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Impact of load management on PV self-consumption in residential sector

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Executive summary

Self-consumption of photovoltaic renewable energy – where self-generated PV electricity is consumed at its source, makes the homeowner simultaneous producer and consumer, or ‘prosumer’. This paper discusses how a load management implementation can increase PV self-consumption and the economic benefits of this model. It also explores what loads can be shifted and how, and their individual and collective impacts.

Introduction

Photovoltaic (PV) energy is one of the most promising technologies available to address the global challenge of climate degradation and the pressing need for green, renewable energy and sustainable development. Pushed by sustainable energy policies, extensive country engagement, technology development, and cost reduction, residential households today are experiencing rapid growth of PV energy production.

Photovoltaic production use in households can be described as two economic models:

- Export to grid.
- Self-consumption.

Exporting-to-the-grid option offers a long-term contract with guaranteed rates for exported PV energy (feed-in tariff policy). This model was popular in the past because it was supported by massive, subsidized campaigns to expand solar energy deployment. With the decrease of PV system costs and the increase of PV installed capacity, feed-in-tariff rates have progressively decreased in many countries, becoming even lower than end-user electricity rates. When that is the case, self-consumption becomes more profitable, and thus progressively replaces exporting to the grid model.

Self-consumption of photovoltaic renewable energy is the economic model where the residential entity uses generated PV electricity for its own electrical needs, thus acting as both producer and consumer, or 'prosumer'. The solar energy being produced is consumed instantaneously.

This model is promoted and supported today by a growing number of countries because it makes citizens active players in the energy transition and contributes to meeting the objective of increasing the share of renewables in the energy mix.

Prosumers also prefer the self-consumption model for several reasons:

- It offers, or will offer soon, greater economic benefits and better control of energy bills.
- It allows prosumers to consume their own solar energy.
- It promises greater future independence from the grid and electricity rate variations.

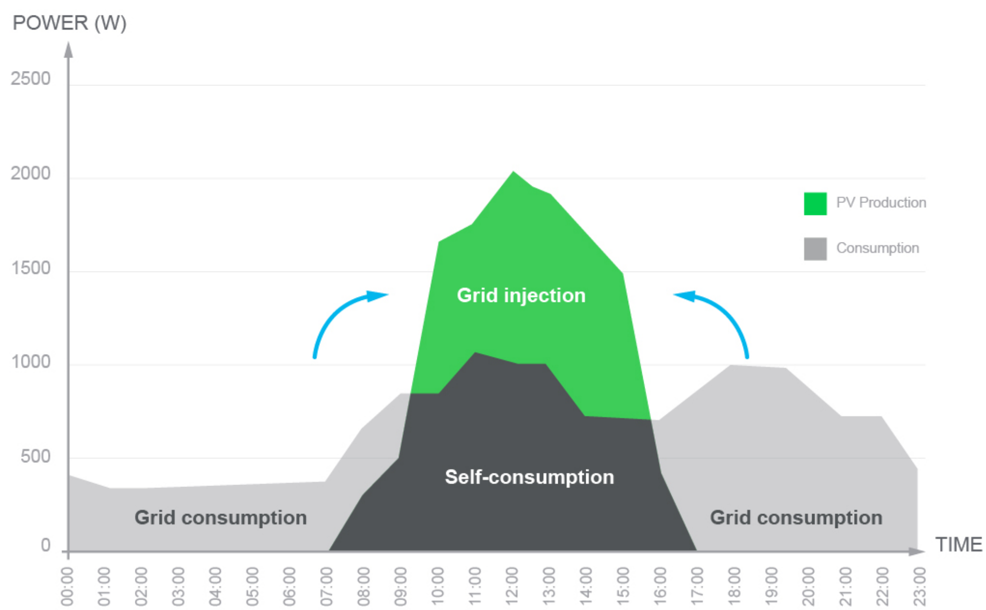
A challenge to be solved in residential photovoltaic consumption is management of excess PV production. Household consumption occurs mainly in the morning and in the evening when solar irradiations are low: load consumption is therefore not synchronized with the photovoltaic power production profile. With these conditions, photovoltaic self-consumption is relevant only if end-user usages are shifted in the hours of sunlight.

As shown in Figure 1 (a typical household case with daily consumption in grey and standard PV production in green) PV production can exceed the household consumption. The self-consumption ratio (the ratio between the PV production versus the part of the PV production consumed by the household loads) is not optimal (<100%). In this case, the possible options to manage the PV excess are:

- Inject the excess of PV production to the grid. This is the simplest solution, but not the most profitable. The injected PV electricity is purchased at a price lower than the wholesale price, or not paid at all.
- Another option is to use a storage system to store the excess of the PV production and restore it later in the day. Although very effective, today this option is costly and often has a long payback period.
- A third option is to make loads operate during the period of PV production, when it is possible (a load management strategy).

Figure 1

Typical household energy consumption (in grey) and standard photovoltaic production (in green)



The load management strategy has obvious advantages: it is cost effective, easy to implement and guarantees a quick payback. Compared to storage integration solution it does not require the installation of additional equipment and thus presents a better profitability. When the load shifting strategy is not enough to absorb the total excess of PV production it can be used in association with a storage system. In this case, load shifting has additional benefits to reduce the size and optimize the use of the storage system.

The self-consumption rate reflects the local use of photovoltaic electricity while the self-sufficiency rate reflects how the photovoltaic production can cover the needs of the place where it is installed (Figure 2).

