0.5	1.0	1.0	1.0	1.0	0.5	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0.5	1.0	1.0	1.0	1.0	0.5	0.0
Apartment (Bathroom)	Lighting	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.0	0.0
	Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.0	0.0
Apartment (Bedroom)	Lighting	8.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
	Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	12.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
Hallway	Lighting	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0
	Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Drying room	Lighting	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Equipment	200.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0
	Presence	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Storage	Lighting (1	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0
	Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Presence	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

HVAC equipment

A-C Unit	Type	η, heat recovery	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Apartments	CAV (2	75%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hallway	CAV (2	57%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sauna	CAV (3	50%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

hot water circulation pump [W]	400
Heating auxiliary devices [W]	300
Yard lighting, automatic [W]	200

Residene presence	
Winter	100%
Spring	80%
Summer	60%
Autumn	80%

(1 Weekend schedule 9 AM- 8 PM
(2 Always on
(3 Monday - Sunday

Building electricity load profiles of the residential building is presented on a daily, weekly and yearly basis in figure 20.

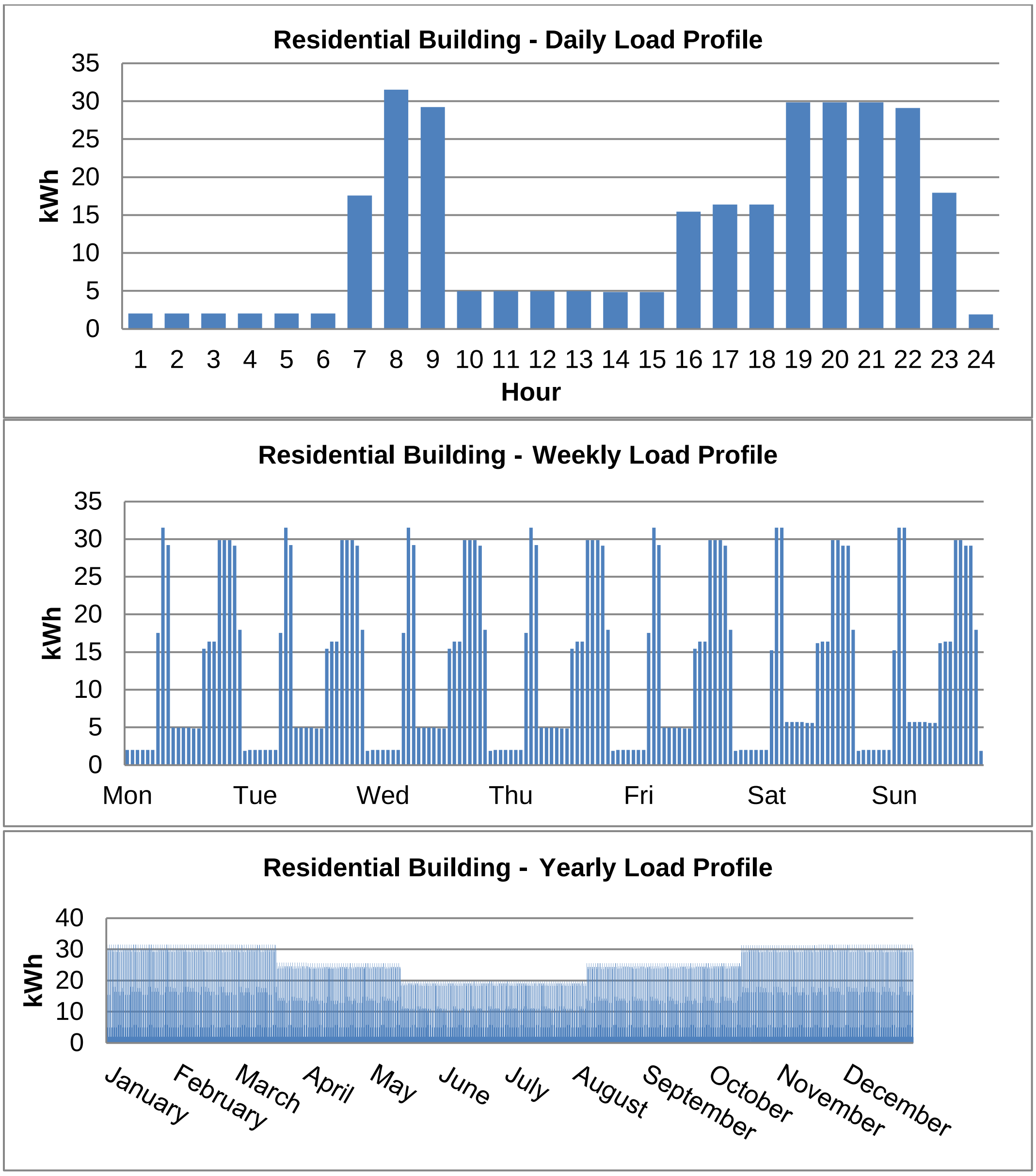

Figure 20. Electricity load profile the residential building.

As shown in the yearly load profile, the user profile takes the decreased residence in the summer months into account.

6.5 LCC analysis parameters

The **investment costs** of a PV system are generally relative to the size of the installation, with a decreasing price per peak Watt (€/W_p) as the system peak output increases. The investment costs of PV systems in this study are estimated to range from 3 €/W_p for small-scale installations to 2 €/W_p for big-scale installations (see figure 21).

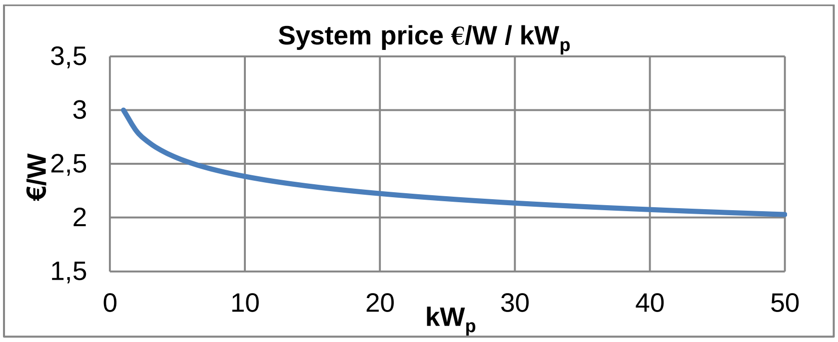

Figure 21. Investment costs as a function of PV system output.

PV systems have relatively high up-front investment costs, making the cost of capital an important factor in the overall feasibility of such an investment. Interest rates on loans can significantly decrease the IRR on an investment of this nature. [34.] This study aims to solely examine the economic prospects of PV system dimensioning optimization. Thus, for the sake of simplicity, the investment costs in this study are considered to be up-front single payments without additional expenses.

The simulated kindergarten is considered to be eligible for a grant of 30% of the investment cost under the governmental renewable energy support scheme issued by the ELY-centre. The simulated residential building receives no financial support for its PV system installation.

O&M costs are minimal for PV systems. The technology is simple, reliable and easy to maintain. O&M mainly consists of administration and monitoring, minor repairs of system components and preventative maintenance, such as snow, leaf and dust removal. [43] The O&M costs are estimated to be 0.5% for large PV systems and 1% of system initial cost per year for small systems.

