Estimation of load shifting impact on energy expenses and self-consumption in the residential sector

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Abstract

Demand side management is an increasingly diffused practice for large energy consumers, while the disaggregated nature of residential loads makes its adoption in the residential sector more complex. Among the demand side management practices, load shifting allows to match demand and production. In the case of prosumers, harnessing the load shifting potential from available technologies allows to increase self-consumption ensuring benefits both for the customer and the local grid. In order to evaluate the actual potential of load shifting in the residential sector, two major steps are needed: (1) a reliable and disaggregated, both with respect to time and technologies, estimation of demand curves and, (2) an evaluation of the actual possibility to shift each load and its corresponding impact on self-consumption and energy bills. In this work, both steps are conducted for the Belgian residential sector. Stochastic demand curves are obtained for a set of representative cases through a framework composed of different open source models, allowing to obtain the electricity consumption from appliances, electric boilers for domestic hot water, heating through heat pumps and electric vehicles charging. Load curves are validated by comparison to historical real-world data. The load shifting potential is then estimated, both considering time-of-use tariffs and, in case photovoltaic panels are present, self-consumption maximization, also through batteries. Results highlight the contribution to load shifting from each different technology, suggesting that correctly structured tariffs could reduce peak hour demand and increase self-consumption.
Keywords: load shifting, residential sector, self-consumption

1 Introduction

Energy self-consumption consists in the use of electricity produced on-site to cover for electricity demand. When considering on-grid dwellings, photovoltaic (PV) panels output can be consumed on-site or exported to the grid. Self-use occurs when electricity is concurrently produced and consumed or when it is stored in an energy storage system, which can consist both of batteries or, in a wider sense, of load control devices that leverage on storage capabilities of certain home appliances to store energy [6].

High battery costs [7] and PV export compensation schemes [2] have so far limited the ability of customers to self-consume the energy produced on-site. Yet, falling battery costs [5], the emergence of low-cost load control devices [6], and the reduction of compensation for grid exports [2] have started to invert the trend in the last years. Future behind-the-meter PV systems will hence be increasingly integrated with batteries and load control devices, increasing self-consumption.

In this article, a framework for the evaluation of load shifting in the residential sector is presented through the analysis of a set of cases studies for Belgium. The developed framework unifies all major steps required: disaggregated load demand modelling, PV and batteries modelling, and specific load shifting evaluation methods per each technology considered.

2 Methodology

This section outlines the fundamentals methodologies applied in this study. Subsection 2.1 deals with how demand curves have been obtained, while subsection 2.2 outlines the modelling approach adopted for all the technologies for which load shifting is considered. Finally, subsection 2.3 introduces the economic analysis and the main economic parameters considered for the analysis.

2.1 Energy demand modelling

All thermal and electrical energy consumption are modelled in a bottom-up fashion and with a one-minute time step through a set of open source models:

- StROBe is a stochastic residential occupant behaviour model based on Markov chains and is used to obtain electricity consumption associated to appliances and lights, and to estimate internal heat gains, hot water withdrawals, and the household's members occupancy profiles [1].
- Building thermal demand is obtained through a dedicated RC equivalent building model following the implementation of Jayathissa et al. [3].
- Hot water and house heating demand are converted to electrical demand through two ad-hoc developed models of an electric boiler and a heat pump.
- Finally, charging profiles for electric vehicles are obtained through RAMP mobility, a tool for the generation of European electric vehicles mobility and charging profiles at high temporal resolution [4].

The models are integrated in a unified framework for the generation of electrical load curves in the residential sector.

2.2 Load shifting modelling

A set of rule based control actions for the evaluation of load shifting and demand side management have been added to the same framework. Such functions are defined both for the displacement of loads based on time-of-use tariffs and, in the case of prosumers installing photovoltaic panels, for self-consumption maximization. In the latter case, the possibility of installing an electrochemical battery is considered and its usage strategy is modelled according to a methodology developed in previous works [7].

Among all household appliances, only wet appliances (namely dishwashers, washing machines and tumble dryers) are considered as time-shiftable. The adopted modelling approach is based on the definition of admissible time windows for the shifting, combined with a user-defined probability of the shifting to actually happen. Such admissible time windows are defined according to the case to be simulated and can hence be based on the presence of households' members at home, energy prices and the availability of energy from PV panels.