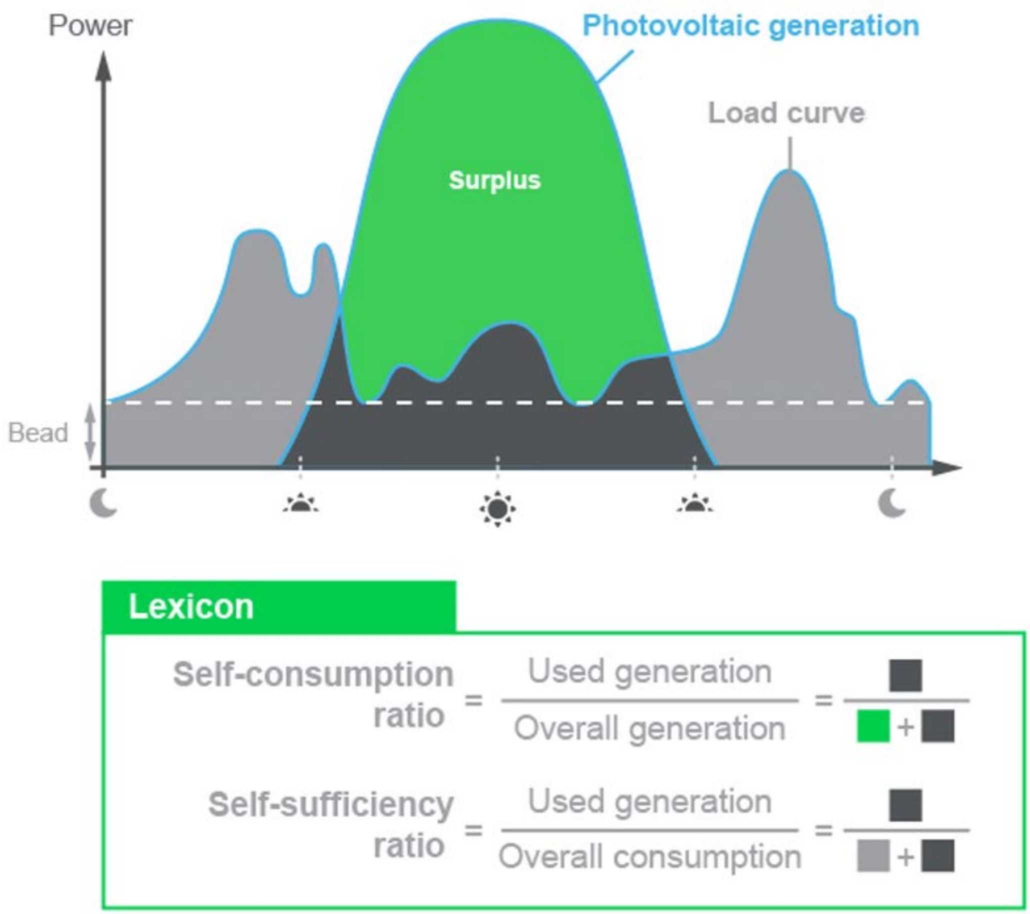


Figure 2

Self-consumption rate and self-sufficiency rate

Self-consumption ratio: people aim to improve this rate to limit their grid injection, and then ensure they take the most benefit from their local production.

Self-sufficiency ratio: people aim to improve this rate to limit grid dependency, and then ensure they are self-sufficient in terms of electrical energy.

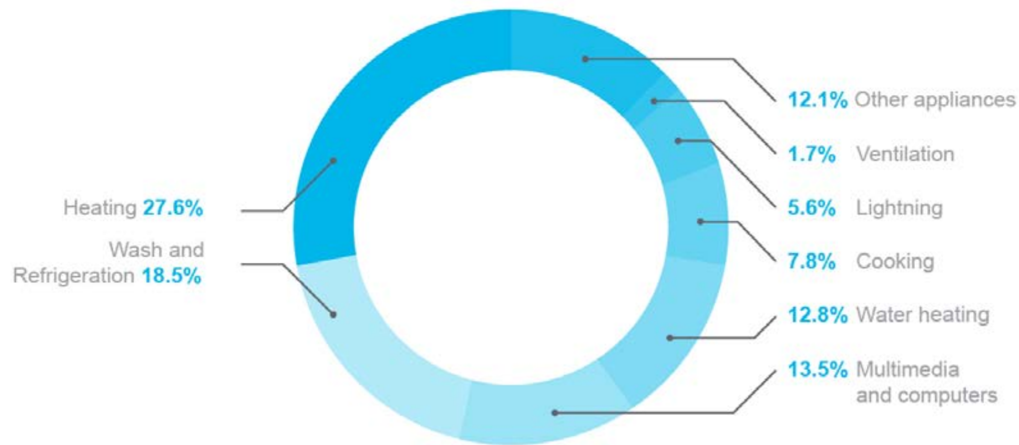
The purpose of this paper is to demonstrate how a load management implementation can increase PV self-consumption and highlight the economic benefits of this model. It explores what loads can be shifted and how, and their individual and collective impacts.

Domestic loads and flexibility

A typical household consumes an average of 15000kW to 20000kW per year in Europe, as shown in **Figure 3**. Energy consumption amounts are also affected by country geography, policy, and inhabitant habits.

The large loads in a typical household are heating, air conditioning, cold storage, hot water heating; and other domestic electrical loads such as dish washer, washing machine and, if electric, stove and oven.

Figure 3
Example of average French household electricity consumption by end use

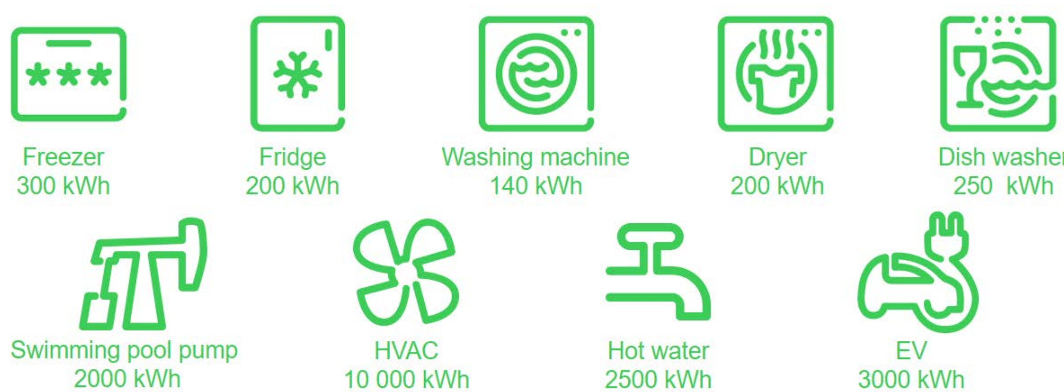


When considering energy demand management, there are three main categories of load:

- **Unshiftable** (or non-flexible) or heavily dependent on the user (high impact on comfort) such as lighting, oven.
- **Shiftable** (or flexible) but not recommended, such as freezer, refrigerator (food preservation).
- **Shiftable** (or flexible) such as dish washer, washing machine, storage water heater, electrical vehicle, pool pump, heating and air.

Orders of magnitude related to energy consumption are given in **Figure 4**: 100m² house with electrical vehicle.

Figure 4
Estimation of average energy consumption of several loads



This white paper presents the impact of the load management on the self-consumption rate. The taken examples are done for storage water heater, dish washer, washing machine, due to their high level of penetration (more than 50% in French households in 2015 for example):

- Hot water 2500 kWh / year.
- Washing machine 140 kWh/year.
- Dish washer machine 250 kWh/ year.

Domestic loads profile

To evaluate the impact of the load shifting, we need to consider:

- The consumption profile of each household load and their capacity to be shifted
- The PV production profile

Load consumption profiles vary depending on their use. For example, a hot water storage is modeled considering hot water consumption and the thermal losses of the tank. The daily consumption profile is given in the **Figure 5**.