Apart from the initial investment costs at the start of the PV system's life-cycle and the annual O&M costs, the only other expense of the PV systems in this study is the replacement of the inverters after 15 years of operation. The price of the **inverter replacements** are estimated to be 0.2 €/W_p, including installation costs. [1.]

The electricity market in Finland is an open market, meaning that private suppliers can sell electricity into the existing distribution grid. This allows for a competitive market where the end-consumer has the possibility to choose their electricity supplier. Finland has a broad selection of power companies offering a wide range of electricity contracts. Companies often adjust their electricity prices according to the real-time Nord Pool market spot-price. Additionally, electricity prices also include delivery charges, taxes and the supplier's profit margin. Prices typically vary for residential, commercial and industrial customers. [44]

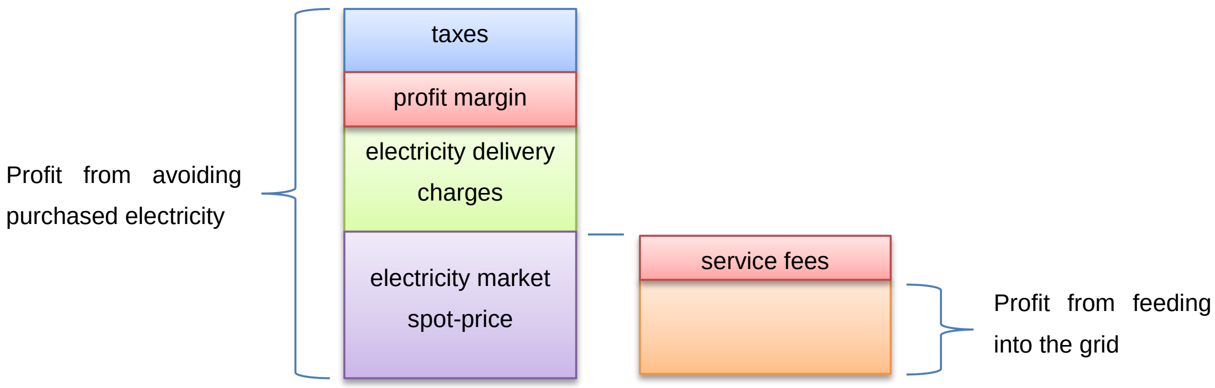

Figure 22. Components of market spot-price based electricity prices.

When replacing purchased electricity with generated PV electricity, the monetary benefit equals the purchasing price of the electricity that was replaced. When generating a surplus of PV electricity that is fed into the grid, the producer is compensated by the contracted buyer, i.e. the power company. However, with the lack of tariffs, the private producer only receives the real-time market spot-price reduced by transaction fees (see figure 22).

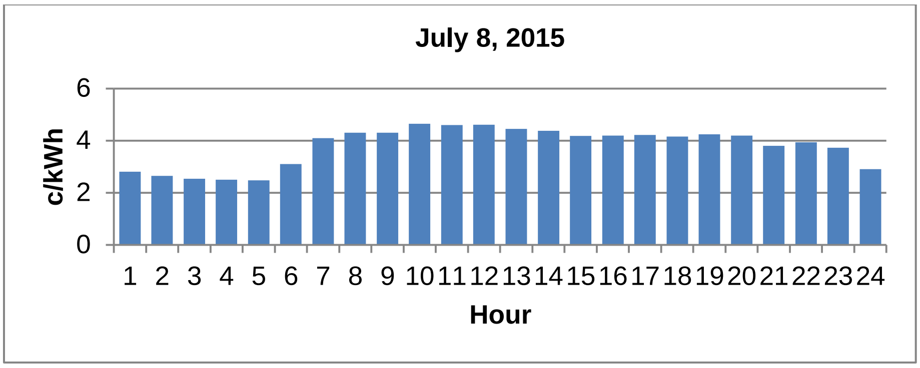

Figure 23. Hourly Nord Pool market spot-prices during July 8, 2014. [45]

Since the real-time market spot-price fluctuates over time, it is appropriate to take this into account when examining the monetary effects of replaced and grid-fed electricity on an hourly basis. In this study we use the Finnish electricity market spot-price for each hour of the year 2014 to calculate the realistic value of the building's electricity balance for each hour (see figure 23 and 24).

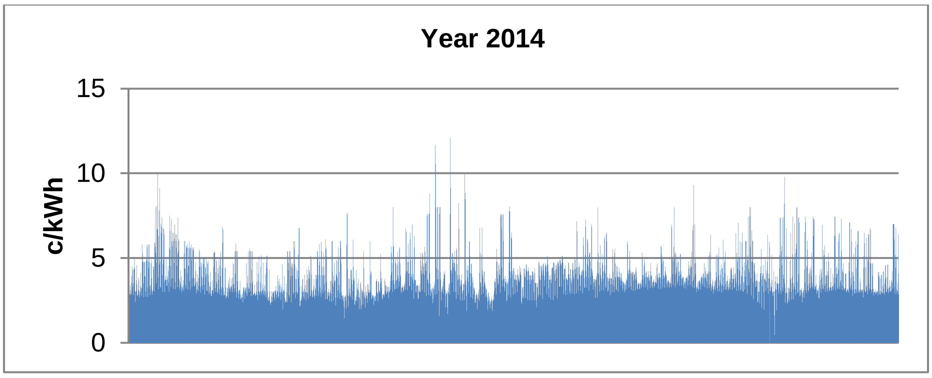

Figure 24. Nord Pool market spot-prices for year 2014. [45]

The electricity prices for the Kindergarten in Case 1 are estimated to consist of the market spot-price plus 57% of additional expenses (incl. 24% tax,) while the additional expenses for the residential building in case 2 are estimated to be 68% of the total electricity costs.

The **levelized cost of energy** (LCOE) for purchased electricity in year 2014 based on hourly market spot-prices are:

- 0.091 €/kWh for the kindergarten (commercial customer)
- 0.123 €/kWh for the residential building (private customers).

A PV system's ability to convert solar irradiance into electricity decreases over time due to component wear. The **performance degradation** of PV panels has a negative effect on the overall feasibility of PV installations and needs to be taken into account in an LCC analysis. A field test report by U.S. National Renewable Energy Laboratory (NREL) estimates a degradation rate of 0.5% per year for crystalline panels [46].

Additional LCC analysis parameters used in this study are as follows:

- Service period = 30 years
- Discount rate = 1.5%
- Electricity price escalation = 2% / p.a.
- Residual value after 30 years = 0 €

The electricity price escalation is a highly speculative parameter and should always be subject to sensitivity analysis. The rate of electricity price escalation has a big impact on the length of the payback period. Since this study focuses on comparing different sized PV systems with similar LCC parameters a set electricity price escalation value at 2% / p.a. is being used.

7 Study Results

7.1 Case 1: Kindergarten

In case 1, the kindergarten, the PV production profile of a 20 kW_p PV system installed at a 30 degree tilt angle is compared to the kindergarten's electricity load profile on both an hourly and monthly basis (see table 6).