Electricity demand from the electrical boiler for domestic hot water is modelled through a battery equivalent approach. The capacity of the boiler to store energy is defined considering the size of the hot water tank, and the possibility of pre-heating water in correspondence of low energy prices or when excess energy from the PV panels is available.

House thermal demand is shifted by modifying the thermostat setpoints, increasing the temperature requested to the heating system of a fixed offset in order to preheat the house during time windows of up to three hours prior to the actual demand.

Electric vehicles are considered as batteries connected to the household energy system. The available capacity is obtained from evaluating when the car is parked and plugged in at home and the minimum state of charge needed to ensure enough charge will be available for the next drive, estimated with a perfect foresight of the car usage throughout the year.

2.2.1 Wet appliances

Three possible situations are considered for the shifting of wet appliances. In the first case, no PV panels are installed and the shifting is manually controlled. Since the shifting happens manually, the considered cycle can be started only when at least one adult household occupant is at home and active. At the same time, energy prices have to be lower than the reference price considered. From the intersection of the two sets of time periods, the useful starting times are obtained. The second case is similar to the first one, with the only difference that the starting time can be set from the user at any time, increasing the useful time windows for the shifting of the appliance. Finally, in the third case, PV panels are introduced and useful time windows depend on the availability of electricity from solar panels.

Once that the admissible time windows are defined, the shifting for all three cases happens based on the same logic. Each cycle happening when electricity prices are higher than the reference one has a user-defined probability of being shifted to the closest admissible time window, provided that the amount of hours of which it will be shifted is lower than the limit imposed. Whenever a cycle is shifted to a new time windows, that time window becomes no more available for other cycles to be shifted.

2.2.2 Domestic hot water

Domestic hot water is provided by an electric boiler. The shifting strategy considers the hot water tank as a battery equivalent. The equivalent capacity Q can be obtained from the typical parameters of an electric boiler. Considering a perfectly-mixed model for the water tank, it can be expressed as:

$$Q = V_{cyl} \cdot c_{p,H_2O} \cdot \rho_{H_2O} \cdot (T_{set} - T_{min}) \tag{1}$$

where V_{cyl} is the cylinder volume, c_{p,H_2O} and ρ_{H_2O} are water thermophysical properties, and T_{set} and T_{min} are respectively the target temperature inside the boiler and the minimum temperature at which water can be supplied to the users. As a consequence the equivalent state of charge is expressed as a function of the temperature:

$$SOC = \frac{T_i - T_{min}}{T_{set} - T_{min}} \tag{2}$$

where T_i is the temperature inside the boiler. The equivalent battery efficiency is considered equal to one both when charging and discharging, as in the first case it is assumed that the boiler efficiency is unitary, while in the second case the water is directly drawn from the cylinder and no losses are to be considered. Maximum charge and discharge power are fixed and equal to the maximum electrical power of the electric boiler. Heat losses towards the environment are neglected, but could be considered as self-discharge in the equivalent battery model.

Once that the equivalent battery model is defined, two possible control logic can be considered. In the first one, the battery is charged buying low cost electricity from the grid, while in the second one it is charged with electricity produced from the PV panels, as to increase self-consumption.

2.2.3 House heating

To estimate the potential contribution of house heating to load shifting, the following strategy is put into place. The temperature setpoint is increased of a fixed ΔT when inside a three hours time window preceding the actual heating starting, and either electricity prices are below the threshold or there is electricity available from the PV panels. The house thermal model is contextually re-run, as to account for the new temperature setpoint profile and its impact on the thermal losses and internal comfort.

2.2.4 Electric vehicles

The electric vehicle load shifting contribution is estimated starting from the charging profiles happening at home. No vehicle-to grid (V2G) strategies is considered, meaning that energy can only be stored in the EV battery, and not used to cover part of the household load. For each at-home charging event, the corresponding time window during which the household's main driver is at home is identified. Inside the identified time window and before the actual charging event happening, when low cost energy or electricity from the PV panels is available, the car is charged. If no low cost energy or energy from the PV panels is available, the charging happens in correspondence of the original charging event. The amount of energy stored inside the battery at the end of the time window considered is always equal to the original amount of energy stored in that same time window through the reference charging events.

