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Technical and economic assessment of the self-consumption of a prosumer with photovoltaic and electric vehicle

Bachelor's Thesis, June 2020

DTU Electrical Engineering
Department of Electrical Engineering

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Preface

This document is a bachelor's thesis written during the Spring 2020 exchange semester in the Technical University of Denmark (DTU). This project represents the final step to obtain the degree in Energy Engineering of Polytechnical University of Valencia (UPV).

The thesis has challenged me to apply all the knowledge and skills acquired during the past four years to develop a study in the field of solar energy and self-consumption. This period of my life has been really intense and has enabled me to grow a lot personally and academically. Now that my bachelor has come to an end, I would like to acknowledge all the people who have contributed to it.

First of all, I would like to thank my bachelor's thesis supervisors Mattia Marinelli and Charalampos Ziras for this opportunity of working together the last four months. They have given their support, knowledge, advice and guidance crucial for the development of this thesis. Moreover, they have made me comfortable in every meeting we had together, and given the difficult situation created by the COVID-19, they have made their best so the thesis and our meetings were not affected. Thanks to them I have learnt a lot in the fields of domestic solar installations and energy netting. Besides, even though this is a theoretical work, as the values came from a real installation, I was able to understand more how a real photovoltaic installation works and the problems and inconsistencies derived from working with realistic data.

Secondly, I would like to thank professor Carlos Vargas Salgado from UPV, for being my supervisor in my home university. Although he has not participated in the content of the thesis, he did interesting suggestions at the beginning and has revised the content to ensure it matches with the degree's curriculum.

Finally, my sincere gratitude to my family for their unconditional support and love throughout my whole life trying to make my life easier so I could focus in studying and enjoying life. Besides, I also want to thank my friends back in Spain and the ones I did during this exchange for making the experience of studying an engineering degree unforgettable. On top of that, I am really glad to have done an exchange to finish my bachelor because I have learnt new skills, experienced life changing moments and acquired a wider vision of the different world's cultures that from now on will always be part of who I am.

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1. Abstract

The project intends to assess the technical and economic performance of a Danish household characterized by several domestic (1-phase) appliances and a 5.4 kW (3-phase) photovoltaic (PV) plant. The PV installation consists in 18 solar panels (300W). Besides, there is a three-phase inverter (6kW) which produces in a balanced way over the three phases.

The thesis quantified the amount of photovoltaic production and domestic consumption on each phase. To do that, an analysis of the amount that was self-consumed was developed, depending on the metering mode. One method consisted of measuring the 3 phases together, while the other measured them individually. With the second procedure energy imports and exports could occur simultaneously in two different phases, whereas with the 3-phase method imports and exports were mutually exclusive quantities. These two methods were applied monthly, considering the energy over: every second, every five minutes, every hour and every day. In the end, with the different results obtained, a quantification of the production and consumption depending on the scenario was conducted.

Once the quantification over the months was done for the different periods, based on typical values of energy selling and purchasing, an economic study was conducted to determine in which months and scenarios the household obtained profits. In addition, a study in the voltage quality of the photovoltaic supply was done taking as reference the European Standard EN 50160.

Furthermore, for the results obtained, it was assessed how much photovoltaic production could be used to charge an electric vehicle, instead of being injected to the grid, considering realistic driving patterns. The analysis was based on the fact that in maximum production hours (noon) the car cannot be charged as is being used (not at home) attending to the typical usage of a vehicle for a labour timetable.

The data used in this study for both photovoltaic installation production and household consumption came from the energy supplier's meter, the inverter's meter and an additional smart meter. The supplier takes the measurements with a per second resolution whereas the other two use a 5-minutes resolution. The months subject to this study were from September 2019 until May 2020 and the tool selected to process all this data was *MATLAB*.

Finally, the results obtained have shown the economic advantages of the 3-phase billing method for the owner, compared to the individual billing, as well as the benefits of having longer netting periods, like hourly or daily. In addition, the voltage analysis showed a correct performance of the photovoltaic installation meeting always the established standards. In the end, regarding the electric vehicle charging, it was discovered that it was only possible to actually produce spare energy to charge the car, during the decided charging window (18:00 to 20:00), in September, April and May. Moreover, not even in the best-case scenario it was achieved enough spare photovoltaic production to cover the whole charge needed.

2. Introduction

2.1. Background

Conventional power plants that use fossil fuels such as coal, oil, or natural gas have an expiration date as the planet resources are limited. Besides, to overcome climate change and atmosphere pollution numerous sustainability protocols and goals need to be followed and achieved, such as Sustainable Development Goals (SDG) or the Paris Agreement. In order to achieve them an energy transition towards renewable energy technologies is needed.

The combined cycle power plants or combined heat and power (CPH) represented the first step towards a more environmentally friendly energy outlook but renewable energies are the ones needed to achieve a sustainable future. There are different types that use inexhaustible natural resources such as the wind, the sun or the potential energy from the water. As a result, numerous different power plants have been developed during the years as wind farms, solar fields and hydroelectric and biomass power plants, among others.

However, even though renewable energies are based on unlimited resources, those resources are subject to unpredictable changes throughout time and the unknown future availability. Moreover, all these new types of energy creation, transform the source into electricity and as it is widely known electricity cannot be stored easily. All these problems make renewable energies difficult to introduce in a system where the production must always meet the demand. Many studies of system balancing and batteries are being conducted in the moment, nevertheless, right now renewable energies are still highly dependent on the uncertainty and variability of their resources.

Furthermore, society has an especially important role in the energy transition. Social awareness must be risen, as adapting as much as possible the demand to the production constitutes a key factor towards the integration of renewable energies. Along with that, the transition from consumers to prosumers is also an interesting way of making society play an active role in the change and contributing to the system's flexibility.

Photovoltaic technology has been developing during the past years and nowadays is advanced enough to be commercially competitive. Thanks to that, small photovoltaic installations are now affordable for the general public and have become the most common self-consumption installations.

Nevertheless, for consumers to become prosumers they need to be given appropriate information and supporting technologies to be able to respond to the varying price signals of the energy market. Net metering and billing schemes will include self-consumers as part of the electric market engaging and empowering them towards a greener energy sector. In the line of that, the automatization of various components of the PV systems is essential for ensuring the correct operation of the system. [1]

To sum up, the energy sector is developing technologies and net billing schemes to include renewable energies into the power system without compromising it and ensuring flexibility and quality of service. All in all, there are technical and regulatory requirements to be settled and achieved as well as responsibilities to be distributed among the system's participants. In this scenario, self-consumption renewable energy installations play an important role and, as a result, studying their correct implementation as well as their advantages and disadvantages has become an imperative field of study in the energy sector.

2.2. Formulation of the problem

As it has been said above self-consumption is a relatively new development and there are still a lot of questions to be solved. In this study, using the data of a household with a photovoltaic installation, some of them will be investigated:

- Which type of net metering is more appropriate for households with photovoltaic installations?
- Which net billing periods are more beneficial for the owner to obtain better results of consumption and production?
- Which combinations of net metering and billing periods give the best economic results?
- Does the domestic installation have spare energy to use in other applications such as charging an electric vehicle?

The answers to all these questions are vital to understand the best working conditions for the self-consumption system as well as the economic profits for the owner. The following section contains the objectives of this thesis used to respond to these proposed questions.

2.3. Objectives

The project's main objective is to study from a technical and economical approach the performance of a Danish household characterized by several domestic (1-phase) appliances and a 5.4 kW (3-phase) photovoltaic plant. The installation is also equipped with a three-phase inverter of 6kW which produces in a balanced way over the three phases.

The project has the following objectives:

- Analysing and quantifying the consumption and production of the household over various months considering an energy metering over: 1 second, 5 minutes, every hour and every day (24 hours).
- Applying two different methods of measurements in each of the previous periods: net over the 3-phase vs net on the individual phases.
- Assess quality of supply throughout the months in terms of voltage amplitude (for the individual phases).

- Assessing how much PV production can be used to cover an electric vehicle charging considering realistic driving patterns.

2.4. Methodology, conditions and limitations

The process followed to achieve the different goals of this thesis began with the data collection from the solar PV installation in the household. The system had two components taking measurements: the inverter and an additional smart meter, besides the data compiled by the energy supplier was also used in this study. From all the different quantities measured the ones used were the power flows and the voltages measurements. The months studied in this thesis started in September 2019 until May 2020.

Once the data was gathered and understood the first step was creating a *MATLAB* function to study the different scenarios settled in this project to understand how they affected to the final energy imports and exports. The six scenarios evaluated for each month were:

- Adding the energy over five minutes, hour and day creating three different scenarios.
- That three scenarios were analysed with 1-phase and 3-phase billing resulting in the six mentioned scenarios.

In addition, the netting period of per second, calculated with the data provided by the energy supplier, could only be conducted for the individual phase billing because there were no data for analysing the 3-phase billing. As a result, the *MATLAB* function gives for each month the exports and imports of energy over the different situations described, obtaining a total of 14 values as it is shown in the tables of the results section.

However, an important fact to consider is that on 29th of April the energy meter changed to a summation meter, meaning that the data from the energy supplier onwards will be balanced netting on the overall 3 phases. As the change occurred in the last days, April was considered as the rest of the months. However, May had to be considered as different and so the values for the 1 second netting period were considered as a billing over the three phases rather than over individual phases as it was previously. For this reason, May will be represented separately in the results.

As a first step, the economic study was approached with the selection of the prices to sell and buy electricity. It was decided to use average buying/selling values coming from the real electric bills of the house owner that also included any taxes or additional tariffs. This decision was made as tariffs dominate prices and the minor differences of energy prices can be safely neglected. The calculations were done with another *MATLAB* function.

Before continuing with the electric vehicle charging evaluation it was found interesting verifying the voltage quality of the photovoltaic supply considering the European standard *EN 50160* furtherly explained in the corresponding section.

Finally, a study of the disposable amount of PV production destined to charge the electric vehicle was assessed. As the owners of the house do not own an electric vehicle, in this project, generic car and battery characteristics were selected. As well, although the car is used in average twice a week, to simplify the calculations, the distance driven in both days was divided between the five working days of the week. Using these considerations and generic data led to obtain estimated results that could be useful to be considered as reference for other studies which use a specific car model. All these calculations were also implemented in a *MATLAB* function.