Table 6. Hourly and monthly comparison of the overall electricity balance of PV and electricity load profiles of the kindergarten.

Hourly Comparison

Electricity Load	104262	kWh
PV Output	16359	kWh
Utilized PV Electricity	12035	kWh
Excess PV Electricity	4324	kWh
Ratio	74 %	

Month	Electricity Load [kWh]	PV Output [kWh]	Balance [kWh]	Sold Energy [kWh]
January	9599	52	9548	0
February	8413	124	8289	4
March	9240	991	8249	114
April	8778	2080	6698	387
May	9459	2218	7241	399
June	9486	2371	7116	421
July	2853	3339	-486	2154
August	10293	2512	7781	456
September	8478	1983	6495	387
October	9537	570	8968	3
November	9167	73	9094	0
December	8958	46	8911	0

Monthly Comparison

Electricity Load	104262	kWh
Pv Output	16359	kWh
Utilized PV Electricity	15873	kWh
Excess PV Electricity	486	kWh
Ratio	97 %	

Month	Electricity Load [kWh]	PV Output [kWh]	Balance [kWh]	Sold Energy [kWh]
January	9599	52	9548	0
February	8413	124	8289	0
March	9240	991	8249	0
April	8778	2080	6698	0
May	9459	2218	7241	0
June	9486	2371	7116	0
July	2853	3339	-486	486
August	10293	2512	7781	0
September	8478	1983	6495	0
October	9537	570	8968	0
November	9167	73	9094	0
December	8958	46	8911	0

Although the total monthly electricity consumption and PV electricity production is equal in both calculations, the amount of excessively generated PV electricity fed into the grid, at a ratio of 74% of PV utilization versus 97% in the monthly comparison, is significantly higher in the hourly comparison.

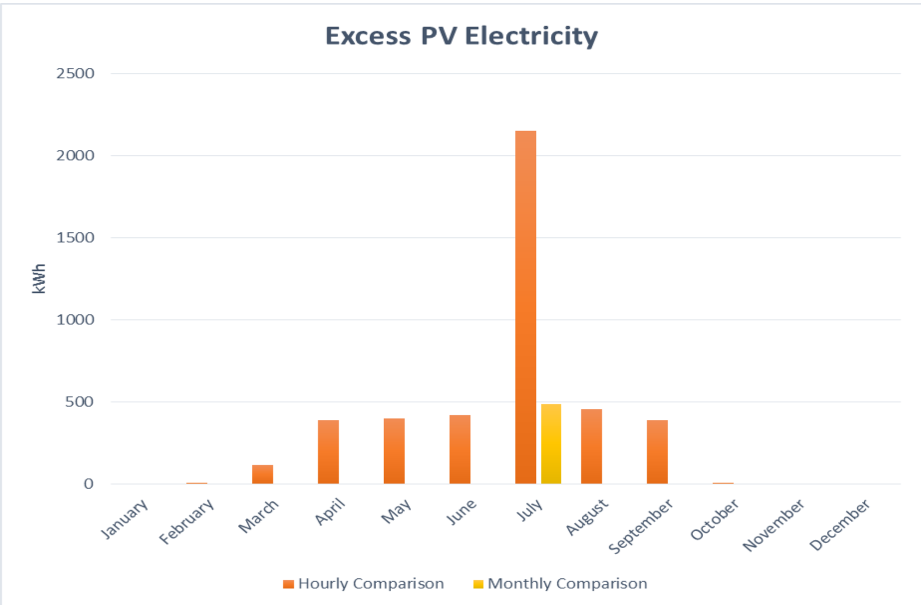

Figure 25. Excessively produced PV electricity in case 1 during 2014.

A closer look at February and onwards in the hourly comparison chart shows that although the produced PV electricity is very limited in wintertime, there is still a small amount of excessively generated PV electricity being fed into the grid with a PV system of this size. In July, when the kindergarten is non-operational during holidays, the building is unable to utilize the excellent solar irradiation conditions. This results in a surge of PV electricity being fed into the grid (see figure 25).

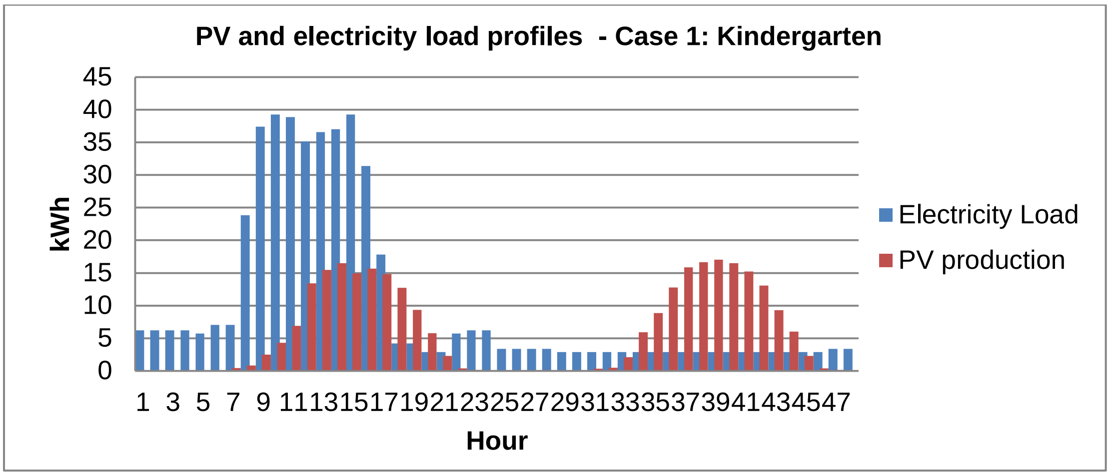

Figure 26. PV electricity and building electricity load profiles of the kindergarten.

By breaking down the profile structures of days when the building is in standard operation and days when the building is empty, i.e. during weekends and holidays, the mismatch of momentary PV electricity production and building electricity consumption can be identified. Figure 26 shows the profiles of Friday, June 15, and Saturday, June 16. On Friday evening after closing time, the PV system produces excess electricity from between 5pm and 8pm. This happens every sunny weekday during summer. In weekends, the building is consumes electricity at base load and can therefore only utilize a small portion of the generated PV electricity.

7.2 Case 2: Residential building

The PV production and electricity load profiles of the residential building further accentuate the effects of hourly profile mismatches. In this comparison, the residential building is equipped with a 30 kW_p PV system installed at a 30 degree tilt angle (see table 7).