2.2.5 Batteries

Battery energy storage systems are considered only when PV panels are installed. The battery is managed to maximize self-consumption. Energy is stored whenever excess electricity is available from the panels and the battery is not already full, while the battery is discharged when solar electricity is not enough to cover demand, until it is empty.

2.3 Economic analysis

The economic analysis is conducted according to the Net Present Value methodology. Investment costs are composed by PV panels, inverter, battery, and energy management systems required to control the cosnidered technologies for load shifting. Electricity expenditure in the reference case, when no investment is made, is considered as an annual saving, and hence as a positive contribution to the cash flow.

2.3.1 Electricity tariffs structure

A time-of-use tarification scheme is considered, based on actual tariffs of the Brussels Region, and in line with tariffs to be proposed for the Walloon Region in the near future. Each day is composed by a combination of four different energy prices in the cold season and three in the hot one. The distribution of the tariffs throughout the day is shown in Figure 1, while Table 1 summarizes the tariffs. A fixed annual expense of 50€/a is to be added the consumption-based fares, and another expense of 50€/a is to be considered for renting the smart meter.

Time slot	Energy price [€/kWh]	Grid costs [€/kWh]	Surcharges [€/kWh]
Peak	0.2178	0.1533	0.0516
Full	0.1936	0.1188	0.0516
Hollow	0.1694	0.0844	0.0516
Heel	0.1452	0.0499	0.0516

Table 1: Electricity tariffs

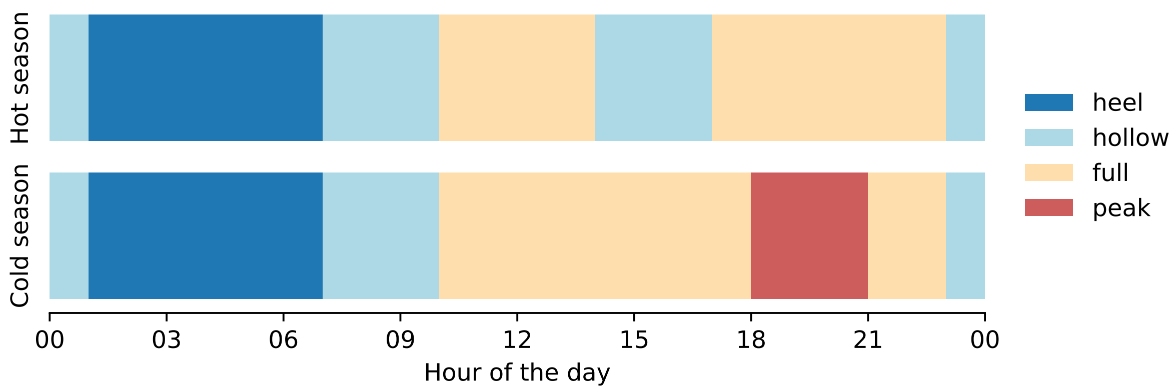

Figure 1: Time-of-use tariffs - Daily distribution during cold and hot seasons

The energy produced from PV panels and injected into the grid is remunerated with specific tariffs up to 2030 for customers installing PV panels before 2024. Electricity fed to the grid is paid the energy prices listed in Table 1, yet grid costs proportional to the amount of energy sold are to be paid as well, again in line with Table 1 fees and up to a maximum fixed annual expenditure. The maximum annual expenditure depends on the size of the PV panels installed and is obtained multiplying the capacity by a factor that averages around 88 €/kW in the Wallon Region. After 2030, or for customers installing PV panels after 2024, energy is considered to be sold at 0.04 €/kWh.

3 Results

Results consist of a set of demand curves representative of the Belgian residential sector and of an analysis of the potential contribution of each technology to the displacement of electricity demand. The impact of different strategies on self consumption and consumers' energy bills is assessed. An extract from the results obtained for a single freestanding household composed by four people is here presented. Examples of demand profiles before and after shifting are shown in Figure 2 and Figure 3.

In the case of a fully electrified freestanding house with four household members and an electric vehicle, a total annual consumption of 9102 kWh/a is obtained. Consumption is distributed between the four time tariffs as shown in the baseline column in Table 2.