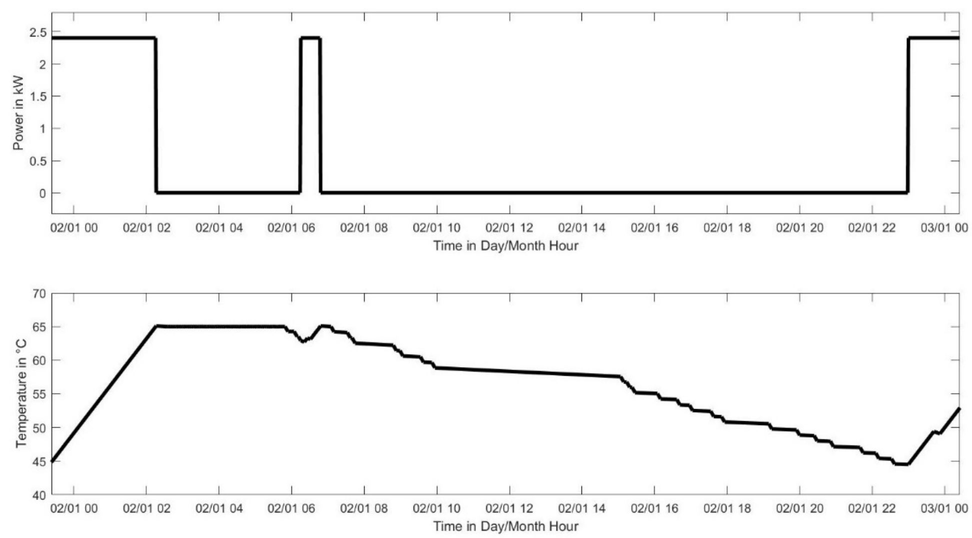


Figure 5
At the top: Usual storage water heater consumption in off peak period (from 23h to 7h)

At the bottom: Evolution of the water's temperature

Another example is the washing machine (**Figure 6**). Its load profile depends on the several phases of a washing program: the baseload is just to rotate the drum, the highest peak to 2.1 kW is used to heat the water and the smaller peaks to speed up the drum until the final spinning. A cycle consumes on average 2.5 kWh.

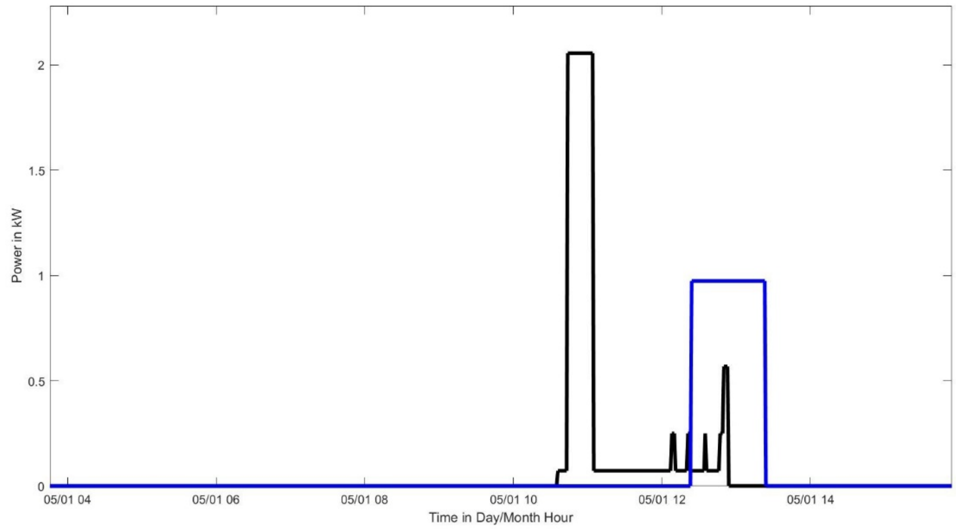


Figure 6
Typical washing machine profile (black) and dishwasher (blue)

Load management strategies

"On/Off" load management strategies

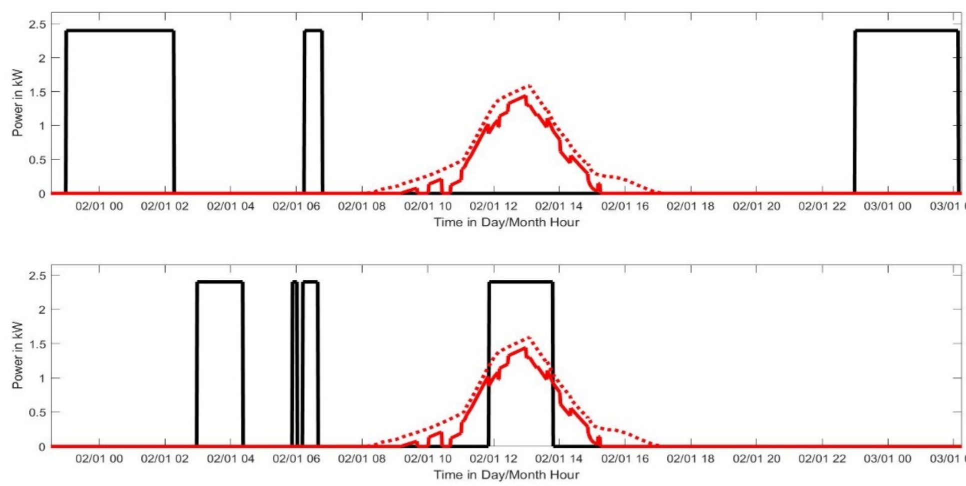
This strategy calculates at which instant a flexible load such as storage water heater, washing machine or dish washer should be shifted to maximize self-consumption. The calculation is made with an algorithm which calculate by step of 10 min the moment when the load consumes the most PV production.

For hot water storage, the reference control is based on a scheduled thermostat that does most of the heating during the night, with only occasional additional day heating when the temperature is too low. The new strategy shift part of the heating during hours of high PV production (Figure 7).