Hourly Comparison

Electricity Load	98343	kWh
PV Output	24539	kWh
Utilized PV Electricity	14949	kWh
Excess PV Electricity	9590	kWh
Ratio	61 %	

Month	Electricity Load [kWh]	PV Output [kWh]	Balance [kWh]	Sold Energy [kWh]
January	9542	78	9464	9
February	8616	187	8430	5
March	8925	1486	7439	450
April	7801	3120	4681	1087
May	7212	3327	3885	1231
June	6390	3556	2834	1456
July	6602	5008	1593	2371
August	7813	3768	4046	1558
September	7810	2975	4836	1157
October	8868	854	8014	255
November	9219	110	9109	12
December	9545	70	9475	0

Monthly Comparison

Electricity Load	98343	kWh
Pv Output	24539	kWh
Utilized PV Electricity	24539	kWh
Excess PV Electricity	0	kWh
Ratio	100 %	

Month	Electricity Load [kWh]	PV Output [kWh]	Balance [kWh]	Sold Energy [kWh]
January	9542	78	9464	0
February	8616	187	8430	0
March	8925	1486	7439	0
April	7801	3120	4681	0
May	7212	3327	3885	0
June	6390	3556	2834	0
July	6602	5008	1593	0
August	7813	3768	4046	0
September	7810	2975	4836	0
October	8868	854	8014	0
November	9219	110	9109	0
December	9545	70	9475	0

Table 7. Hourly and monthly comparison of the overall energy balance of PV and electricity load profiles of the residential building.

The gap between ratios of utilization obtained from the hourly and monthly comparisons of the residential building is even greater than that of the kindergarten. The hourly comparison shows that excess PV electricity will be produced during every month of the year with an overall utilization ratio of 61%. The monthly comparison does not detect this and suggests that 100% of PV electricity will be utilized by the building (see figure 27).

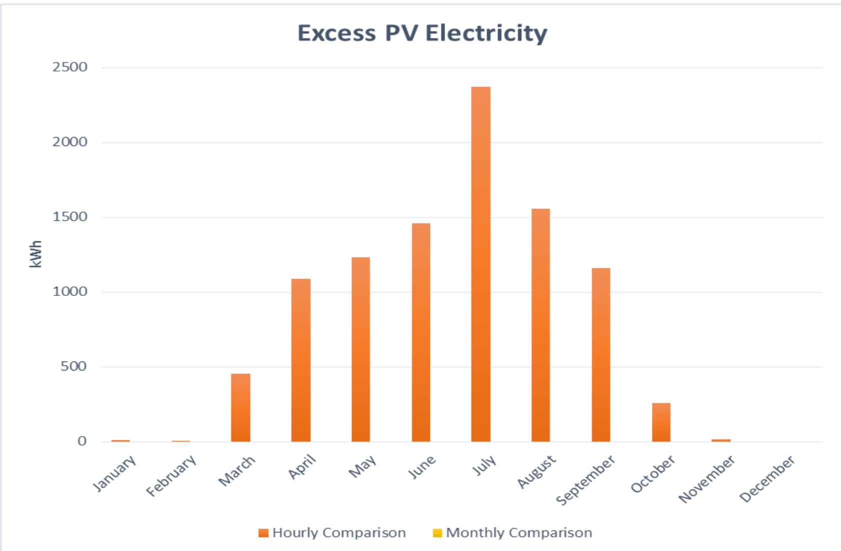

Figure 27. Excessively produced PV electricity in case 2 during 2014.

The system output is big enough to produce an amount of electricity that almost covers the building's electricity peak load. The daily electricity load profile, however, consists of morning and evening peaks with a significant drop during the middle of the day (see figure 28). This is when PV electricity production peaks, resulting in a great amount of excessively generated PV electricity being fed into the grid.

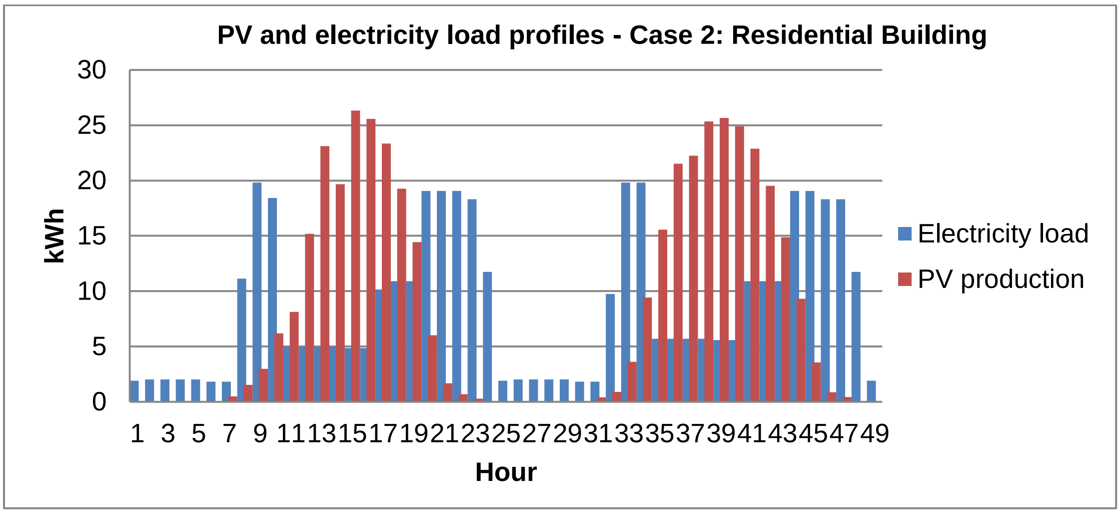

Figure 28. PV electricity and building electricity load profiles of the residential building.

7.3 LCC analysis

The differences in simulation accuracy between the hourly and monthly comparisons are clearly illustrated by projecting a PV system's IRR over the course of its service period is against the corresponding system output.

Figure 29 shows the IRR of a PV system of selected size, installed at a 30 degree tilt angle on the rooftop of the kindergarten. The irradiation data is obtained from the MetroSol laboratory from year 2014 with minimal shading.

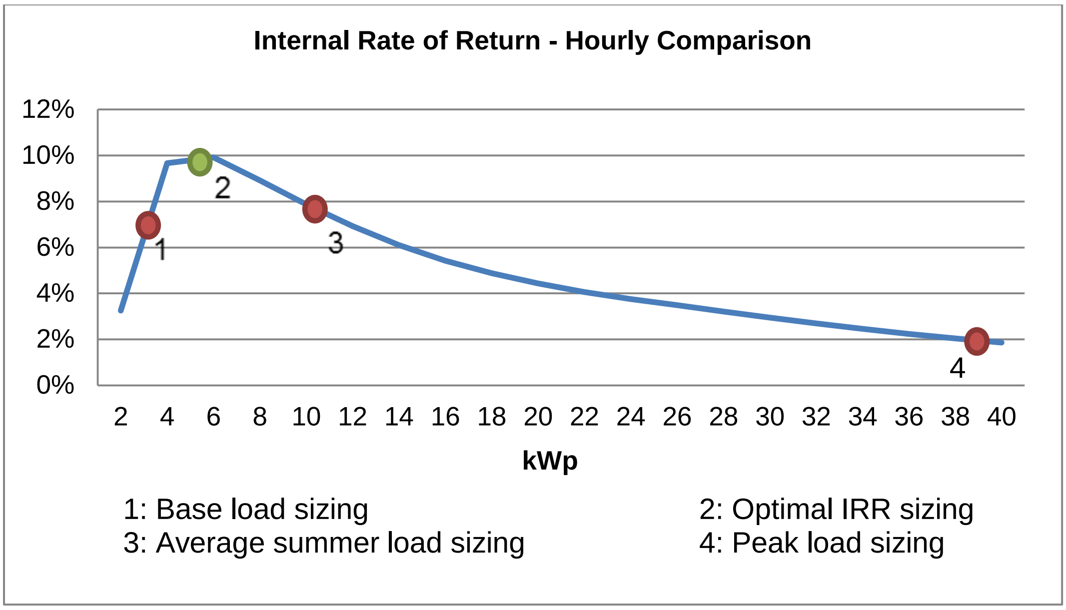

Figure 29. IRR of a PV system in case 1: Kindergarten. Hourly comparison. The green dot is the optimized IRR output.