3. Overview of the market and netting tendencies regarding self-consumption

3.1. Energy sector outlook in Europe and Denmark

The energy market in Europe is changing towards the integration of renewable energies in the system. According with the BP - Statistical Review of World Energy form of 2020 [4] the total energy produced in Europe with renewable technologies ascends to 836.6 TWh in 2019. The amount generated by solar energy in that year was 154.7 TWh representing a 18.5% of the total renewable energy produced. The growth rates were 14.6% in wind power, 11.6% in solar and an overall growth of all sorts of renewables of 10.6%. The leading countries with higher production of renewable energies were Germany (224.1 TWh) followed by UK (113.4 TWh) and Spain (77.5 TWh). However, looking into the energy produced with solar sources the leading countries were Germany (47.5 TWh), Italy (24.3 TWh) and Spain (15 TWh).

The energy outlook in Denmark in 2019, according to IRENA (International Renewable Energy Agency) [2], reflects an installed solar power capacity of 1079 MW (12% of the total). Nevertheless, Denmark's most important renewable technology is wind energy. The country has 4415.82 MW (49% of total) installed of on-shore wind and 1700.8 MW (18.9% of total) of off-shore wind energy. This data shows that Denmark is a country really committed to the substitution of conventional power plants with renewable technologies contributing to the energy transition and the accomplishment of the sustainable protocols and goals.

The Danish retail market has developed throughout the two last decades resulting in a market that stimulates competition and innovation as well as motivates the consumers to play an active role in Denmark's transition towards renewable energies. The journey to the development of the current market began in 2003 with the liberalisation of the market, enabling all Danish consumers to choose their electricity supplier. It continued in 2013 when the first version of Danish DataHub was implemented. DataHub is a data centre that stores all the information about the electricity consumption in Denmark including business processes such as change of the supplier. Then it processes the metered data and business processes being able to transfer it to other operators of the system. Finally in 2016, the supplier centric model was established, a new market design that together with a deregulation of the consumer electricity prices was aiming to increase competition as well as stimulating the development of new products and services for the consumer. The DataHub was upgraded in that year also as it represents the technical prerequisite for the new market model to function.[5]

The supplier centric model results in a market where there is total contact between electricity suppliers and consumers. Besides, the consumer receives one bill for electricity and has a single point of contact with the electricity market through its supplier. In the end, the consumer is billed directly for the energy, network use and taxes by the electricity supplier. The following figure shows a diagram of the structure of the supplier centric model.[5]

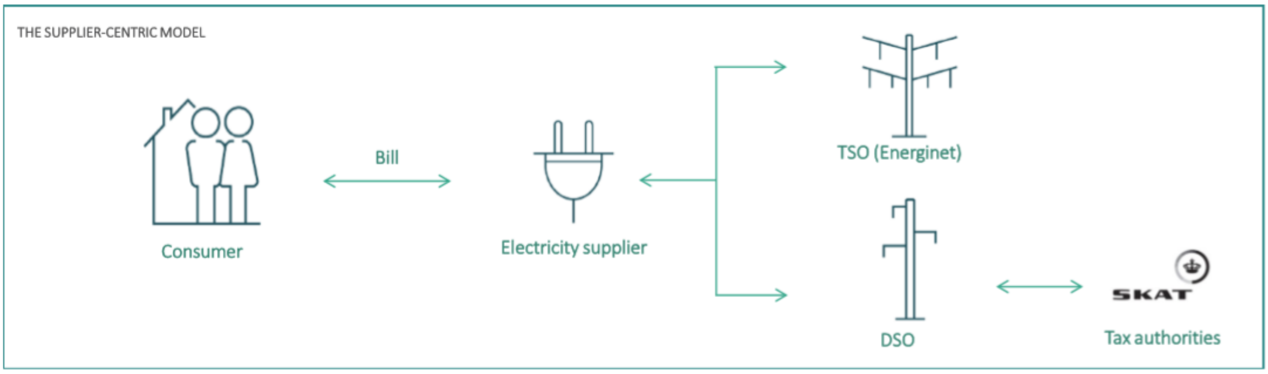

FIGURE 1: DIAGRAM OF THE SUPPLIER-CENTRIC MODEL (SOURCE: ENERGINET.DK [5])

3.2. Self-consumption and prosumers in Denmark

According to another study conducted by IRENA, "*The total installed costs in the residential rooftop PV market are higher than utility scale due to their small size, but decreased by between 47% and 80% between 2010 and 2019 depending on the market*." [3] Besides, governments have started giving subsidies to stimulate the prosumer movement as it helps to reach the goals of renewable energies' transition and climate change targets. All in all, the decrease in the costs plus the economic compensation have resulted in an increase of the number of prosumers and households functioning with self-consumption.

A prosumer, in general, is an energy consumer that also produces its own energy using a range of diverse onsite generators. To be more specific, residential prosumers use as generators small-scale PV installations or, in some cases, small wind turbines. The households acting as prosumers can be either connected to the grid or isolated from it, residing the main difference between the two of them in the energy storage. The connected installations use the grid as a battery: sending energy when there is overproduction of PV energy (compared with the house consumption) and taking energy when there is a lack of PV production. On the other hand, off-grid systems need to install an actual battery that will help the installation have an adequate performance, so the house always has electric service. Albeit, batteries technologies are still developing nowadays as there are problems that need to be solved regarding the battery performance such as capacity, losses and battery life. As a result, connected grid installations are the most common ones and therefore different types of net billing to include the prosumers into the electricity market are being developed.

Inside the Danish retail market prosumers are allowed, after an approval process, to sell their excess produced energy to the grid. The prosumers are related with two electricity suppliers one for the consumption and the other for the production. For the latter it is compulsory for the supplier to be, when it is renewable energy, the TSO (Energinet) whereas for the consumption, the prosumer is free to choose an electric company just as any of the other normal consumers. The reason for the obligation of the renewable energy production to relate to TSO are the subsides provided to these types of plants. [5]

3.3. Types of tariffs related to prosumers

As it was said above the energy market is implementing measures and plans to include the prosumers, specifically of PV installations, in the power system trying to maximize the benefits of both parts: the prosumer and the market. For compensating prosumers for their energy injections to the grid two principal schemes are being introduced in many countries: net energy metering (NEM) and feed-in tariff (FiT).

On the one hand, under NEM the consumer is charged for his electricity consumption from the grid, after netting off the electricity injected to the grid. In this case, the prosumer will receive a compensation only upon the actual injected energy, i.e. after the self-consumed electricity is subtracted. The exact payment per kWh is determined by the agreement with the supplier. This method requires bidirectional meters that keep account of the energy flow between the prosumer household or installation and the grid.

On the other hand, FiT schemes separate the measurements of electricity generation and consumption with two different meters in the installation, and as a result these quantities are accounted for differently. The energy consumed from the grid is charged at the retail electricity tariff (including any additional tariff and taxes) whereas the injected energy into the grid is compensated at a tariff that was previously fixed and notified by the regulator called "feed-in tariff". This methodology considers that the PV installation is producing for injecting into the grid, rather than for self-consumption. However, the physical import/export of energy from/to the grid is the same as in NEM. The advantage of this methodology is that FiTs can be settled higher than the retail electricity tariffs to stimulate consumers to become prosumers helping the transition to a sustainable energy system. [1] This type of market billing was used by more than 56% of the 2018 PV market, according to a source of the IEA (International Energy Agency). [6]

However, the introduction of prosumers in the power system brings new challenges like causing an oversupply in the grid that could lead to curtailment of power plants and the appearance of negative electricity prices, which will be harmful for producers. To lead with that, NEM schemes pay the prosumers at the system prices (e.g. with hourly prices) giving the electricity its true value, as it is more rewardable injecting at peak hours of demand. With all this NEM schemes constitute a market-friendly method that encourages self-consumption. Unlike NEM, FiT are being phased-out as they are indeed flat and exogeneous and distort the market. They were interesting at the beginning, but given the great reductions of the PV technologies cost they are not needed anymore.

Currently in Denmark, the spot market price called balancemarkedet *for produktion* is being used as the basis of the compensation value for the PV production.[12]

To sum up, the introduction of prosumers and self-consumption installations will increase the system's flexibility improving the services. Nevertheless, this new situation requires a market adaptation and investigation in the best ways of grid integration and economic compensations.

4. Set up of the system

The following section contains a description of the system's components as well as an explanation of the data used. Besides, any limitations regarding these elements are also explained.

4.1. Installation elements

The system object of study consists in a house located in Denmark equipped with various domestic appliances (1-phase) and a photovoltaic installation that provides, in combination with the grid, the needed energy for the house to function. In figure 2 the diagram of the installation is shown followed by the explanation of the different components:

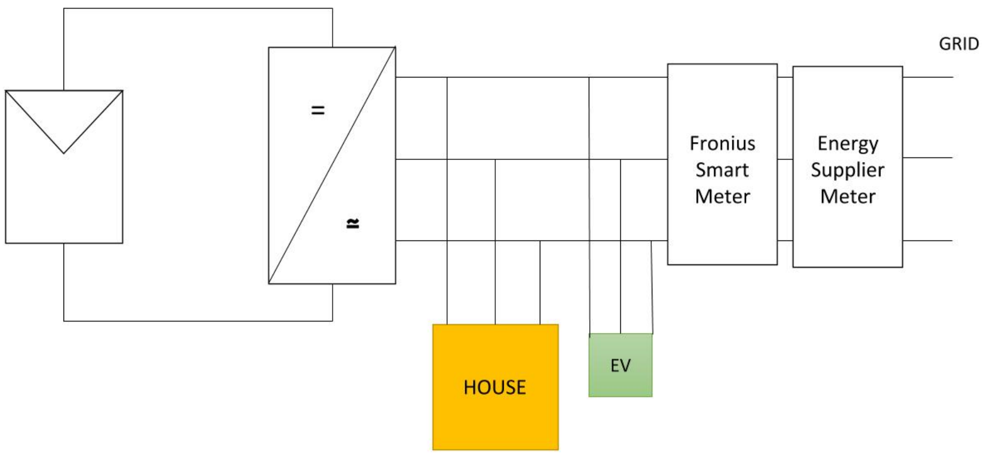

FIGURE 2: DIAGRAM OF THE INSTALLATION

4.1.1. Solar panels

The photovoltaic installation of the house consists in 18 panels of 300 W installed in the rooftop giving a total power installed of 5.4kW. The model used is the *ECO LINE FULL BLACK M60/290-310W* from the company *Luxor.* Some key characteristics of the panel are compiled in table 1:

Rated power Pmpp	300Wp
Short-circuit current Isc	9.88 A
Open-circuit voltage Voc	38.89V
Efficiency at STC	18.46%

TABLE 1: LUXOR PANEL CHARACTERISTICS [9]

FIGURE 3: SOLAR PANELS ECO LINE FULL BLACK M60

4.1.2. Inverter

The 3-phase inverter transforms the direct current (DC) coming from the solar panels into alternating current (AC) producing it balanced over the three phases. The model selected from the brand *Fronius* is the *SYMO 6.0-3-M.* The size of the inverter is 6kW, which is logical as it needs to be capable of operating with the 5.4kW photovoltaic installation. In figure 5 the efficiency curve of the inverter is shown. Note that, even though in the graph indicates model *SYMO 8.2-3-M*, the *SYMO 6.0-3-M* has the same one as they both belong to the same range of inverters. Furthermore, other important parameters that characterize the inverter are shown in table 2. Apart from the DC/AC conversion, the inverter also acts like a meter storing data of voltages, currents and powers of the solar PV installation.