Figure 7
Top: Usual storage water heater consumption in off peak period (from 23h to 7h)

Bottom: Storage hot water shifted with ON/OFF strategy consumption

PV production for a 3kWp installation (dotted red), remaining PV production after house baseload consumption (red)



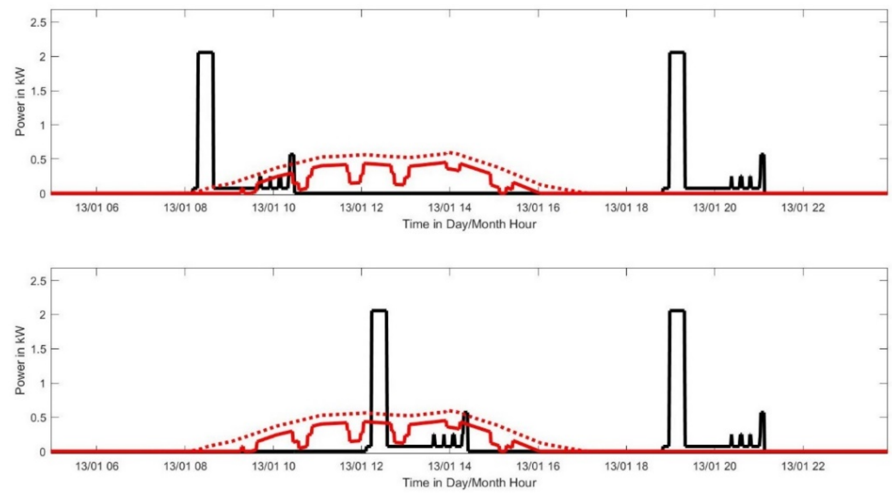
Regarding shifting the load of the washing machine and the dish washer, the main objective is to maximize self-consumption without changing user behavior too much. Indeed, it is assumed that it is possible to use start time preselection only for the first cycle of the day which is the only one shifted.

Figure 8

Top: Usual washing machine consumption in off peak period (from 23h to 7h)

Bottom: Washing machine shifted with ON/OFF strategy consumption

PV production for a 3kWp installation (dotted red), remaining PV production after house baseload consumption (red), washing machine power (black)



For example, in **Figure 8**, the first cycle has been shifted from 8:00 to 12:00 but the cycle beginning at 18:45 remains the same. One issue with On/Off strategy arises when energy rate includes Time of Use (TOU), e.g. variable price depending on the hour. If the PV does not cover the full heating power, there is a risk that the remaining power purchased from the grid will cost more than the actual cost of night consumption.

"Setpoint" strategy

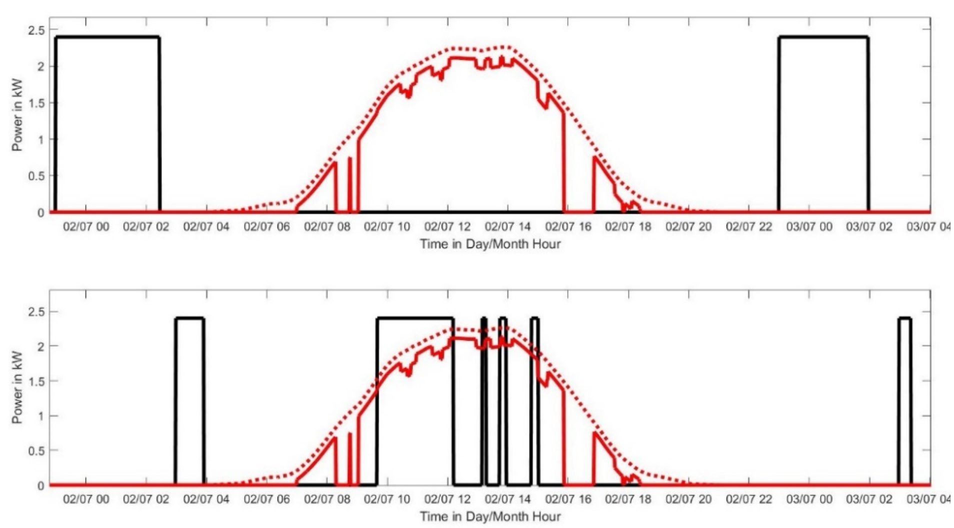
The setpoint strategy is a first solution to remove the risk for over cost. This strategy still uses an on/off approach, but the load is switched on only if remaining PV power at least compensates for the price difference. In this way the customer is sure he/she will not pay more than without the shifting strategy. The drawback is that there might be many days during the year where this condition will not be met to recover the PV (**Figure 9**).

Figure 9

Top: Usual water heater consumption in off peak period (from 23h to 7h)

Bottom: Storage hot water shifted with Setpoint strategy consumption

PV production for a 3kWp installation (dotted red), remaining PV production after house baseload consumption (red), water tank power (black)



“Dimmer” strategy

This strategy shifts storage hot water and controls its power consumption to use only the PV production. This strategy is the best method to maximize the rate of self-consumption, although it might require new actuator. We also notice a slight elevation of the tank energy consumption due to higher losses caused by a higher mean temperature (Figure 10).

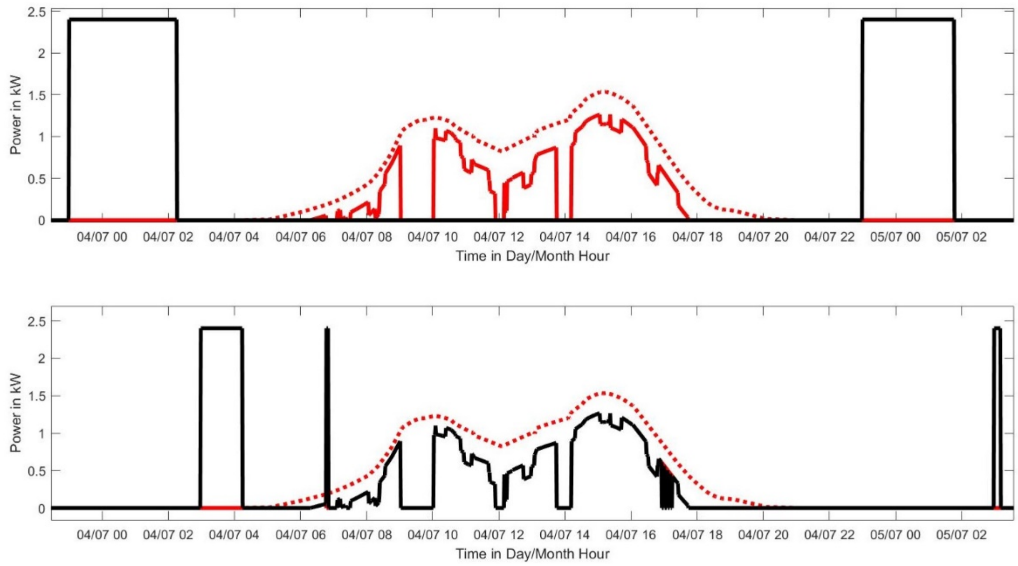


Figure 10

Top: Usual water heater consumption in off peak period (from 23h to 7h)

Bottom: Storage hot water shifted with Dimmer strategy consumption

PV production for a 3kWp installation (dotted red), remaining PV production after house baseload consumption (red), water tank power (black)

Load management impact on PV self-consumption

To evaluate the impact of load management on PV self-consumption, we will simulate photovoltaic production, house flexible and non-flexible loads and the load management strategy. Yearly simulation with a step time of 1 minute will allow us to get detailed evaluation of the photovoltaic self-consumption as well as the impact on the energy bill. The results are dependent on the following parameters:

- PV production (panels size and orientation, irradiance….).
- House HVAC consumption, which depend on the house envelope, weather, HVAC systems and internal gains.
- House occupancy profile and usage (including consumption profile for plug loads).
- Energy tariff (flat or time of use).
- Load management strategy.