With the calculation parameters used, it is possible to determine a theoretical optimal size for a PV system in terms of maximum IRR. In this case the optimal IRR is 10.2% at a nominal PV system output of 4.9 kW_p. For reference, the three red dots represent the outcome of three commonly used sizing methods for grid-connected micro-scale PV systems in Finland.

The reduced accuracy of a monthly comparison of the analysis results obtained from the kindergarten simulation is shown in figure 30. Since the monthly comparison is unable to detect the true ratio of utilized and excessively generated PV electricity, it takes the value of utilized PV electricity into account with little to no consideration of the excessively generated PV electricity that inevitably follows as the PV system output increases.

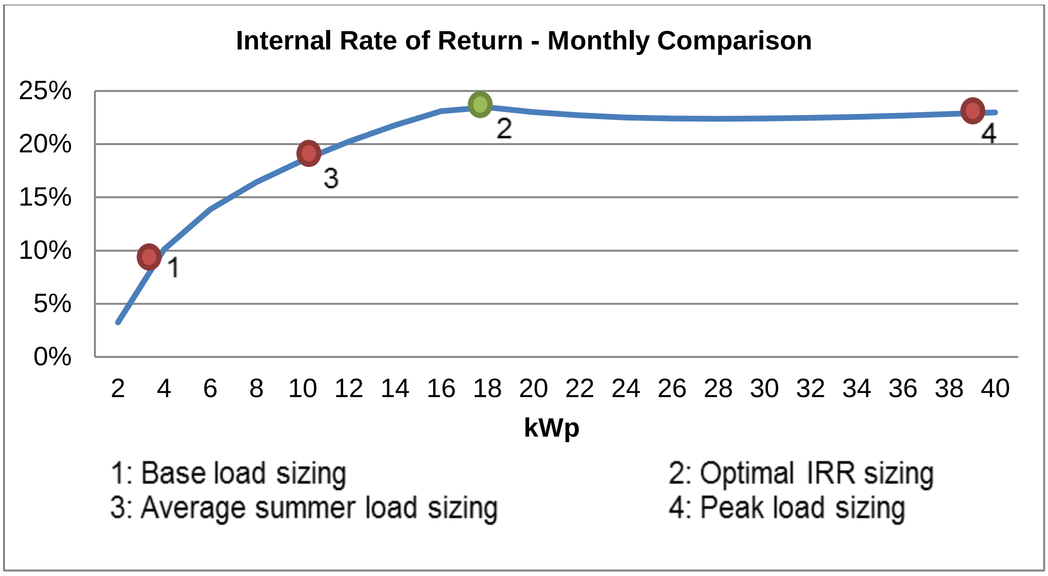

Figure 30. IRR of a PV system in case 1: Kindergarten. Monthly comparison. The green dot is the optimized IRR output.

The same mismatch is present with the different electricity load profile of the residential building. As figure 31 shows, there is an even larger gap between the base load sizing and optimal IRR sizing outputs.

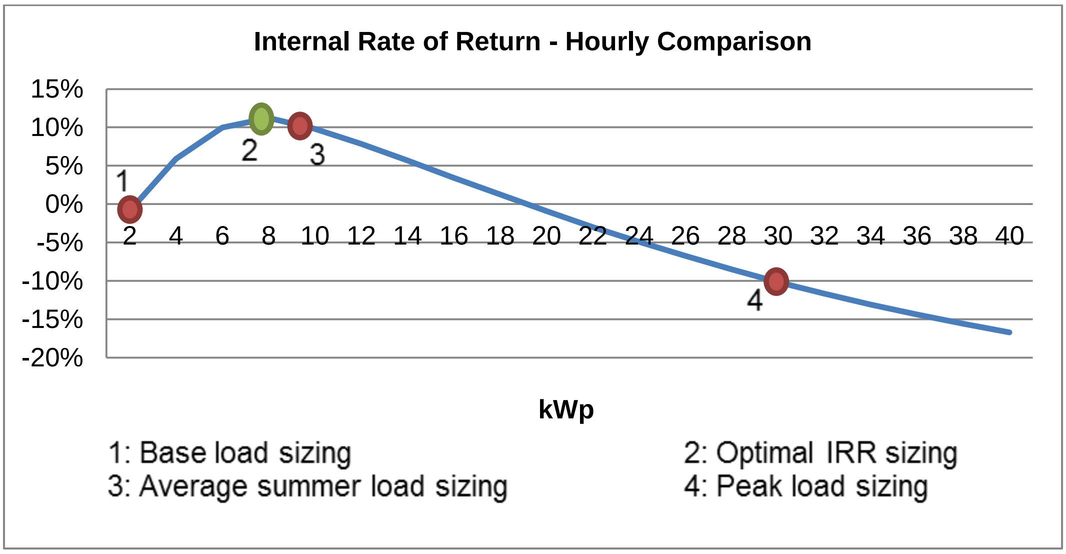

Figure 31. IRR of a PV system in case 2: Residential building. Hourly comparison. The green dot is the optimized IRR output.

The monthly comparison of the residential building shows an even greater inaccuracy than the comparison of the kindergarten (see figure 32).

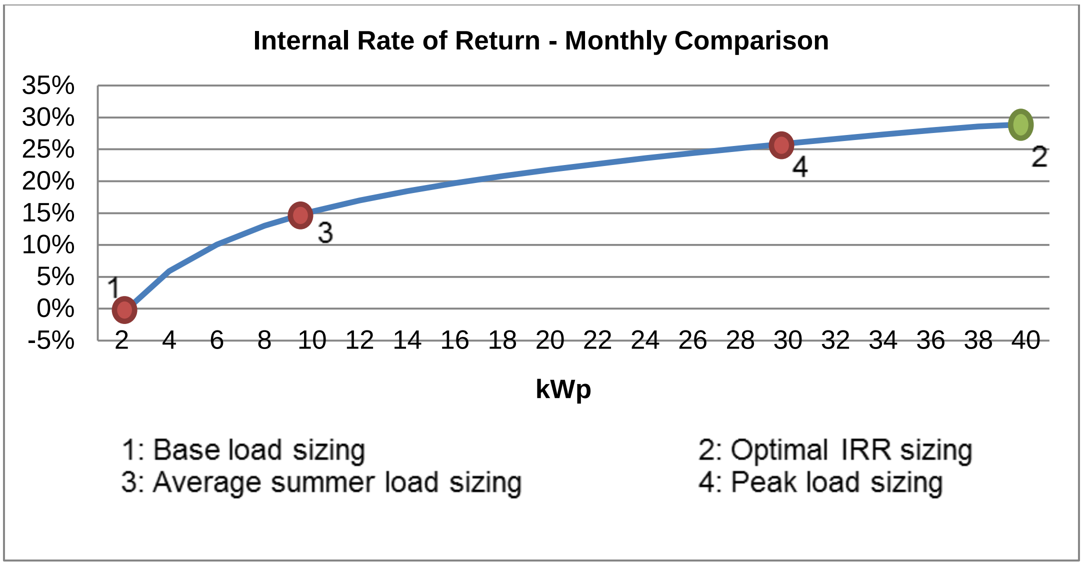

Figure 32. IRR of a PV system in case 2: Residential building. Monthly comparison. The green dot is the optimized IRR output.