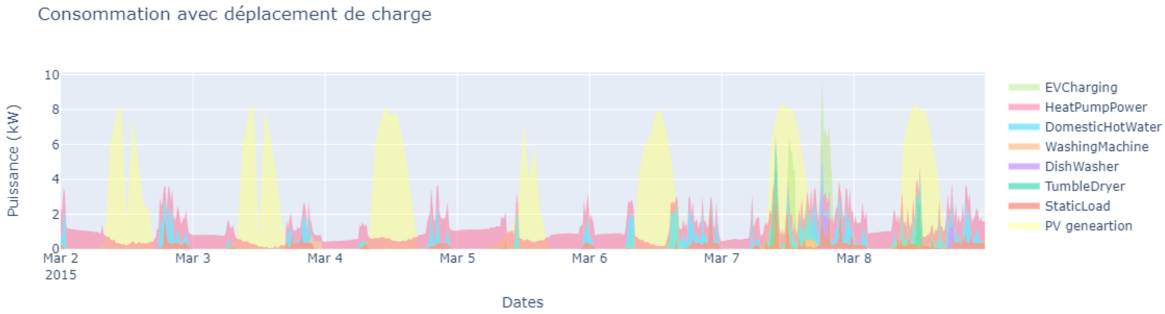

Figure 2: Load demand profile before shifting

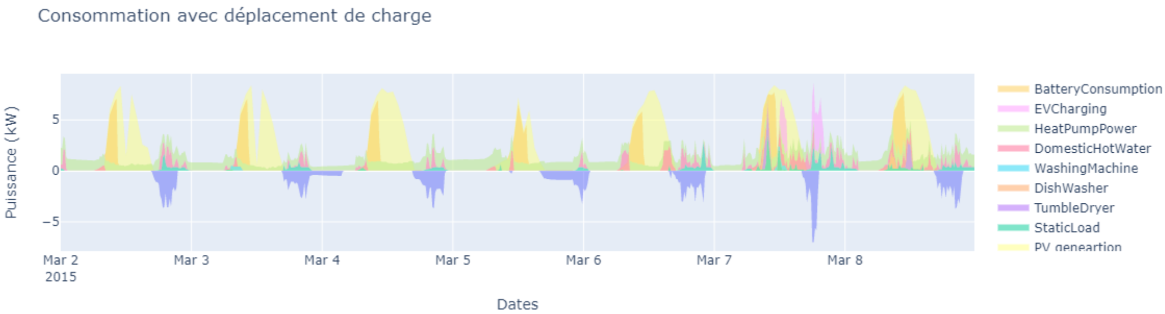

Figure 3: Load demand profile after shifting

As a first strategy, all shiftable loads are shifted. Priority is given to wet appliances, then to domestic hot water, house heating, and EV charging. Results are listed in the second column of Table 2. An overall reduction in consumption is observed. This might be ascribed to a better overall heating strategy for the dwelling, as in well insulated homes preheating could coincide with less steep ramps when heating is turned on. A reduction of less than 1% is obtained in the peak time slot, while more than 12% reduction is observed in the second price class, where most of the consumption is placed. Shifted consumption is mostly redistributed to the hollow price class, yet a significant consumption increase is observed also in the least cost price range. Considering an initial investment for the energy management system of 500€ and an annual fee of 30€/a, the payback period is just slightly less than two years.

The introduction of PV panels, without load shifting, is then considered. A capacity of 9.5 kW$_p$ is installed, resulting in an annual production equal to the demand and a self-consumption of 2269 kWh or 24.9% of the total demand. In this case the payback period of the investment is 15.4 years. Reliance on the grid to cover demand is mostly reduced in the central prices class, while almost no variation is obtained during peak hours, as the production from PV panels in winter between 18:00 and 21:00 is almost null.

If PV panels are used in combination with load shifting strategies, reliance on the grid is reduced up to 6834 kWh/a. The modest increase in investment and annual costs is justified by the increased self-consumption and the payback period is lowered to 10.9 years.