Hypothesis

For this case, we consider a typical house with 4 occupants. The HVAC consists of a return air ventilation and electrical heating. For simplification, we also made the hypothesis that shifting some load profiles will not impact the heating consumption profile.

Methodology

To create the plug loads profile, we use the CREST Demand Model, a stochastic profile generator developed by the Centre for Renewable Energy Systems Technology (Loughbourough University, UK). It provides, for a given house configuration, a power profile for every plug load in the house.

For the house HVAC modeling, we use IDA-ICE, a building simulation that provides a detailed load profile for lighting, heating, and auxiliaries (fans, pumps...). These plug load profiles defined by CREST are inserted in the building model so that their internal gains can be considered.

We finally obtain all the building load profiles. The next step is to implement how one or several loads can be shifted. The methodology does not consist of development of a real control solution, but more on the use of simple heuristics described previously.

The two main outputs calculated at the end are:

- Photovoltaic self-consumption.
- Energy bill.

One challenge with the simple heuristics considered is that they do not take costs into consideration. This means that, in some cases, load shifting will indeed increase self-consumption but with a global higher cost of energy. This is especially true in case of TOU prices.

Examples of application

For a 130m² standalone house with four occupants, the obtained results are:

- Irradiation 800-1000 kWh/kWp.
- Production at 3kWp: 2900 kWh/year.
- Loads: Storage water heater operating in off-peak period, washing machine, dryer, dish washer, landline telephone, hi-fi, iron, vacuum, two televisions, DVD player, modem, micro-wave, electric oven, and stovetop.
- Energy consumption: 16050 kWh/year.
- Heating consumption: 62,6 kWh/m²/year.

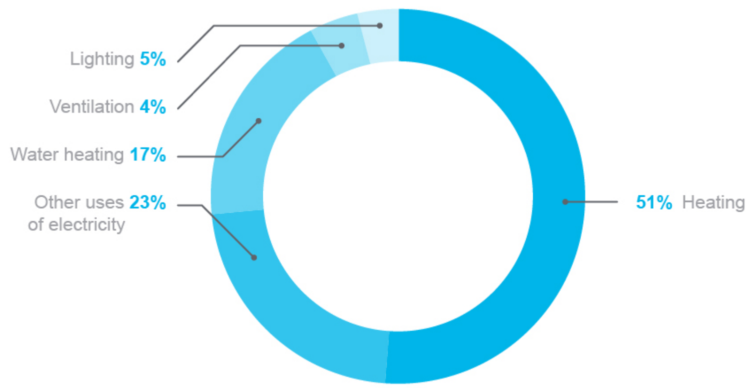


Figure 11
IDA-Ice house energy consumption by end use

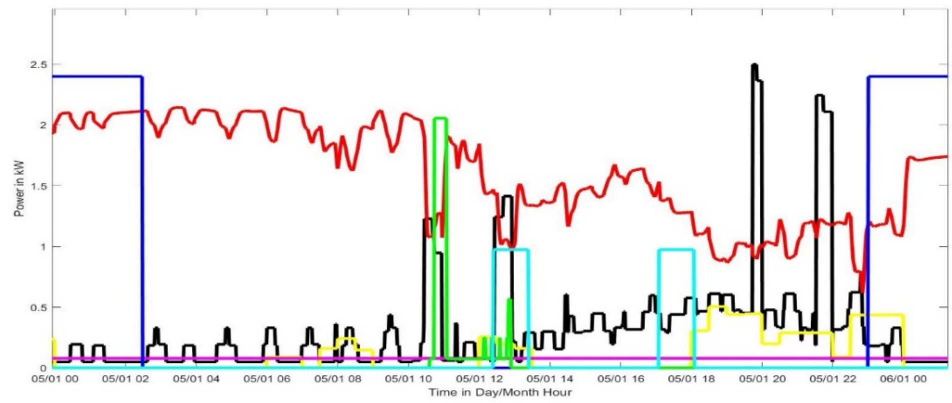


Figure 12
Usual storage water heater (blue), usual washing machine (green), usual dish washer (cyan), heater (red), lighting (yellow), ventilation (magenta), remaining loads (black)

Simulation results

Significant energy savings can be achieved by implementing load management strategies

The simulations give several results on the self-consumption rate or the energy saved depending on the load management strategies. It is important to keep in mind that these results are based on a unique model of a residential household and therefore apply only for this model (**Figure 13**).

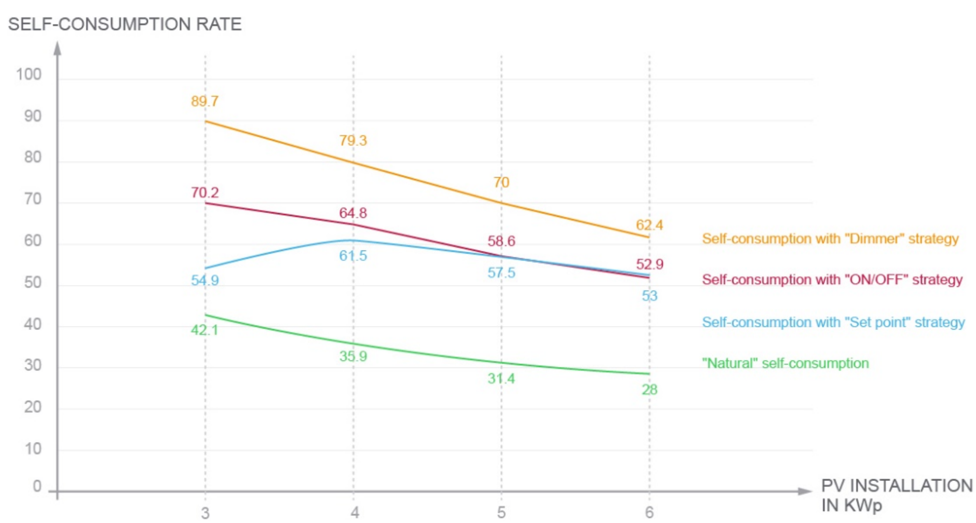
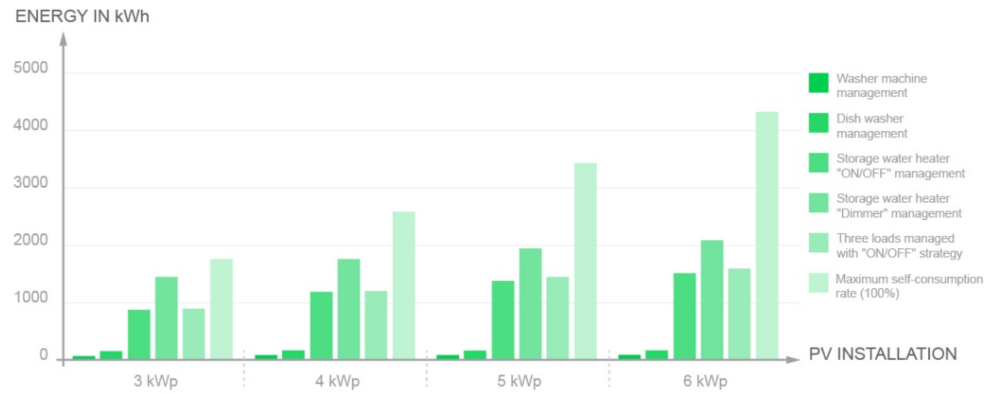