It is important to point out that LCC analyses of this nature are highly speculative with several unknown simulation factors at play. The factors that have the greatest impact on the results in this kind of evaluation are the ones that are tied to the system output size. As the investment cost is a major factor in overall feasibility, it is appropriate to investigate its effect on the IRR curve in these analyses. The investment cost parameter used in the study follows the system price curve presented in chapter 6.5 (see figure 33). It illustrates the assumption that the €/W_p cost of a PV installation will be slightly reduced as the system output increases.

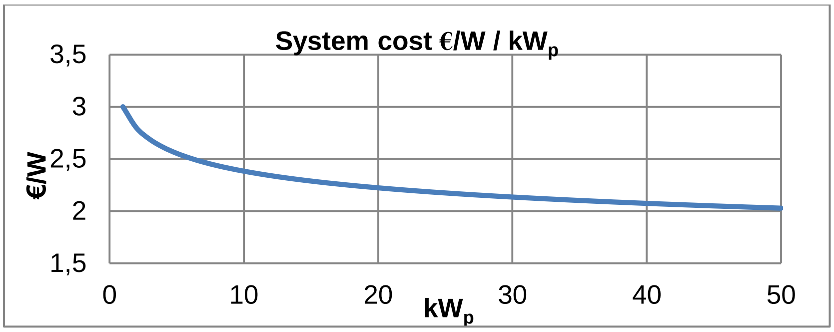

Figure 33. PV system cost parameter used in the LCC analysis.

In order to determine the impact that the system price assumption has on the IRR curve, the same LCC analysis is done using a fixed 2.5 €/W_p PV system cost. Figure 34 and 35 show the IRR curves of the hourly comparison calculations for each simulation case.

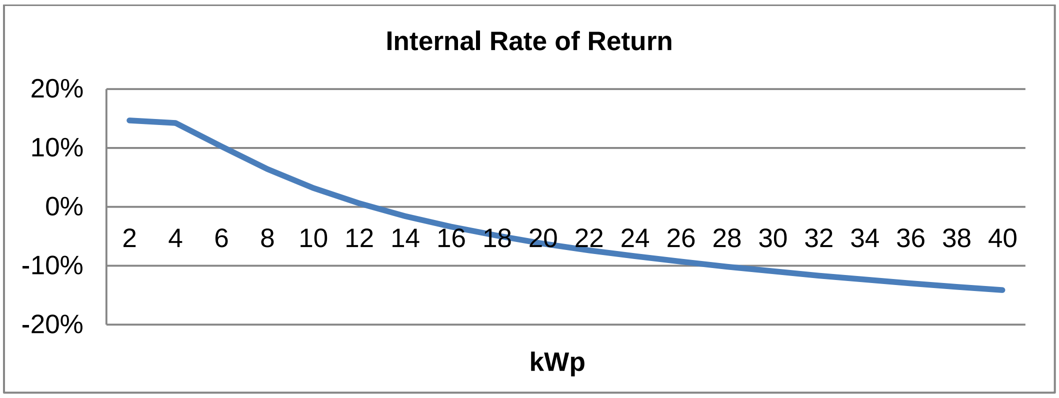

Figure 34. IRR of case 1: Kindergarten with a fixed 2,5 €/Wp PV system cost.

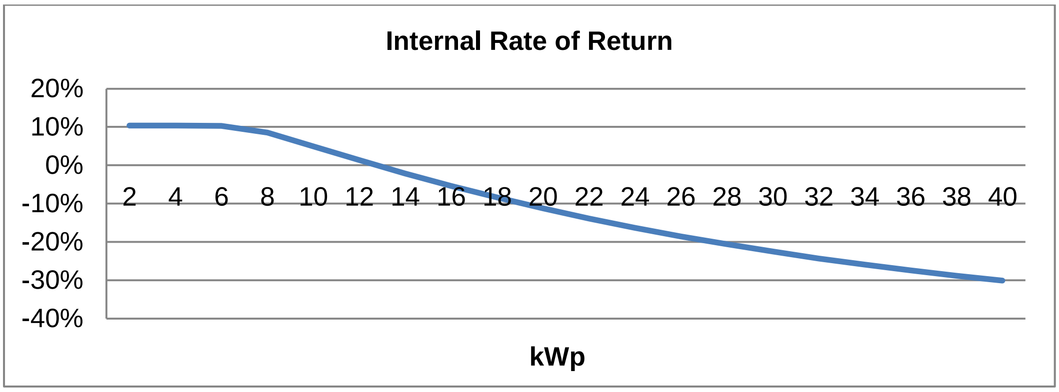

Figure 35. IRR of case 2: Residential building with a fixed 2,5 €/Wp PV system cost.

With a fixed 2.5 €/W_p PV system cost, the IRR curves of both cases promote a PV base load sizing, where all excessively produced PV electricity is avoided. In other words, with a fixed PV system cost parameter, feeding into the grid is never feasible in Finland.

8 Conclusions

The study results strongly suggest that PV electricity and building electricity load profiles should be compared on an hourly basis in order to have sufficient accuracy for feasibility and sizing purposes in a region without tariff systems. It can further be discussed whether an hourly comparison is sufficient enough, since both PV production and building electricity loads can fluctuate heavily within an hour. The monthly comparison completely fails to notice the momentary mismatches between PV production and building electricity load profiles, and severely underestimates the amount of excessively produced PV electricity.

The analysis of the PV production data of 2014 for the MetroSol laboratory also indicate that panel shading, in this case self-shading, has a significant impact on PV production and should be avoided through careful site planning and monitoring.

It can be concluded that the €/W_p PV system cost is an important LCC analysis parameter and that it should be carefully assessed in an attempt to reach a realistic case of optimal IRR sizing. The base load sizing recommendation for regions without grid feed-in compensation is valid when assuming a fixed €/W_p PV system cost. It is a safe method of sizing a PV system in Finland. However, the IRR optimization tool seems to be useful in case-by-case PV system sizing. When estimating a €/W_p PV system cost that declines as PV system output increases, the IRR tool suggests that a certain amount of excessively produced PV electricity is allowed, as long as the economic gains of a higher portion of building electricity consumption replaced by produced PV electricity outweighs the negative aspects of feeding into the grid. As a recommendation, thorough data analysis should be conducted when sizing a PV system.