FIGURE 4: FRONIUS INVERTER

Accuracy	Class 1
Maximum output power	6000 VA
Nominal current	8.7 A
Maximum efficiency	98%
European efficiency (ηEU)	97.5%
MPP adaptation efficiency	>99.9%

TABLE 2: FRONIUS INVERTER PARAMETERS [10]

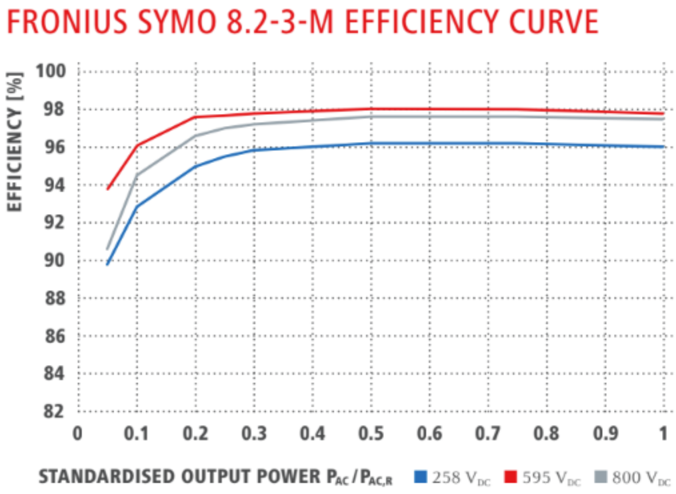

FIGURE 5: FRONIUS INVERTER EFFICIENCY CURVE

4.1.3. Smart meter

In addition to the inverter's measurements, a smart meter has been also installed. The model selected is the *FRONIUS SMART METER 63A-3.* The most significant parameters of it are compiled in table 3.

Accuracy	Class 1
Nominal voltage	400 - 415 V
Grid frequency range	50 - 60 Hz
Maximum current	3 x 63 A
Power consumption	1.5 W
Starting current	40 mA

TABLE 3: FRONIUS SMART METER PARAMETERS [11]

This meter is located just before the energy supplier (electric company) so the expected measurements will be similar to the ones the electric company is actually measuring and billing the house owner. Among others, the smart meter measures powers and voltages in the feed-in point that have been the values used in the calculations of this thesis.

FIGURE 6: FRONIUS SMART METER

4.1.4. Energy supplier meter

The energy supplier uses an IEC Poly Phase Smart Meter [8] that can take power quality measures of voltage, current, frequency, power factor and Total Harmonic Distortion (THD). The device is a smart meter and a grid sensor all in one which can conduct load profiling, billing for time-of-use, prepay, optional maximum demand and power-quality analysis of 271 grid health measurement elements. It has also a remote-controlled disconnect/reconnect switch, comprehensive display and home area networking support. Besides, to enable customer micro-generation sources and power quality monitoring it has net active energy, kvarh import/export, forward, reverse and four-quadrant measurements. The following table collects some of the characteristics of this device.

FIGURE 7: ENERGY SUPPLIER METER

Accuracy	Active: Class1 (certified to IEC 62053-21), Class B (certified to EN 50470-3 (MID))
	Reactive: Class 2 certified to IEC 62053-23
Voltage	220V to 240V phase-to-neutral, range -20% to +15%
	220V to 240V phase-to-phase, range is -20% to +15%
	380V to 415V phase-to-phase, range is -20% to +15%
Frequency	50 Hz ± 5%
Service Type	3-phase, 4-wire Wye/Star
	3-phase, 3-wire Delta

TABLE 4: ENERGY SUPPLIER METER CHARACTERISTICS [8]

4.1.5. House

The installation object of study consists in a household located in Denmark. This house measures around 124 m^2 and is occupied by a family of three people. One important characteristic regarding the energy consumption is that the house has a non-electrical heating (using pellets) which reduces the energy consumption during winter months. Besides, as temperatures in the winter season in Denmark are low, the expected amount of energy consumed in heating would be substantial. By eliminating the energy used in heating, the elements that consume the larger amount of energy are the biggest household appliances:

- The electrical stove: which consists of an oven connected to one phase and 4 heating elements on the top using 2 phases each.
- The dishwasher
- The washing machine

The remaining energy is consumed by the numerous illumination points and other less energy demanding domestic appliances.

4.1.6. Electric vehicle

The house owners do not own an electric vehicle so non-specific characteristics can be used for this study. However, it was decided to use generic data of electric vehicle usage and batteries to assess the possibility of recharging a car with the PV production of the house. By doing this, in the future if an actual car were purchased the conclusions obtained in this study could be easily adapted.

The generic vehicle considered uses a 1 phase charger of 3.7kW. To simplify the calculations, a charging efficiency of 100% has been assumed. The car is equipped with a battery of 60kWh of capacity and its consumption is 5 km/kWh.

As for the driving pattern, based on the owners real needs the car would be used only twice a week to go to another city for job meetings resulting in a round trip of 80 km/day. However, the distance driven is splitted equally throughout the five working days of the week, as it was explained in the methodology. With this assumption the calculations will be simplified, and the results will show the real possibility of charging the vehicle each working day of the month with the PV production.

4.2. Data

The data used for this study comes from the smart meter, the inverter itself and the energy supplier.

The data from both the smart meter and the inverter are measured with a 5 minutes resolution and are collected together in an EXCEL sheet that will be later imported to the *MATLAB* function. This sheet is composed of 27 columns of data plus one column which indicates the date and the time. The different values disposable in this EXCEL sheets are the following:

- From the smart meter values of: *Consumed directly (Wh), Consumption (Wh), Energy from grid (Wh), Energy to grid (Wh), PV production (Wh), Apparent power L1 feed-in point (VA), Apparent power L2 feed-in point (VA), Apparent power L3 feed-in point (VA), Effective power L1 feed-in point (W), Effective power L2 feed-in point (W), Effective power L3 feed-in point (W), Voltage AC L1 feed-in point (V), Voltage AC L2 feed-in point (V), Voltage AC L3 feed-in point (V).*
- From the inverter's meter values of: *Apparent power (VA), Current AC L1 (A), Current AC L2 (A), Current AC L3 (A), Current DC MPP1 (A), Energy (Wh), Power factor (pu), Reactive power (var), Specific yield (kWh/kWp), Voltage AC L1 (V), Voltage AC L2 (V), Voltage AC L3 (V), Voltage DC MPP1(V).*

When calculating the exports and imports on the netting periods of 5 min, 1 hour and 1 day the data resolution needed is 5 min and so the data of *Effective power feed-in point* of the 3 different phases from the smart meter is used. The effective load/power of each phase is equal to the consumption minus the PV production. In that sense, a positive value indicates an import of energy from the grid, and a negative value an export to the grid; in short it represents the load the net is experiencing for being connected to the installation.

To calculate the monthly exports and imports with the netting period of 1 second the values from the energy supplier are the ones needed. The energy supplier data is contained in a different EXCEL sheet and is netted only on 1-phase. This means that is not possible to calculate the exports and imports with 1 second resolution for the 3-phase billing method. For this reason, there will be missing numbers in the tables of results. In addition, as it was explained in the methodology section, May is treated separately as the energy supplier metering conditions changed from single phase to 3-phase summation.

In this study the sign convention selected for distinguishing the direction of the power and energy flows is positive when importing from the grid and negative when exporting from the system.

5. Types of billing methods

The way the actual power flows in the three phases are netted leads to different results. In this project, the production and consumption of the system has been netted in two different ways: Netting over the individual phases separately and netting over the three phases. In both cases, different netting periods are considered. Next, the per phase and total billing methods are described in more detail.

5.1. Net on the individual phases – Per phase billing

In this case the effective load per phase is considered. The per second values come from the retailer and will be used to calculate the individual phase billing for that netting period. From the smart meter, the original data is measured over 5 minutes. This 5-min data is then used to net the effective load over a period of one hour and one day, for every individual phase. Results are reported on a monthly basis, irrespective of the netting period, following the procedure described next.

For each period, it is determined whether energy is imported or exported, on each phase. Then, the results are summed for the whole monthly period, resulting in 6 values (3 phases * 2 (export/import)). Secondly, the exports and imports of all phases are summed up, resulting in two final values: the total exported and imported energy for a determined netting period and month. This type of billing allows simultaneous imports and exports of energy in the same time step in the different phases.

5.2. Net over the three phases – Total billing

For this billing method the total effective load of all 3 phases together is considered. The procedure is similar to that of the one phase billing, with the exception that for each time step, the effective load of the 3 phases is added. Only then, it is determined whether the household imports or exports energy at that time step. Next, all the values for import are added, to obtain the monthly imports, and the same is done for the exports. As in the previous case, this process is done for 5 min, one hour and one day netting periods.