A straightforward comparison can be made between the latter configuration and one considering PV

Time slot	Baseline	LS	PV	PV, LS	PV, BAT	PV, LS, BAT
Peak	1272	1343	1135	1073	1034	963
Full	1928	3035	1236	1104	1017	927
Hollow	4386	3110	2956	2290	1646	1503
Heel	1516	1294	1507	1177	836	766
Total	9102	8781	6834	5644	4534	4158

Table 2: Annual consumption [kWh/a] covered buying from grid per time slot.
LS - Load Shifting PV - Photovoltaic panels BAT - Battery.

panels and batteries. Despite batteries being able to reduce grid reliance of an additional 1190 kWh/a, the higher investment costs are not justified if looking at the payback period, which reaches its highest value of 17.6 years. It must be noted that the decrease in the amount of energy bought from the grid during peak and full hours is significantly improved with respect to the load shifting case, suggesting that higher price oscillations during the day might make batteries a cost competitive solution.

Finally, a combination of all available technologies is considered. As expected, grid reliance is minimized. Yet, the reduction with respect to the PV-only case is of 2676 kWh, which is lower than the sum of the single reductions obtained through load shifting (1190 kWh) and batteries (2300 kWh). The payback period is 16.2 years.

4 Conclusions

A framework for the assessment of load shifting potential has been introduced and the fundamentals approaches adopted have been listed. The developed framework has been applied to a case study and a fully electrified Belgian household has been investigated in multiple configurations combining PV panels, batteries and load shifting practices. Results show that the best economic performances can be obtained through load shifting. Low investment costs are fully justified by the redistribution of consumption throughout the day to exploit lower energy prices, and also when PV panels are installed, as self-consumption increases. Batteries are found to be the most effective solution in increasing the consumption from PV panels, yet high investment costs lead to the poorest economic performances. When all technologies are considered together, self-consumption reaches 45.7%, with an increase of 20.7% percentage points with respect to the case where only PV panels are installed.

Acknowledgements Région wallonne project Autoconsommation: estimation & potentiel

References

[1] Ruben Baetens and Dirk Saelens. Modelling uncertainty in district energy simulations by stochastic residential occupant behaviour. *Journal of Building Performance Simulation*, 9(4):431–447, jul 2015. ISSN 19401507. doi: 10.1080/19401493.2015.1070203. URL https://www.tandfonline.com/doi/abs/10.1080/19401493.2015.1070203.

[2] Stephen Comello and Stefan Reichelstein. Cost competitiveness of residential solar PV: The impact of net metering restrictions. *Renewable and Sustainable Energy Reviews*, 75:46–57, aug 2017. ISSN 1364-0321. doi: 10.1016/J.RSER.2016.10.050.

[3] P. Jayathissa, M. Luzzatto, J. Schmidli, J. Hofer, Z. Nagy, and A. Schlueter. Optimising building net energy demand with dynamic BIPV shading. *Applied Energy*, 202:726–735, sep 2017. ISSN 0306-2619. doi: 10.1016/J.APENERGY.2017.05.083.

[4] Andrea Mangipinto, Francesco Lombardi, Francesco Davide Sanvito, Matija Pavičević, Sylvain Quoilin, and Emanuela Colombo. Impact of mass-scale deployment of electric vehicles and benefits of smart charging across all European countries. *Applied Energy*, 312:118676, apr 2022. ISSN 0306-2619. doi: 10.1016/J.APENERGY.2022.118676.

[5] Lukas Mauler, Fabian Duffner, Wolfgang G. Zeier, and Jens Leker. Battery cost forecasting: a review of methods and results with an outlook to 2050. *Energy Environmental Science*, 14(9):4712–4739, sep 2021. ISSN 1754-5706. doi: 10.1039/D1EE01530C. URL https://pubs.rsc.org/en/content/articlehtml/2021/ee/d1ee01530chttps://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee01530c.

[6] Eric O'Shaughnessy, Dylan Cutler, Kristen Ardani, and Robert Margolis. Solar plus: A review of the end-user economics of solar PV integration with storage and load control in residential buildings. *Applied Energy*, 228:2165–2175, oct 2018. ISSN 0306-2619. doi: 10.1016/J.APENERGY.2018.07.048.

[7] Sylvain Quoilin, Konstantinos Kavvadias, Arnaud Mercier, Irene Pappone, and Andreas Zucker. Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. *Applied Energy*, 182:58–67, nov 2016. ISSN 0306-2619. doi: 10.1016/J.APENERGY.2016.08.077.