The LCC analysis made it evident that the investment cost of a PV system is the most critical parameter in feasibility calculations of PV systems. As the PV production can be expected to be relatively stable throughout the service period, it is possible to establish the LCE of PV projects, which in turn can act as a reliable factor in project decision-making. The prediction of future electricity prices and inflation rates are highly speculative and should therefore be subject to careful sensitivity analysis and risk assessment.

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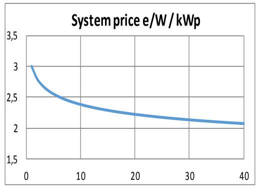
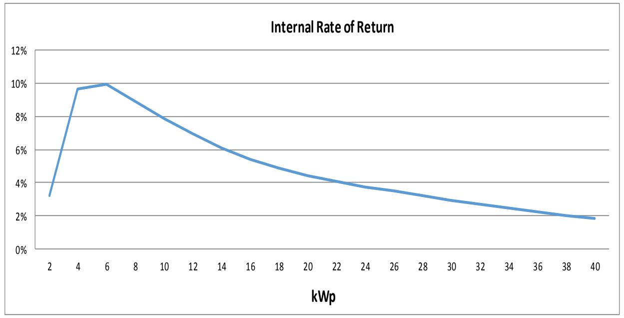
LCC analysis: Kindergarten, 4.9 kW$_p$, 30 degree tilt angle, 2-3 €/W$_p$

Nominal PV output	4,9	kWp	Time span	30	years
Investment cost	8778	€	Discount value	1,5%	
	2,56	€/W	Annual electricity consumptio	104262	kWh
Investment support	30 %		Annual PV system production	4008	kWh
Inverter cost	980	€	Utilized PV electricity	3904	kWh
Electricity purchasing pri	0,092	€/kWh	Purchased electricity	100358	kWh
Electricity selling price	0,034	€/kWh	Excess PV electricity	104	kWh
Electricity price escalatio	2,0%	p.a.	PV output degradation	0,5 %	p.a.
O&M costs	0,5%	p.a.	Utilization ratio	97 %	



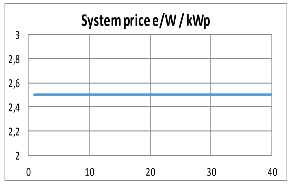
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Investment cost [€]	8778															980															
O&M costs [€]		44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44
NPV of annual expenses [€]	**8778**	**43**	**43**	**42**	**41**	**41**	**40**	**40**	**39**	**38**	**38**	**37**	**37**	**36**	**36**	**819**	**35**	**34**	**34**	**33**	**33**	**32**	**32**	**31**	**31**	**30**	**30**	**29**	**29**	**29**	**28**
Savings from utilized PV electricity [€]		365	372	379	387	395	403	411	419	427	436	445	453	462	472	481	491	501	511	521	531	542	553	564	575	587	598	610	622	635	648
Revenues from sold PV electricity [€]		4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6
Annual savings [€]		368	376	383	391	399	407	415	423	431	440	449	458	467	476	486	496	505	516	526	536	547	558	569	581	592	604	616	629	641	654
NPV of annual savings [€]		**363**	**365**	**366**	**368**	**370**	**372**	**374**	**375**	**377**	**379**	**381**	**383**	**385**	**387**	**389**	**391**	**392**	**394**	**396**	**398**	**400**	**402**	**404**	**406**	**408**	**410**	**412**	**414**	**416**	**418**

NPV of total expenses in 30 years [€]	10616
NPV of total savings in 30 years [€]	11698
Balance after 30 years [€]	1082
Levelized cost of energy [€/kWh]	0,095
Internal rate of return	**10,2 %**



LCC analysis: Kindergarten, 3.4 kW_p, 30 degree tilt angle, set 2.5 €/W_p

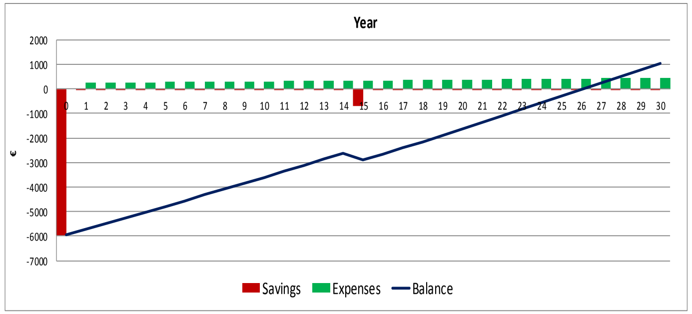
Nominal PV output	3,4	kWp	Time span	30	years
Investment cost	5950	€	Discount value	1,5%	
	2,50	€/W	Annual electricity consumptio	104262	kWh
Investment support	30 %		Annual PV system production	2781	kWh
Inverter cost	680	€	Utilized PV electricity	2780	kWh
Electricity purchasing pri	0,092	€/kWh	Purchased electricity	101482	kWh
Electricity selling price	0,030	€/kWh	Excess PV electricity	1	kWh
Electricity price escalatio	2,0%	p.a.	PV output degradation	0,5 %	p.a.
O&M costs	0,5%	p.a.	Utilization ratio	100 %	

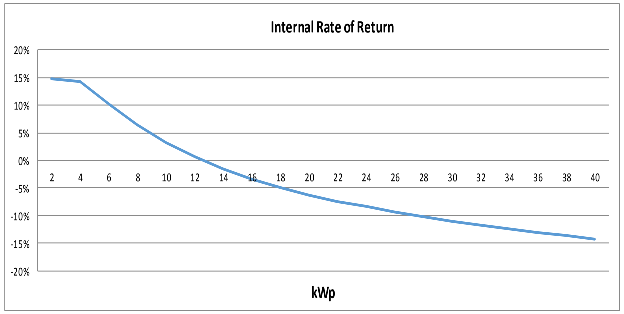


Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Investment cost [€]	5950															680
O&M costs [€]		30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
NPV of annual expenses [€]	**5950**	**29**	**29**	**28**	**28**	**28**	**27**	**27**	**26**	**26**	**26**	**25**	**25**	**25**	**24**	**568**
Savings from utilized PV electricity [€]		260	265	271	276	282	287	293	299	305	311	317	323	330	337	343
Revenues from sold PV electricity [€]		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Annual savings [€]		260	265	271	276	282	287	293	299	305	311	317	323	330	337	343
NPV of annual savings [€]		**256**	**258**	**259**	**260**	**261**	**263**	**264**	**265**	**267**	**268**	**269**	**271**	**272**	**273**	**275**

Year	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Investment cost [€]															
O&M costs [€]	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
NPV of annual expenses [€]	**23**	**23**	**23**	**22**	**22**	**22**	**21**	**21**	**21**	**21**	**20**	**20**	**20**	**19**	**19**
Savings from utilized PV electricity [€]	350	357	364	372	379	387	394	402	410	418	427	435	444	453	462
Revenues from sold PV electricity [€]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Annual savings [€]	350	357	364	372	379	387	394	402	410	418	427	435	444	453	462
NPV of annual savings [€]	**276**	**277**	**279**	**280**	**281**	**283**	**284**	**286**	**287**	**288**	**290**	**291**	**293**	**294**	**296**