With this net billing only one action can happen in each time step, meaning, the installation either exports or imports but could never do both actions simultaneously, in contrast to the individual phase method.

6. Results

6.1. Different billing methods

The following section presents the monthly results obtained with the implemented *MATLAB* function for every netting period and billing method. Note that the first row, per second, shows the actual values for which the owner was billed as the data used to calculate them came from the energy supplier itself.

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-366.43	132.05	-	-
5 minutes	-358.65	124.35	-337.59	103.29
1 hour	-336.63	102.33	-323.56	89.26
1 day	-254.43	20.13	-247.99	13.69

TABLE 5: RESULTS SEPTEMBER 2019

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-209.26	144.19	-	-
5 minutes	-205.76	139.84	-194.99	129.07
1 hour	-194.22	128.30	-185.16	119.24
1 day	-112.14	46.10	-102.99	36.95

TABLE 6: RESULTS OCTOBER 2019

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-58.33	198.26	-	-
5 minutes	-56.34	194.33	-48.51	186.51
1 hour	-50.11	188.11	-43.53	181.52
1 day	-7.36	145.36	-2.44	140.44

TABLE 7: RESULTS NOVEMBER 2019

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-49.34	148.43	-	-
5 minutes	-48.21	145.57	-43.05	140.41
1 hour	-44.60	141.96	-39.98	137.34
1 day	-12.43	109.79	-9.18	106.54

TABLE 8: RESULTS DECEMBER 2019

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-54.21	182.08	-	-
5 minutes	-52.86	178.79	-46.48	172.41
1 hour	-47.72	173.64	-41.94	167.87
1 day	-12.15	138.08	-8.51	134.44

TABLE 9: RESULTS JANUARY 2020

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-127.05	137.98	-	-
5 minutes	-124.43	134.10	-114.58	124.24
1 hour	-116.16	125.83	-106.29	115.95
1 day	-47.59	57.25	-38.34	48.01

TABLE 10: RESULTS FEBRUARY 2020

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-466.95	120.59	-	-
5 minutes	-458.46	112.63	-435.98	90.15
1 hour	-438.32	92.49	-428.57	82.74
1 day	-363.11	17.27	-353.96	8.13

TABLE 11: RESULTS MARCH 2020

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-737.54	90.15	-	-
5 minutes	-708.47	84.10	-683.88	59.51
1 hour	-686.57	62.20	-676.84	52.47
1 day	-630.48	6.11	-627.59	3.22

TABLE 12: RESULTS APRIL 2020

Settlement period	1 phase (kWh)		3 phase (kWh)	
	Export	Import	Export	Import
1 second	-	-	-734.32	49.16
5 minutes	-782.96	70.90	-755.66	43.60
1 hour	-758.30	46.24	-749.46	37.40
1 day	-712.06	0	-712.06	0

TABLE 13: RESULTS MAY 2020

In order to have a clearer understanding of the numbers obtained, the following graphs where implemented. Note that May is plotted separately because the meter's configuration changed as it was previously explained.

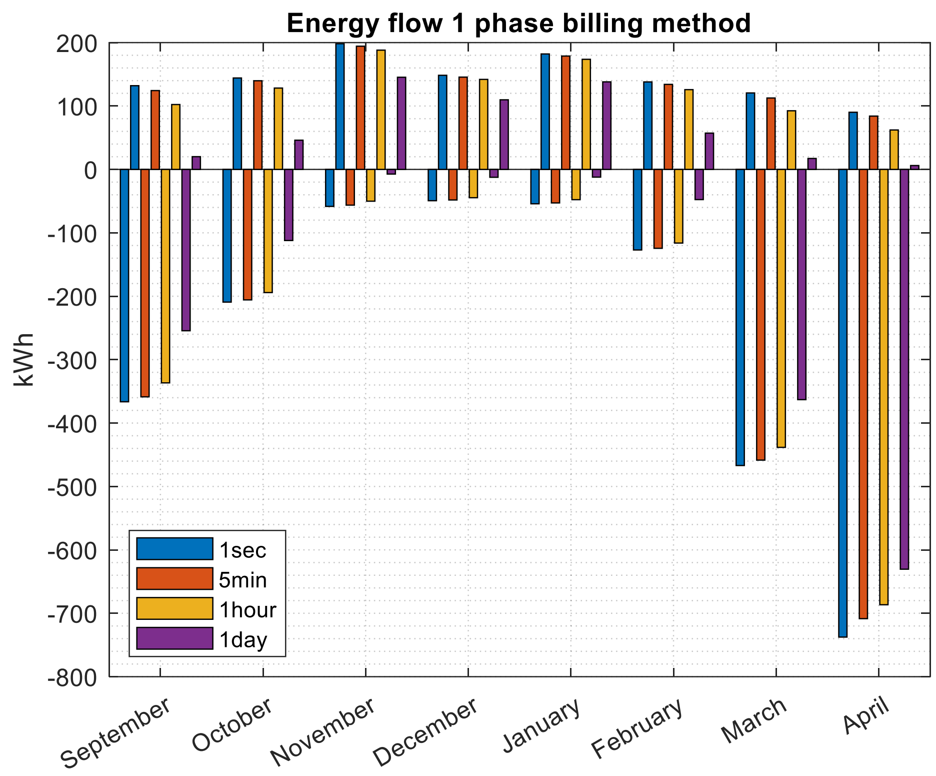

FIGURE 8: RESULTS OF 1 PHASE BILLING [EXPORTS (-)/IMPORTS (+)]

It is observed in figures 8 and 10 that no matter which type of billing is applied the values have common tendencies.

First of all, the most noticeable observation, is that the exported energy grows during the summer months and is very low during winter. In March, April, May and September the energy exported variates from around 350 kWh to almost 800 kWh a month. In contrast, winter months have greater values in energy consumed from the grid that reach at most 200 kWh.

Secondly, is can be observed that the bigger the netting period is, the lower the exports and imports are. This is because in each time step the production is subtracted from the consumption, meaning a compensation is done every time step, and so the wider it is the more likely for the cancellation of exports with imports is to happen. To show that, figure 9 has been captured from the results of the *MATLAB* function of September 2019. Note that the rows represent the different time periods while the columns represent the three phases. It can be observed that the values measured every five minutes (left picture) change as time passes smoothly and with no big steps. When the netting period is hourly (middle picture) the changes are a bit more accentuated. In the end, when the data is netted daily (right picture) significant differences among days' energy can be seen.

8640x3 double

	1	2	3
1	0.0107	0.0018	0.0023
2	0.0105	0.0019	0.0020
3	0.0080	0.0019	0.0020
4	0.0041	0.0022	0.0016
5	0.0041	0.0018	0.0016
6	0.0040	0.0017	0.0020

720x3 double

	1	2	3
1	0.0890	0.0214	0.0212
2	0.0708	0.0191	0.0204
3	0.0889	0.0210	0.0210
4	0.0764	0.0190	0.0214
5	0.0701	0.0194	0.0200
6	0.0859	0.0191	0.0198

30x3 double

	1	2	3
1	0.0014	-0.3083	0.2574
2	-7.8894	-8.3137	-8.6316
3	-2.3636	-2.5679	-1.9593
4	-1.5476	-2.0225	-1.3875
5	-4.4886	-5.0645	-5.9399
6	-1.2386	-2.1997	-1.8214

FIGURE 9: SEPTEMBER 2019 DATA SAMPLE FROM LEFT TO RIGHT NETTED: EVERY 5 MIN, EVERY HOUR, EVERY DAY

It is observed in both figures 8 and 10 that the difference between imports and exports for the different netting periods are always the same except for April and May. In these months, in the per second period there is an alteration of this general trend as April exports are larger than they were supposed and contrarily May exports are smaller than expected. These results come directly from the energy supplier data, so it is believed that some external error, maybe due to the change of the energy meter, has caused these inconsistencies.

Looking into figure 11, representing May's results, it is remarkable that for the one-day period no matter which billing method is used there is no import needed from the grid, meaning that in the supposed bill only the compensation for the PV production will appear. In April, although the imported energy for one day period is not zero, it is extremely low as well. This concludes that the photovoltaic installation constitutes a great improvement for reducing energy imported from the grid during the summer months.

Finally, it noticeable by comparing the individual phase and three-phase billing results that regardless of the netting period selected the energy imported and exported will always be higher with the individual phase metering.

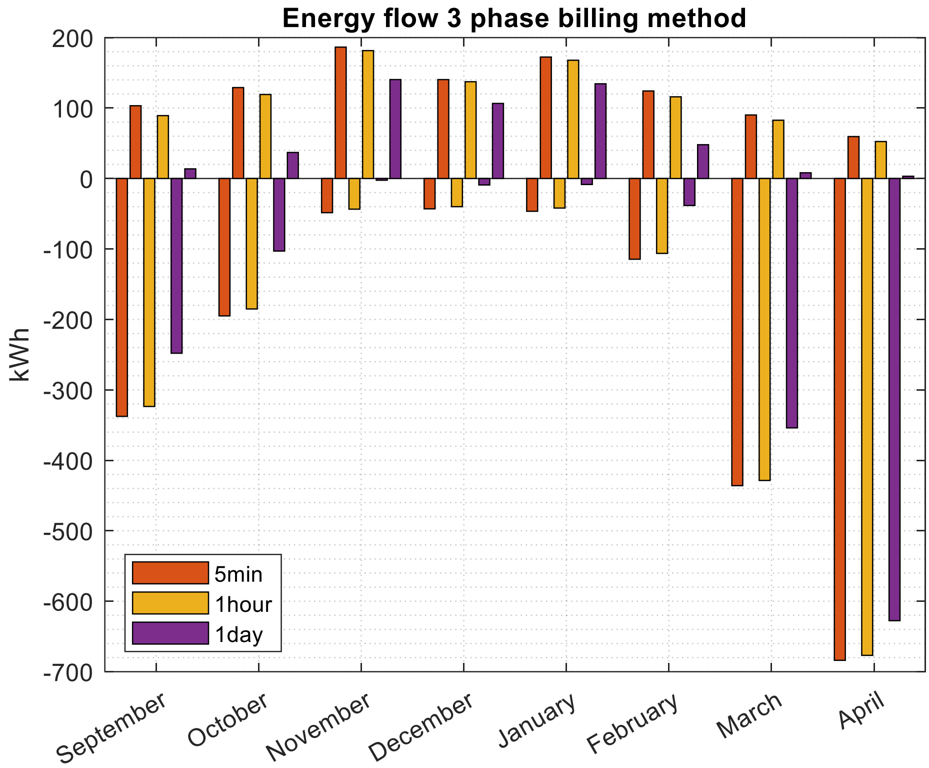

FIGURE 10: RESULTS OF 3 PHASE BILLING [EXPORTS (-)/IMPORTS (+)]