Figure 13
Evolution of the self-consumption rate for a house with non-electric heater depending of PV installation

The evolution of the self-consumption rate shows that the more PV energy is available, the more difficult it is to consume it and therefore the rate of self-consumption decreases. According to the results, each load management strategy improves self-consumption, albeit differently. In particular, the “Setpoint” strategy used is based on the French Time of Use tariff and thus activates the storage water heater around 1380 W, a value which is difficult to reach for a 3 kWp PV installation (Figure 14).

Figure 14
Yearly energy saved for the different load management



Storage and water heater shifting has a strong impact on self-consumption rates

The results of the energy gain presented in Figure 14 indicate energy saved (i.e. not consume from the grid) by shifting loads such as the washing machine and the dish washer is relatively low. Indeed, theses loads are already naturally used during the day, already consuming PV electricity, and in our model only the first cycle is shifted. Conversely, the storage water heater with ON/OFF and Dimmer management strategy are interesting. For a 3 kWp PV installation the gain is close to the maximum.

Annual financial benefits of hundreds of euros can be achieved

As it is easier to understand these results by showing the money saved instead of the energy saved, Figure 15 presents an example of the financial consequences in Germany with an electricity tariff of 0,28 €/kWh and a Feed in Tariff for the PV electricity rejected to the grid of 0,10 €/kWh.

Figure 15
Yearly benefit of the different load management strategies in Germany

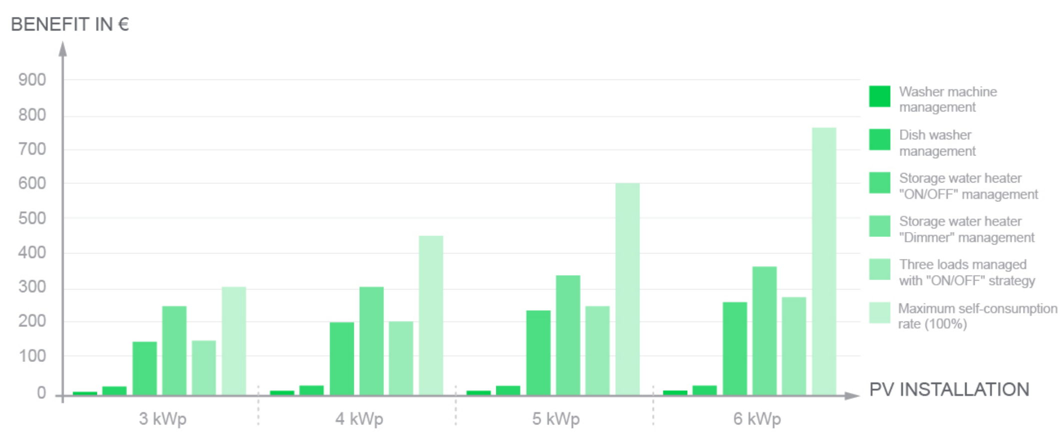


Figure 15 shows that washing machine and dish washer management provides low economic benefits and, in addition can create end-user discomfort. The yield of storage water heater management is more important with no impact on comfort.

Compare to total resale, a yearly additional profit of 301€ can be generated by a 6 kWp PV installation (5975 kWh/year with 28% self-consumption ratio), considering that the retail price of electricity is 0,28 €/kWh; and the feed-in-tariff is 0,10 €/kWh.

This profit is composed of savings on the energy bill and revenues from the sale of the surplus of electricity.