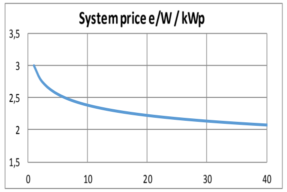
NPV of total expenses in 30 years [€]	7208
NPV of total savings in 30 years [€]	8265
Balance after 30 years [€]	1056
Levelized cost of energy [€/kWh]	0,093
Internal rate of return	**14,7 %**





LCC analysis: Residential building, 7.6 kW$_p$, 30 degree tilt angle, 2-3 €/W$_p$

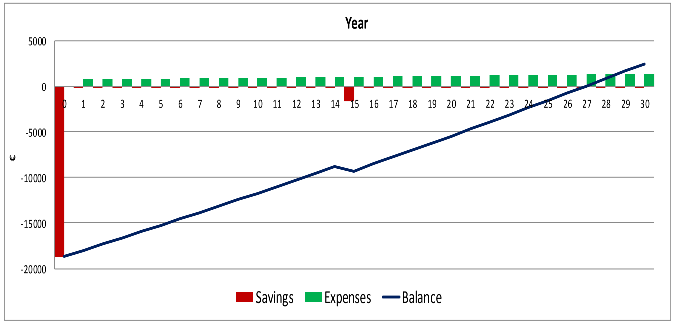
Nominal PV output	7,6	kWp	Time span	30	years
Investment cost	18681	€	Discount value	1,5%	
	2,45	€/W	Annual electricity consumptio	98343	kWh
Investment support	0 %		Annual PV system production	6241	kWh
Inverter cost	1526	€	Utilized PV electricity	6145	kWh
Electricity purchasing pri	0,123	€/kWh	Purchased electricity	92198	kWh
Electricity selling price	0,032	€/kWh	Excess PV electricity	96	kWh
Electricity price escalatio	2,0%	p.a.	PV output degradation	0,5 %	p.a.
O&M costs	0,5%	p.a.	Utilization ratio	98 %	

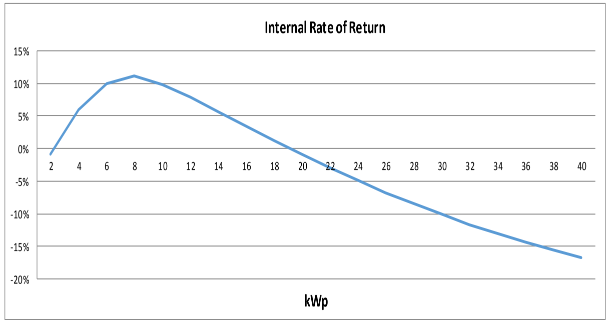


Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Investment cost [€]	18681															1526
O&M costs [€]		93	93	93	93	93	93	93	93	93	93	93	93	93	93	93
NPV of annual expenses [€]	**18681**	**92**	**91**	**89**	**88**	**87**	**85**	**84**	**83**	**82**	**80**	**79**	**78**	**77**	**76**	**1295**
Savings from utilized PV electricity [€]		772	788	804	820	836	853	870	887	905	923	941	960	980	999	1019
Revenues from sold PV electricity [€]		3	3	3	3	3	3	4	4	4	4	4	4	4	4	4
Annual savings [€]		775	791	807	823	839	856	873	891	909	927	945	964	984	1003	1023
NPV of annual savings [€]		**764**	**768**	**772**	**775**	**779**	**783**	**787**	**791**	**795**	**799**	**803**	**806**	**810**	**814**	**818**

Year	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Investment cost [€]															
O&M costs [€]	93	93	93	93	93	93	93	93	93	93	93	93	93	93	93
NPV of annual expenses [€]	**74**	**73**	**71**	**70**	**69**	**68**	**67**	**66**	**65**	**64**	**63**	**62**	**62**	**61**	**60**
Savings from utilized PV electricity [€]	1039	1060	1081	1103	1125	1148	1171	1194	1218	1242	1267	1292	1318	1345	1372
Revenues from sold PV electricity [€]	4	4	4	4	5	5	5	5	5	5	5	5	5	5	6
Annual savings [€]	1044	1065	1086	1108	1130	1152	1175	1199	1223	1247	1272	1298	1324	1350	1377
NPV of annual savings [€]	**822**	**827**	**831**	**835**	**839**	**843**	**847**	**851**	**855**	**860**	**864**	**868**	**872**	**877**	**881**

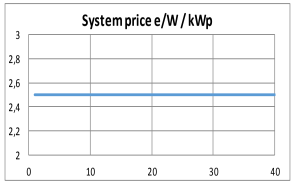
NPV of total expenses in 30 years [€]	22144
NPV of total savings in 30 years [€]	24636
Balance after 30 years [€]	2491
Levelized cost of energy [€/kWh]	0,127
Internal rate of return	**11,3 %**





LCC analysis: Residential building, 5.7 kW$_p$, 30 deg tilt angle, set 2.5 €/W$_p$

Nominal PV output	5,7	kWp	Time span	30	years
Investment cost	14250	€	Discount value	1,5%	
	2,50	€/W	Annual electricity consumptio	98343	kWh
Investment support	0 %		Annual PV system production	4662	kWh
Inverter cost	1140	€	Utilized PV electricity	4662	kWh
Electricity purchasing pri	0,123	€/kWh	Purchased electricity	93681	kWh
Electricity selling price	0,031	€/kWh	Excess PV electricity	0	kWh
Electricity price escalatio	2,0%	p.a.	PV output degradation	0,5 %	p.a.
O&M costs	0,5%	p.a.	Utilization ratio	100 %	



	Year																														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Investment cost [€]	14250															1140															
O&M costs [€]		71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71
NPV of annual expenses [€]	**14250**	**70**	**69**	**68**	**67**	**66**	**65**	**64**	**63**	**62**	**61**	**60**	**60**	**59**	**58**	**969**	**56**	**55**	**54**	**54**	**53**	**52**	**51**	**51**	**50**	**49**	**48**	**48**	**47**	**46**	**46**
Savings from utilized PV electricity [€]		586	598	610	622	634	647	660	673	687	700	714	729	743	758	773	789	805	821	837	854	871	888	906	924	943	962	981	1000	1020	1041
Revenues from sold PV electricity [€]		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Annual savings [€]		586	598	610	622	634	647	660	673	687	700	714	729	743	758	773	789	805	821	837	854	871	888	906	924	943	962	981	1000	1020	1041
NPV of annual savings [€]		**577**	**580**	**583**	**586**	**589**	**592**	**595**	**598**	**601**	**604**	**607**	**610**	**613**	**616**	**619**	**622**	**625**	**628**	**631**	**634**	**637**	**640**	**643**	**647**	**650**	**653**	**656**	**659**	**663**	**666**

NPV of total expenses in 30 years [€]	16873
NPV of total savings in 30 years [€]	18620
Balance after 30 years [€]	1747
Levelized cost of energy [€/kWh]	0,130
Internal rate of return	**10,4 %**