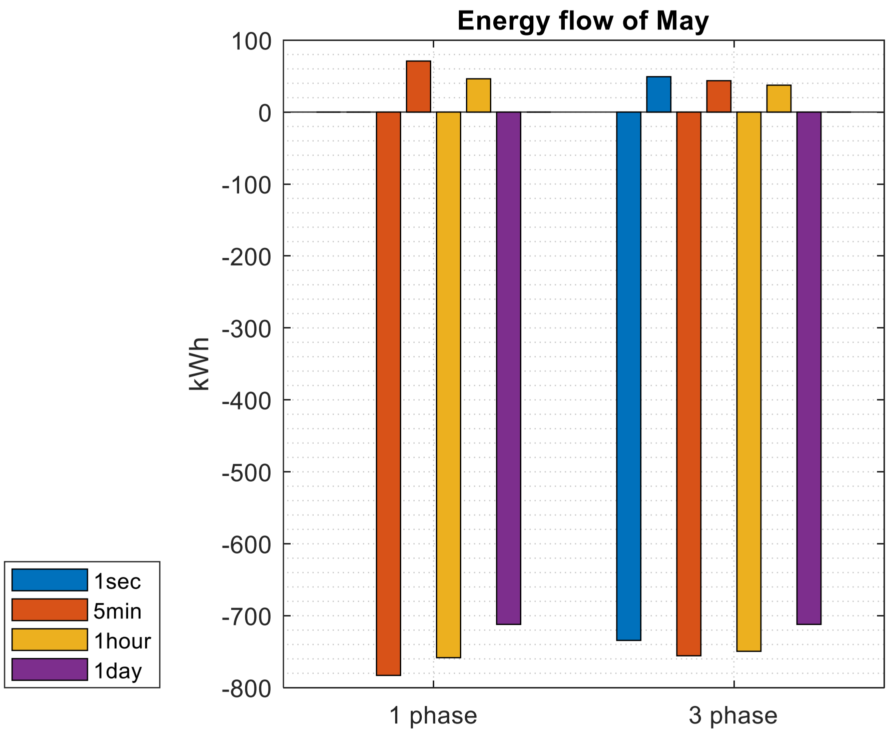

FIGURE 11: MAY 2020 RESULTS [EXPORTS (-)/IMPORTS (+)]

6.2. Economic aspect

The information needed to approach the earnings and payments of the energy produced and consumed was extracted from the company's bills given to the owner of the house. From those bills the average price including electricity, grid services taxes and charges was rounded and considered the same for every month. With all these considerations the final values obtained were**: 2 DKK/kWh** for purchasing electricity from the grid and **0.3 DKK/kWh** for selling the produced electricity via the PV installation.

To approach this section the results from the *MATLAB* function of the exports and imports over the months and for each scenario were imported to a new function. In the new program, the exports and imports were multiplied by the corresponding incentives described in the previous paragraph. Once the energy was translated into money, the earnings (coming from the exports) were subtracted from the payments (coming from the imports) obtaining for each netting period, billing method and month the overall cash balance.

The following graphs show the results obtained. Note that May is again separated for the same reason as before. It is understood in the graphs that when the value is negative it means a payment to the energy supplier company while positive values represent earnings of the house owner.

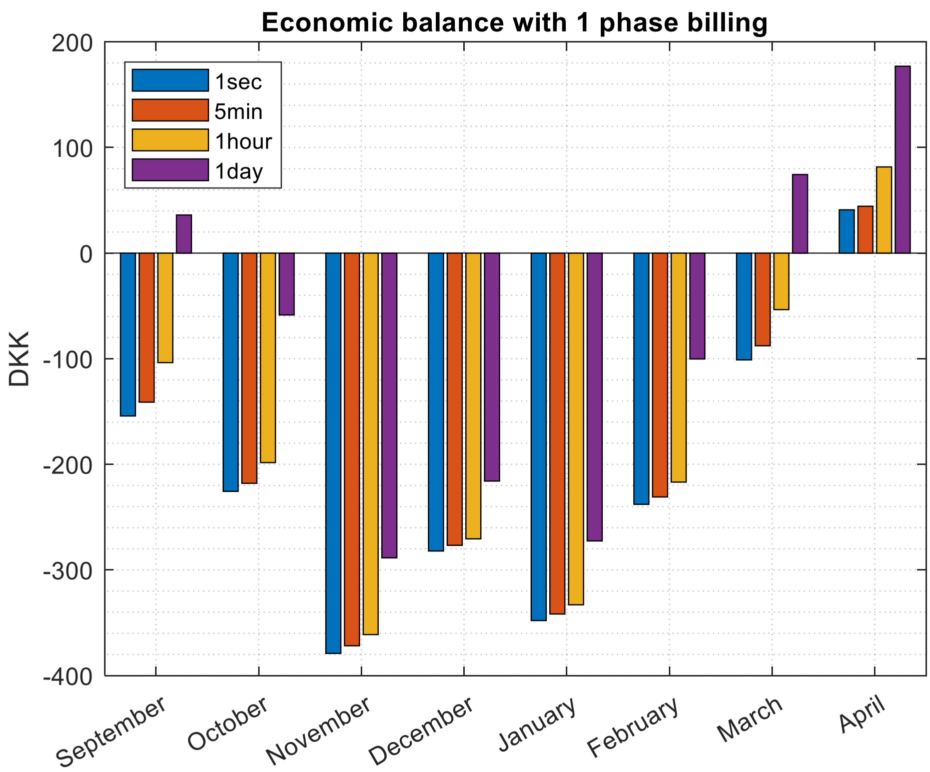

FIGURE 12: ECONOMIC BALANCE WITH 1 PHASE BILLING [PAYMENTS (-)/EARNINGS (+)]

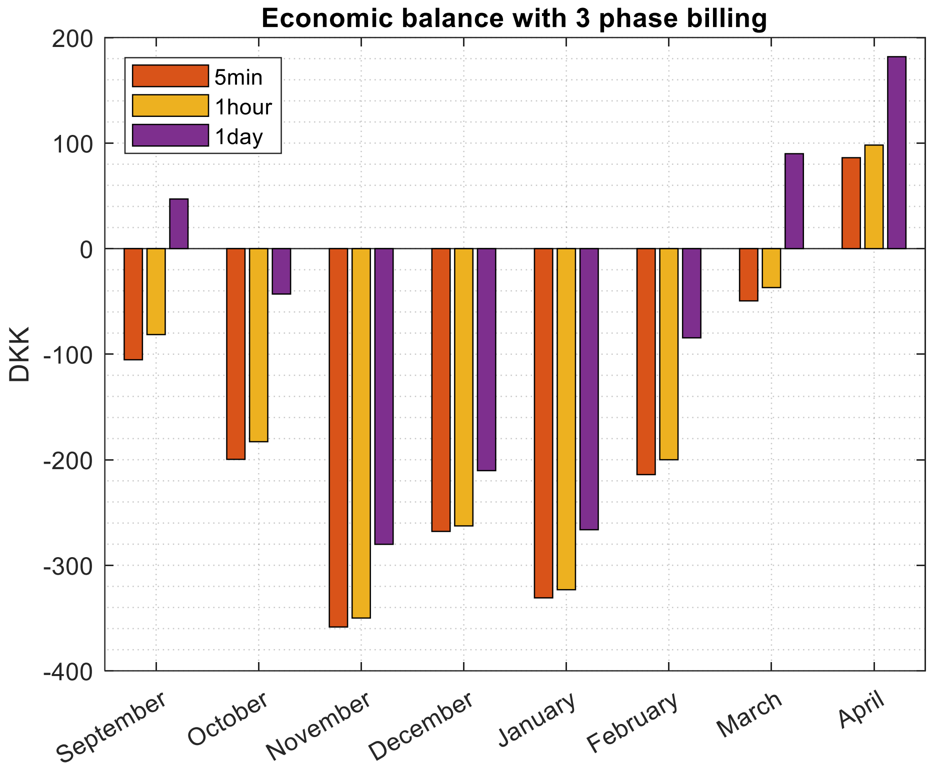

FIGURE 13: ECONOMIC BALANCE WITH 3 PHASE BILLING [PAYMENTS (-)/EARNINGS (+)]

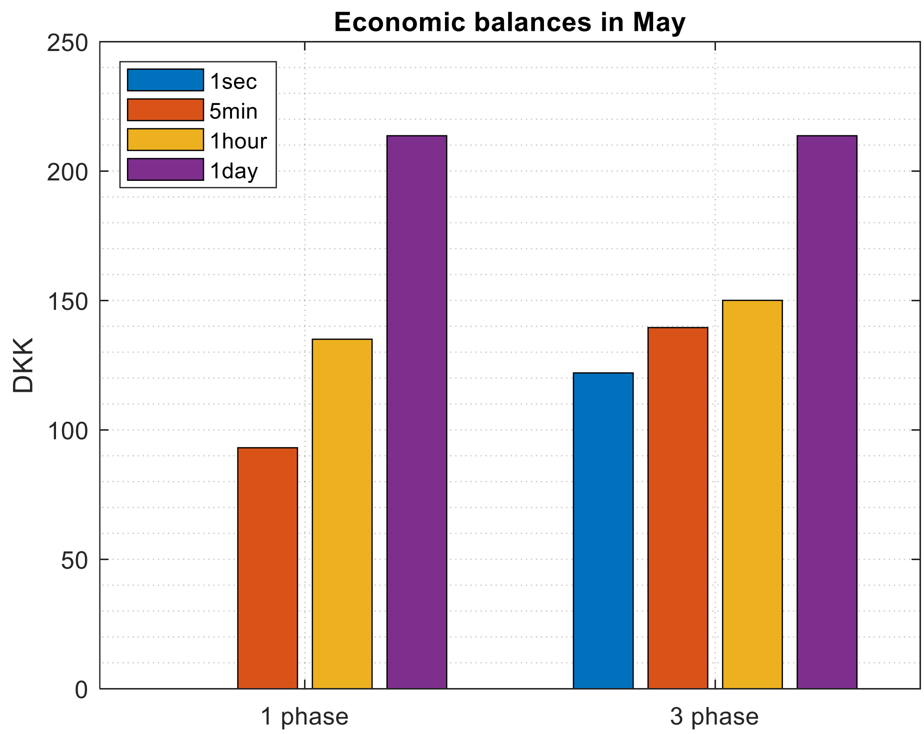

FIGURE 14: ECONOMIC BALANCE IN MAY 2020 [PAYMENTS (-)/EARNINGS (+)]

The tendencies observed in figures 12, 13 and 14 are consistent with the ones from figures 8, 10 and 11. During the winter months, when there is not much exportation, the economic balance shows a cash flow from the owner to the energy supplier company. Otherwise, during summer months the payments of the owner are lower in general (around 100 DKK) and there are also earnings. During April and May benefits are obtained no matter which billing or period is considered as the exported energy was remarkably high. March and September are months with lower sun irradiance, therefore only if the energy is balanced over the day the benefit appears.