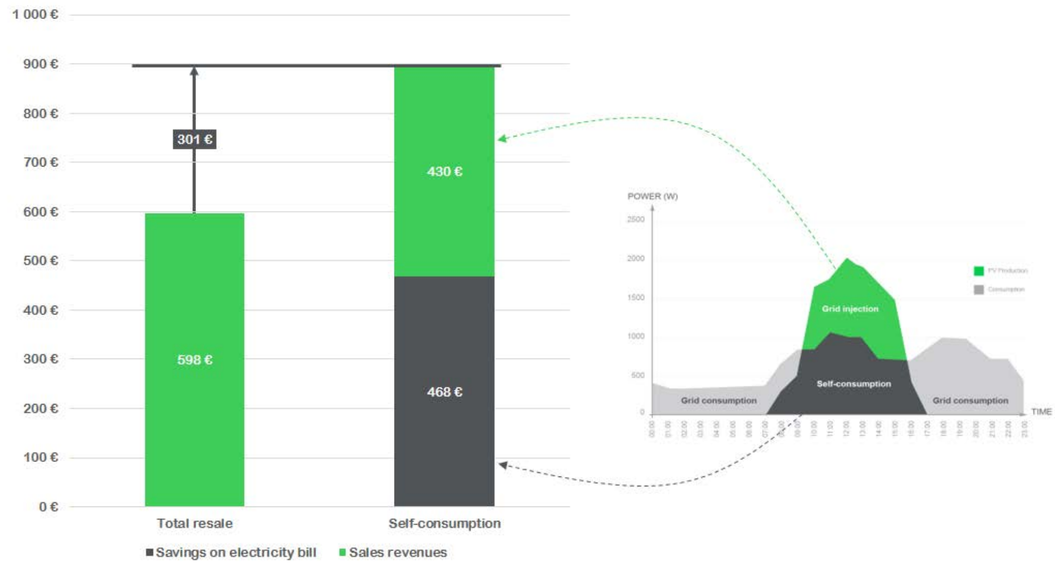


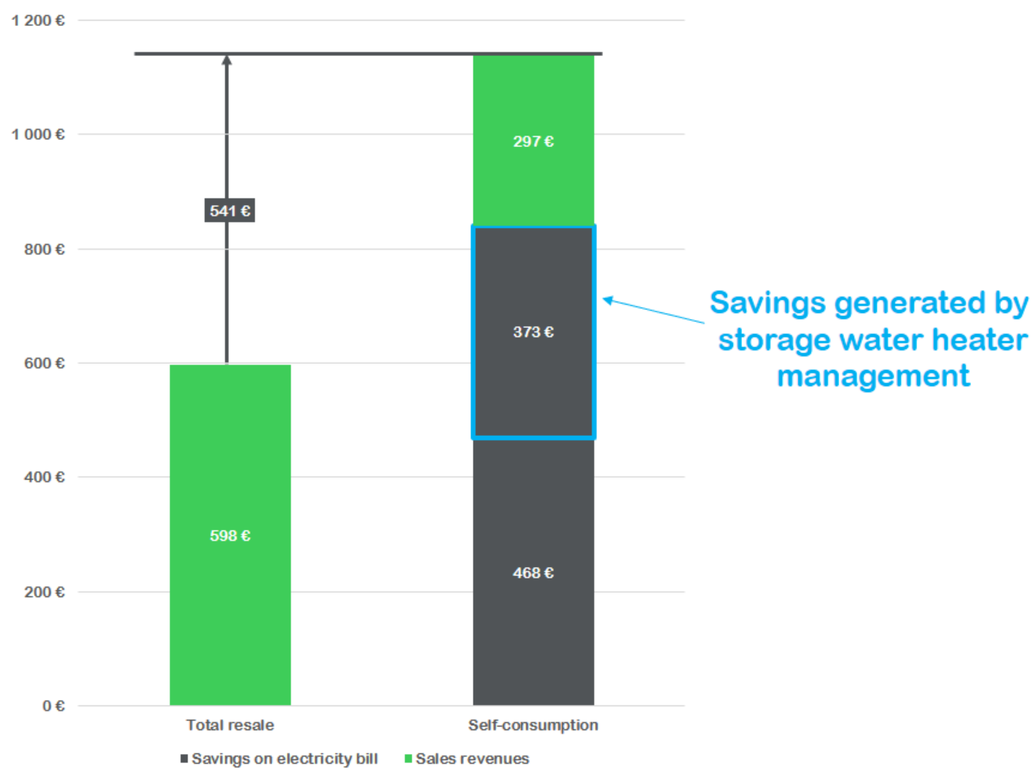
Figure 16
Total resale vs Self-consumption for a 6 kWp PV installation with a 28% self-consumption ratio

Note: in Figure 16, a one-year simulation of two different scenario with photovoltaic is presented:

- In the first one, the resale of the PV electricity to the grid generates an annual income of 598€.
- In the second one, a part of the electricity is self-consumed, this part generates an annual saving of 468 €, and the excess of electricity is sold to the grid, the annual revenue is 430 €.

With storage water heater management, the self-consumption rate can be increased to 50% and the yearly additional profit generated is 541€ as shown in Figure 17.

Figure 17
Total resale vs Self-consumption for a 6 kWp PV installation with a 50% self-consumption ratio



Load management on photovoltaic for residential sector in order to increase self-consumption rate can be very effective depending on the load and this is a very good solution to get the most of assets and to enhance the performance of the installation with a quick payback.

Conclusion

Households with photovoltaic installations can maximize the use of their production and significantly increase their self-consumption rate by integrating a load shifting strategy. As this paper demonstrates, not all shiftable loads are worth managing: the shift of daily-used loads with low consumption such as washing machines, dryers, and dish washers have limited impact on self-consumption rates. Conversely, management of loads such as tank water heaters, characterized by high energy consumption and previous night operation, can increase self-consumption rates by up to 50%, in function of the implemented control strategy.

Associated financial benefits depend on the electricity purchase and sellback prices, any PV production, and the daily profile of the electrical loads. As this paper demonstrates, financial benefits usually account for several hundreds of euros annually, and provide quick payback on the implementation of load management solutions.

Schneider Electric solutions for maximization of the household self-consumption rate are presented in the Appendix.

Appendix

Self-consumption optimization could be achieved with Schneider Electric's Wiser connected offer.

Wiser is a cloud connected system composed of:

- The Wiser app and his appealing user interface
- Wiser IP module, the gateway to connect the system
- PowerTag E, wireless class 1 energy sensors
- PowerTag C, wireless control relays

Figure 18
PowerTag installed downstream miniature circuit breaker

Figure 19
Example : electrical panel board for PV self-consumption with Wiser connected solution

Thanks to the energy monitoring done by the PowerTag E and algorithms embedded in the cloud, the Wiser system provides an intelligent and automatized energy optimization, ensuring the right source and the right load at right moment, considering external data.

By doing so, Wiser automatically optimize the self-consumption rate and make sure that the solar installation performance is maximize. Users can visualize energy flows, savings and revenues, can get alarms and can control loads and appliances from the Wiser application (cf. Figure 20).

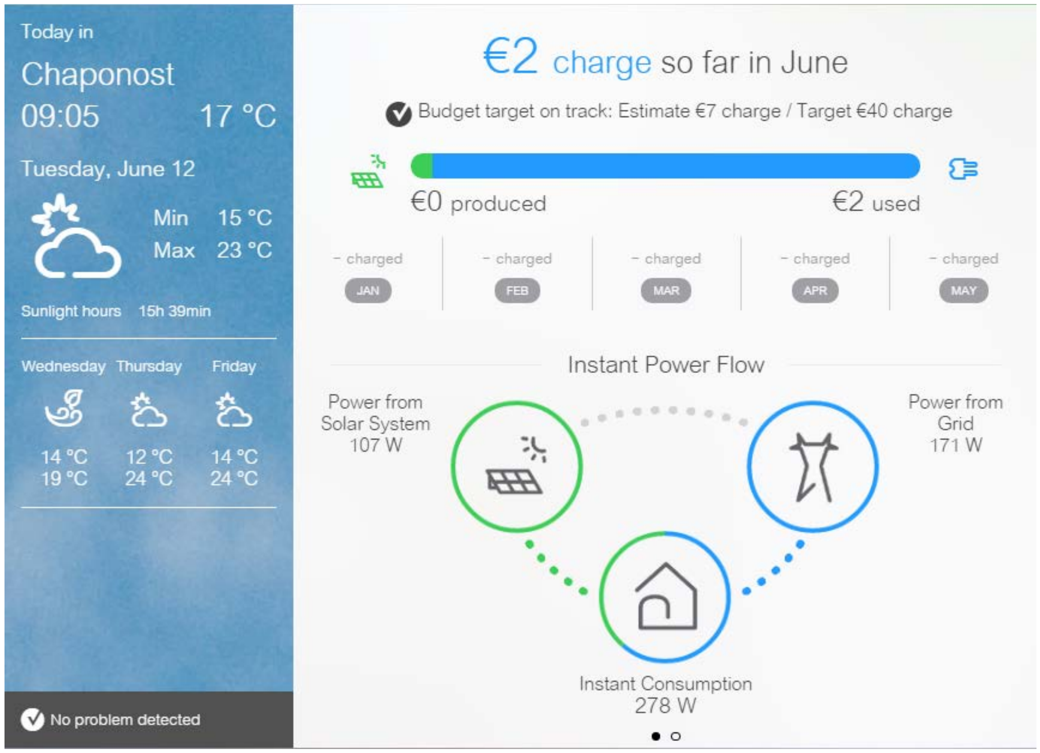


Figure 20
Wiser mobile app user interface: power flows

Figure 21
Wiser mobile app user interface: daily energy consumption

Figure 22
Wiser mobile app user interface: weekly consumption

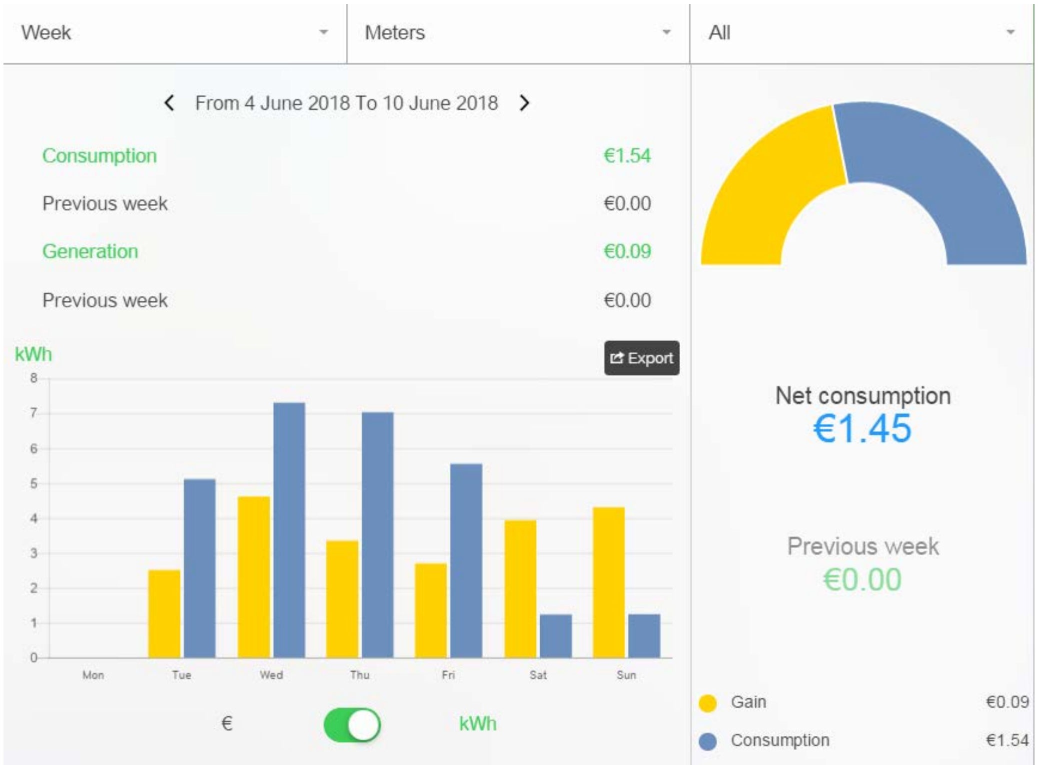
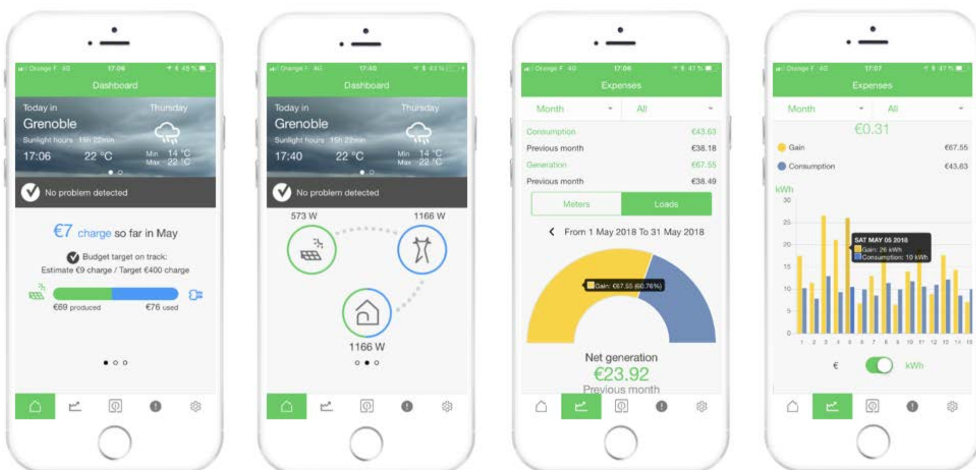


Figure 23
Wiser mobile app user interface



About the authors

Yasmina Benbrahim is a master of science student in power electric engineering at Institut National Polytechnique de Grenoble - Ense[3]. Interested in renewable energies development and innovation, she had the opportunity to join Schneider electric for an internship to work on the impact of load management in the residential self-consumption. She is currently pursuing her studies by doing a project research on microgrid in an electrical engineering laboratory.

Patrick Béguery is part of the Analytics & Artificial Intelligence team, in Schneider Digital organization. He is an engineer from Ecole Centrale de Lyon and received his PhD on automatic from Institut National Polytechnique de Grenoble. After 10 years working for Renault car manufacturer, he joined Schneider Electric in 2007 to work on simulation for building, district and microgrid segments, both to support R&D and provide tools to facilitate design and operation of customer specific solutions. He is also leading the BEES competency network which bring together experts in simulation from different segments.

Sébastien Mathiou is New Energy Landscape Future Offer Manager at Schneider Electric. He has received a Master degree on Electrical Engineering from Institut National Polytechnique de Grenoble and has completed an Executive Master of Business Administration at EMLYON Business School. After 6 years working for the Socotec group, he joined Schneider Electric in 2010 as a power systems expert to carry out high and low voltage power systems studies around different segment applications such as oil and gas, renewable energy, data center, utility and smart grid. Sébastien then held the position of competency center manager for a smart grid offer and later on was responsible for customer low voltage applications. He moved to his current position in 2018.

Vanya Ignatova is Architect of Renewable Energies Integration at Schneider Electric. She has received her Master degree on electrical engineering and her PhD degree on power quality from Institut National Polytechnique de Grenoble. She joined Schneider Electric in 2006, where she brings her expertise on electrical engineering, energy management, power quality and renewable energies integration. She is author of multiple articles and white papers at these domains.