It is interesting to highlight that, as figure 11 showed no imports in May during the daily netting period in either of the billing methods it is expected an equal money balance for both. This is shown in figure 14 where both purple bars equal 213.6 DKK.

Once the economic balances are clear is interesting to see the differences between the earnings resulted on individual phase and 3-phase billing. The following graph is obtained subtracting the economic balance values of 1 phase billing from the 3-phase ones. Note that the per second period is not included in the histogram because from September until April there is no data for the 3-phase billing and in May there is no data for 1-phase billing.

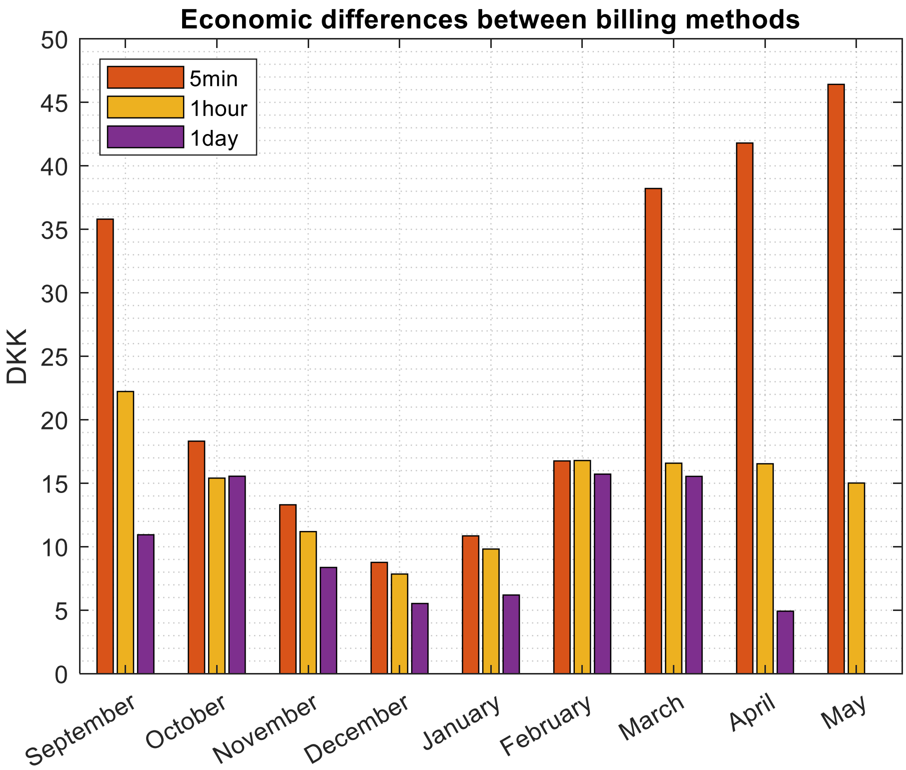

FIGURE 15: DIFFERENCES BETWEEN 1-PHASE AND 3-PHASE BILLING [PAYMENTS (-)/EARNINGS (+)]

It is observed in figure 15, that in every month and regardless of the netting period selected the total billing method always has more economic benefits as the values are all positive, meaning earnings. In conclusion, selecting a 3-phase billing can suppose an average increase in the benefits of **16,46 DKK** which represents a **10,79%** of the average balance of the per phase billing (-152.52 DKK) and a **18.62%** of the average balance of the 3-phase billing (-88.4 DKK).

The reason why the 3-phase billing method achieves greater economic benefits is related to the imports/exports ratio. Taking the results of September (figure 16) as an example it is observed that with 1 phase billing this ratio is higher. Besides, the imports values of 1-phase billing are always higher than the imports of the 3-phase method. Given that the amount payed for an imported kWh is around six times bigger than the amount earnt for an exported kWh, the higher the ratio of imports/exports is, the less economic benefits will produce.

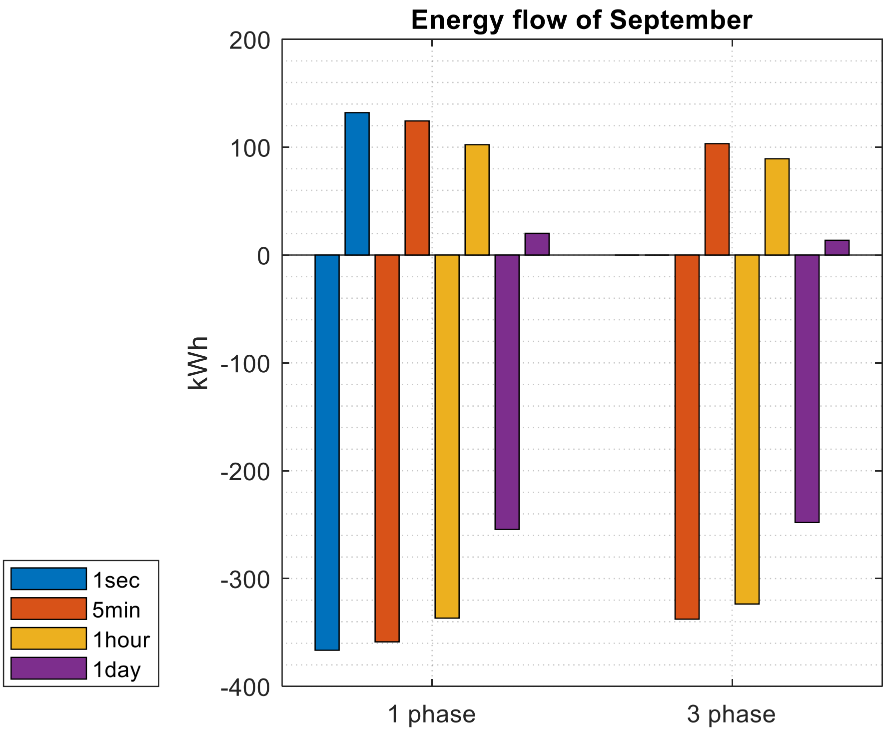

FIGURE 16: SEPTEMBER 2019 RESULTS [EXPORTS (-)/IMPORTS (+)]

7. Voltage quality

According to the European Standard EN 50160 "*the voltage magnitude variation for Low voltage (LV) and medium voltage (MV) systems has to be less than ±10% for 95% of week, mean 10 minutes rms values*".[7]

With another *MATLAB* function a study on the variability of the voltage in every phase has been conducted. For each month, the mean and the standard deviation of the voltage in every phase has been calculated as it is shown in table 14. The data used for this study comes also from the smart meter measurements.

The ideal voltage in a system in Europe equals to $\frac{400}{\sqrt{3}} = 230.94\ \mathrm{V}$, commonly rounded to 230V. According to the EN 50160 a 10% difference is permitted, meaning that any voltage within 230±23V will achieve the voltage quality standards. In conclusion, by observing table 14 is evident that throughout the period studied the voltage has always met the standards.

Month	Mean V1 (V)	Std V1	Mean V2 (V)	Std V2	Mean V3 (V)	Std V3
September	232.35	±1.78	232.61	±1.69	233.46	±1.67
October	232.16	±1.81	232.60	±1.72	233.37	±1.62
November	231.92	±2.13	232.69	±1.93	233.42	±1.87
December	231.50	±2.00	232.55	±1.82	232.75	±1.71
January	231.85	±1.78	232.74	±1.65	232.76	±1.63
February	232.16	±1.81	232.97	±1.70	233.09	±1.70
March	232.15	±1.81	232.97	±1.68	233.30	±1.72
April	232.60	±1.72	233.12	±1.62	233.40	±1.59
May	232.86	±1.74	233.18	±1.63	233.60	±1.67

TABLE 14: VOLTAGE QUALITY

8. Electric Vehicle

As it was explained in the methodology section the household owners do not have an electric vehicle and therefore the characteristics chosen are generic. To see those parameters refer to *section 6.1.5 Electric vehicle*.

The study of the charging viability of the electric vehicle with the produced PV spare energy started with the calculation of the needed charge per day. According with the assumptions made, the total distance driven is 80 km/day twice a week which results in 160 km/week. Then, if the distance is equally divided from Monday to Friday, as it is assumed that the car is used for working purposes and is left at home during the weekends, this results in a driving distance of 32km/day. Continuously, using equation [1] and the car consumption (5km/kWh) the needed charge per day results in 6.4 kWh. For the calculations, this value was rounded to **6 kWh/day**.

$$Charge\ (kWh/day) = \frac{Driven_{distance}\left(\frac{km}{day}\right)}{Car_{consumption}\left(\frac{km}{kWh}\right)} \quad [1]$$

Once the needed energy per day was known, the next step was finding out when it could be satisfied. To start those calculations, it was decided that the charging window every day will go from **18:00 to 20:00**. Besides, it was decided to use the smart meter data (5 minutes resolution) processed with the hourly netting period (the one used to calculate the third row of the results tables) and in the 3 phase billing, as it was thought to be representative, easy to manage and did not have the inconsistencies found in the per second data from the energy supplier.

First of all, with a *MATLAB* function, for every month, a vector containing each day's energy during the charging hours was calculated. The process was like the one followed before, for the netting periods, but this time, the energy was added within those two hours. In the end, each day of the month will be either importing energy from the grid (positive value) or exporting energy to the grid (negative) during the charging window. These vectors were then plotted to see roughly which months had produced PV spare energy (exporting), that could be used to charge the car, as well as whether there was a significant amount of them. It was discovered that from October until March there was not a single day in which between 18:00 and 20:00 the system was exporting energy. In March, the last 3 days had some spare energy, but as they were very few and in the end of the month it was decided to also eliminate it from the viable charging months. In the end, only September, April and May had a considerable amount of days with spare PV energy to charge the vehicle, therefore they were selected for further investigation.

The more exhaustive study for the selected three months consisted in two parts. On the one hand, discovering which days of the month was possible to charge the electric vehicle (EV) and whether if they represented most of the month or just a small part. On the other hand, it was interesting to know the percentage of the charge needed (6 kWh/day) that was covered by the extra PV production, obviously, for the days with negative values (exporting). Both parts were calculated with *MATLAB* using the same data as before. Continuously, there are graphs for each of the three months representing the results of the process described. Note that in both types of graphs the days shown correspond to the actual days of the months in the calendar.

Finally, in table 15 there are some important parameters gathered for the three months of study. Note that the % of days with disposable spare PV production were calculated over the total of working days, not the whole month, as all the results are based on that amount of days.

	Mean % covered energy	% days spare PV production
September 2019	13.27	47.62
April 2020	33.62	86.36
May 2020	49.66	95.24

TABLE 15: REPRESENTATIVE RESULTS OF THE ELECTRIC VEHICLE STUDY

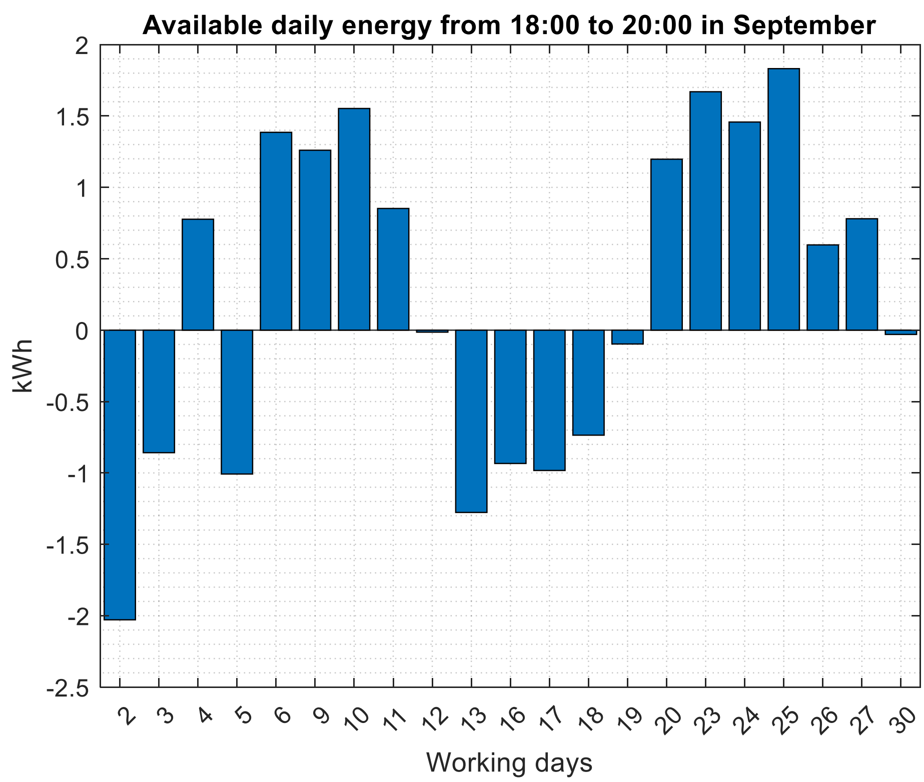

FIGURE 17: AVAILABLE PV ENERGY IN WORKING DAYS OF SEPTEMBER 2019 [AVAILABLE PV (-)/ FROM GRID (+)]

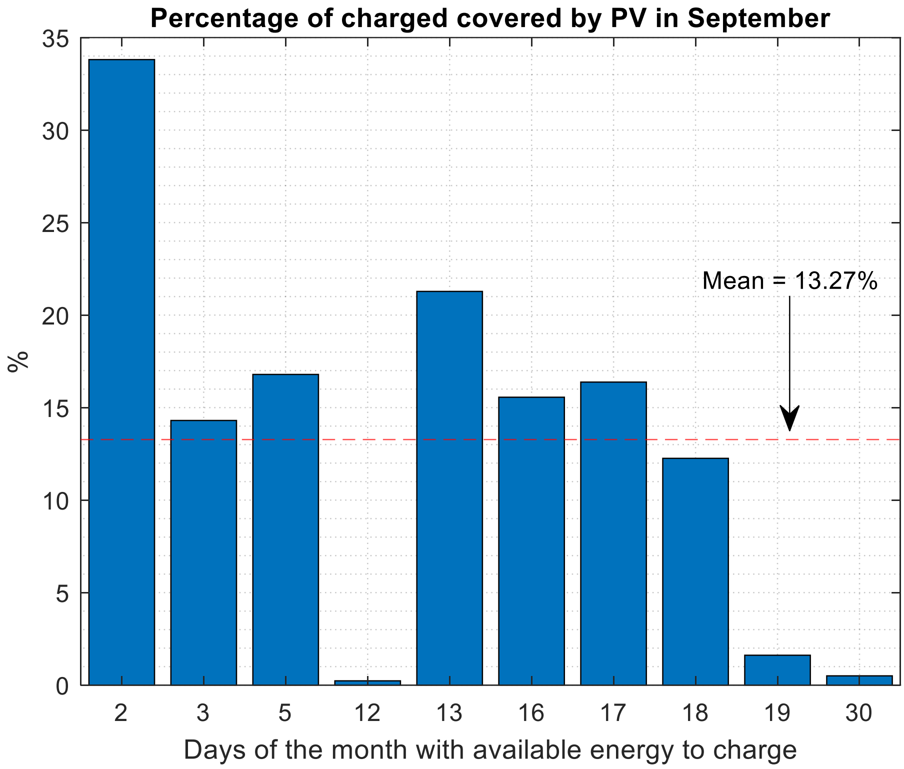

FIGURE 18: PERCENTAGE OF CHARGE COVERED BY THE SPARE PV PRODUCTION IN SEPTEMBER 2019

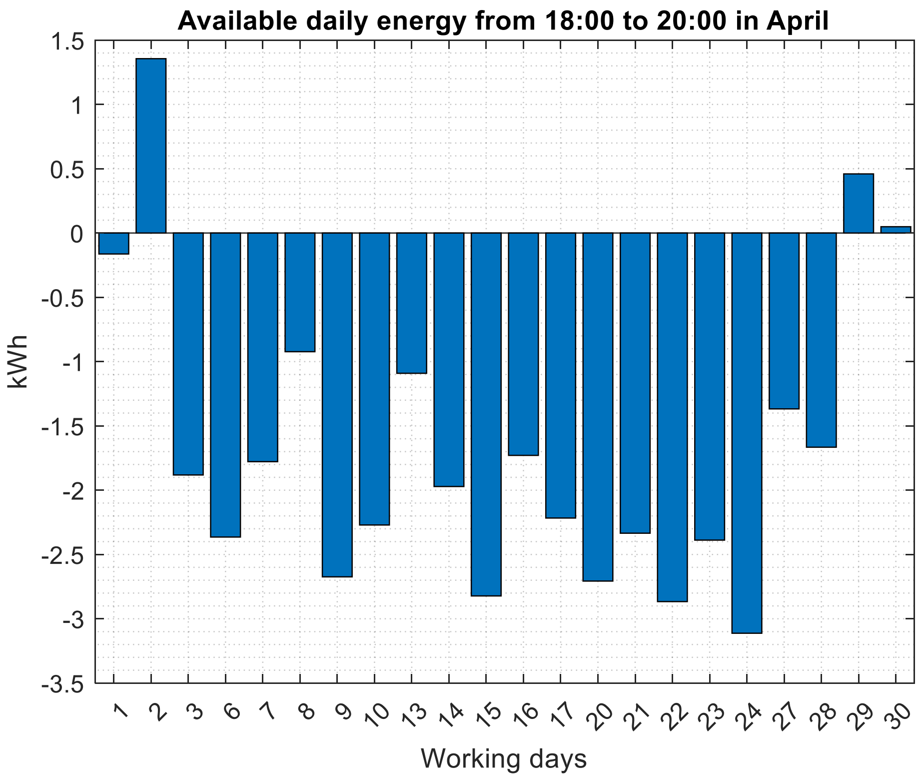

FIGURE 19: AVAILABLE PV ENERGY IN WORKING DAYS OF APRIL 2020 [AVAILABLE PV (-)/ FROM GRID (+)]

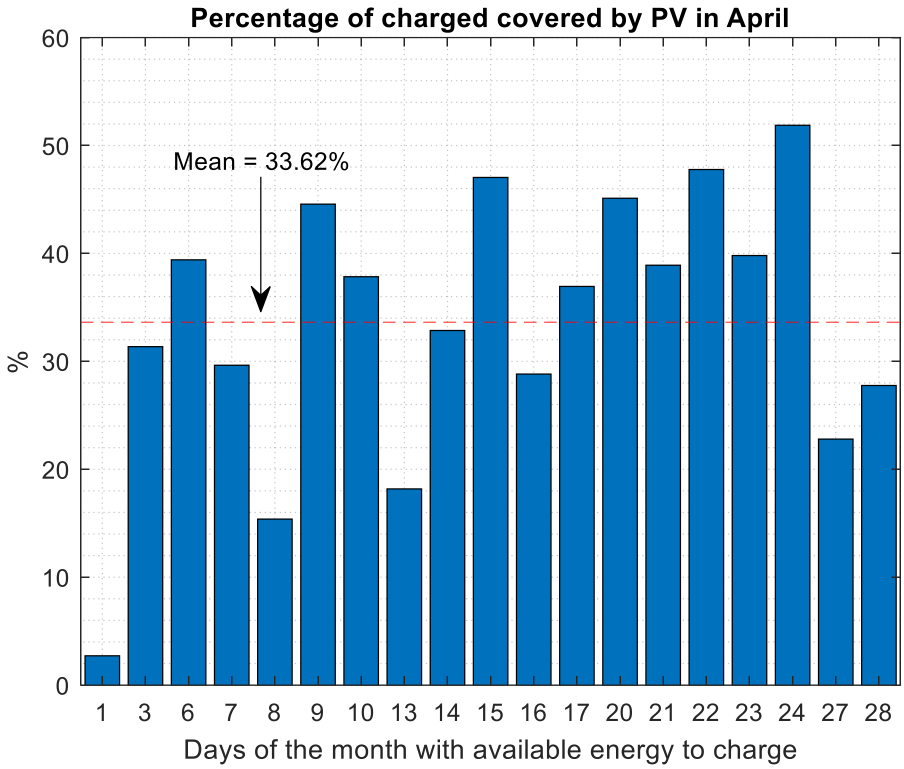

FIGURE 20: PERCENTAGE OF CHARGE COVERED BY THE SPARE PV PRODUCTION IN APRIL 2020

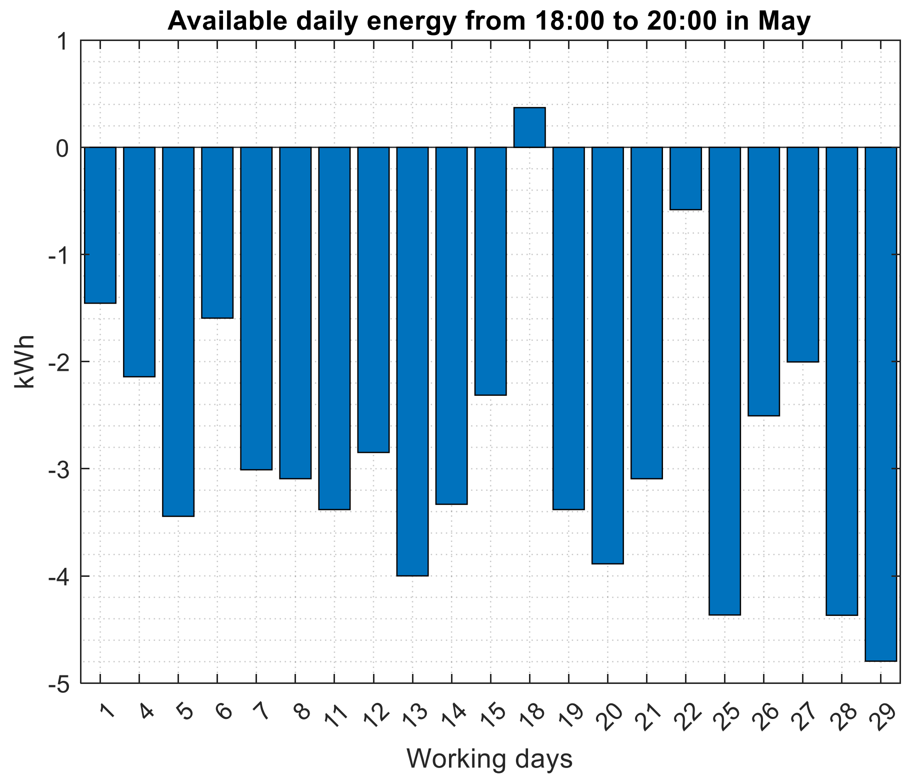

FIGURE 21: AVAILABLE PV ENERGY IN WORKING DAYS OF MAY 2020 [AVAILABLE PV (-)/ FROM GRID (+)]

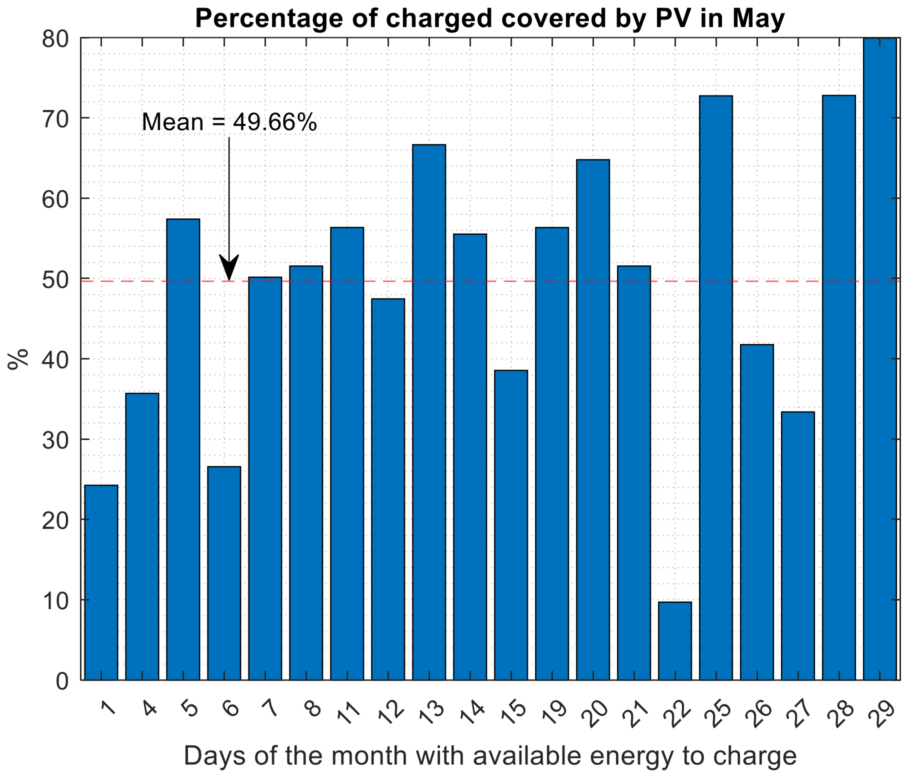

FIGURE 22: PERCENTAGE OF CHARGE COVERED BY THE SPARE PV PRODUCTION IN MAY 2020

From the figures and the table above there are some facts to highlight:

- The more near to the summer the more percentage of days have available energy to charge the electric vehicle as it is logical because the solar irradiation increases in this season.
- The maximum coverage is reached in May as half of the charge needed in average could have been provided by the PV installation.
- The best day registered in these months was the 29th of May 2020 that could have covered the 80% of the charge needed.
- September has quite a varying profile of exports and imports (see figure 17) that makes it not that reliable in terms of ensuring a relatively constant energy availability for charging.
- Contrarily, April and May show large percentages of days with available energy for charging and their export/import profiles are more homogenous, so the service is somehow ensured during these months.
- In April and May the exports are usually much higher than the imports, meaning that the few days that have not available energy for charging could be due to occasional clouds or unusual high consumption of the household.

9. Conclusions

9.1. Results

Taking into consideration the results obtained throughout this thesis there are some conclusions interesting to highlight.

First of all, regarding the netting periods it can be affirmed that larger periods bring more benefits in terms of self-consumption: the ratio of import/exports goes down resulting in a greater economic benefit due to the large difference among the price of purchasing electricity and the compensating tariff for PV production. Following the same reasoning, 3-phase billing always creates more earnings as the ratio of imports/and exports is lower than the one with 1-phase billing.

However, with the 1-phase billing method, regardless of the netting period, the amount of energy exported or imported is always higher than when the three-phase billing is conducted. This happens because when the phases are added, in the three-phase billing method, any per phase exports or imports cancel each other out for every time step. This means that, for example, the energy being consumed in one phase will be subtracted from another phase that is exporting energy at that time. In the end, there will be either an export or an import of energy, for that time step, and the value would be lower than the resulted of the 1-phase billing, which first calculates the total export or import of each phase and then combines the three phases.

Secondly, it is curious to notice that the values obtained with the 3-phase billing using a netting period of 5 minutes are almost the same ones as the results obtained with 1-phase billing and an hourly netting period.

Furthermore, no matter the billing method used, during September, October, March, April and May, months in general with higher exports, the import values in the daily netting period are much lower compared with the corresponding hourly netted periods. On the contrary, from November until January, months with higher imports, the exports values of daily netting period are the ones much lower compared to the hourly netting periods. February constitutes an exception to these conclusions as both imports and exports are lower during the daily netted period, the reason could be that in this month exports and imports are quite similar.

Finally, regarding the charge of the electric vehicle it can be assumed that only during the summer months the PV installation will produce enough energy between 18:00 and 20:00 to charge the vehicle. However, the car needed charge cannot be completed in any of the months studied being the best-case scenario a coverage of around the 80%, although the highest average coverage obtained in a month is only 50%. In addition, Denmark, for being in the north of Europe, during winter months has very few hours of light and the sun never stays out that late in the afternoon. This leads to the fact that the lack of PV production during winter periods is not only due to cold weather conditions but is also subject to the reduced hours of light caused by the Earth rotation.

9.2. Future work and perspectives

The validity of the results obtained regarding the electric vehicle as it was said are merely approximate and generic. However, they can result quite useful in future investigations to be taken as a reference of magnitudes and profiles when being compared with other studies using real cars.

The development of this thesis has pointed out some further investigations that could be done.

Firstly, even though it has been seen that the electric vehicle cannot be charged during winter months in the charging window stablished (18:00-20:00), further investigations could try to find, analysing the data obtained in this study, another charging window specific for the winter months and that tries to interfere as less as possible on the owners schedule.

Secondly, if an actual car was disposable, based on its battery capacity and more realistic energy consumption patterns it could be discovered if the amount of charge achieved during the summer months is enough, even though the car is not completely charged. This means that maybe, the daily discharge is not that deep, and the coverage offered by the PV production will restore the car's deposit sufficiently for being able to drive the following day.

Finally, the different billing methods and periods could be furtherly investigated to discover whether there are existing scenarios in which one of them is preferable than the other into consideration other goals different from economic benefits as it was done in this thesis.

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