Behind the meter developments in households

Marijn Rijken, Julia Jansen, Juan Giraldo Chavarriaga, TNO

June 2026 –TNO-2026-17087

TNO innovation for life

Summary

Background
Adoption of net-intensive assets at households in the Netherlands is growing: solar-pv, heat pumps, EV charging and home batteries. The operation of these assets is to a certain extend flexible and household can use this flexibility to optimise for different objectives: lower energy bill, increase self-sufficiency, or decrease their peak load on the grid. This has an impact on grid planning and system balance.

Problem statement
Grid operators and policy makers have limited insights on these so-called "behind the meter developments" and the effects on the electricity grid.

Research question
What is the effect of the behind the meter developments and different optimisation objectives on the hourly profile of the grid connection of households?

Main finding
In this study we have investigated the effect of currently existing financial incentives (energy pricing and self-consumption) and different optimisation objectives on the grid profile and energy bill of a typical Dutch household. We demonstrate that the optimisation objective embedded in a household energy management system (HEMS) is a key determinant of household energy behaviour and resulting grid interaction. Different optimisation objectives lead to different outcomes for: household costs; self-consumption; peak demand; and grid impact.

Implication
While households naturally optimise for private objectives such as energy cost or self-consumption, these objectives do not necessarily coincide with public system objectives such as congestion mitigation.

Current financial incentives primarily reward energy cost optimisation. Consequently, large-scale adoption of HEMS is likely to increase simultaneity of flexible demand and therefore local grid peaks.

Policy implication
Consequently, future tariff design and flexibility policies should not only stimulate flexibility, but explicitly steer the optimisation objectives that household energy management systems pursue."

Research implication
The optimisation model provides a quantitative framework to evaluate future tariff designs before implementation.

Table of Content

Introduction

Introduction

Background

Adoption of net-intensive assets at households in the Netherlands is growing: solar-pv, heat pumps, EV charging and home batteries. The operation of these assets is to a certain extend flexible and household can use this flexibility to optimise for different objectives: lower energy bill, increase self-sufficiency, or decrease their peak load on the grid. This has an impact on grid planning and system balance.

Problem statement

Grid operators and policy makers have limited insights on these so-called "behind the meter developments" and the effects on the electricity grid.

Research question

What is the effect of the behind the meter developments and different optimisation objectives on the hourly profile of the grid connection of households?

This study can be positioned as the next analytical step in TNO's existing knowledge line on household flexibility. Earlier work in, among others, the GO-e project identified flexibility resources and consumer drivers (Kort et al., 2024), interoperability challenges (Sambeek et al., 2024) and potential undesired system effects of large-scale HEMS deployment (DNV, 2024). What remained largely unexplored is how different optimisation objectives within HEMS translate into different household behaviour and system outcomes. This study addresses precisely that question through quantitative simulation. Herewith, this study operationalises one of the central recommendations from the GO-e DNV guideline, namely, to quantitatively assess how optimisation algorithms and their objective functions may create undesired system effects.

Methodology

Firstly, we have studied the developments behind the meter and the adoption of the flexible assets at households in the recent years, based on a literature review. Next, we did a market scan and held several interviews with market players like energy suppliers and aggregators to obtain a better understanding of: the *values* of the household consumers (e.g. egoistic**)**, the different *incentives* that households and flex assets could respond to (e.g. pricing), and the type of organisations offering flex services to household, e.g. to operate the assets. While households can in principle manage their assets themselves, typically these are managed by a service provider that automatically responds to *incentives*. This has resulted in a scheme of *values* mapped to optimization goals and *incentives* that assets will then respond to (if automated). Finally, the effect of automated management of assets in households that optimize for different goals has been simulated with an optimisation model with different optimisation objectives. This was done for a single house type with a home energy management system for different combination of assets.

Reading guide

The first section describes the behind the meter developments. In the second section service models and incentives are described. In the third section we give the simulation results. In the final section we reflect on the single household results by reasoning the expected effects on system level and linking them to policy developments, such as the introduction of a new grid tariff.

Developments behind the meter

Developments behind the meter – 1 of 2

Adoption trends of flexible assets

This paragraph sets out trends in adoption of flexible household assets in The Netherlands.

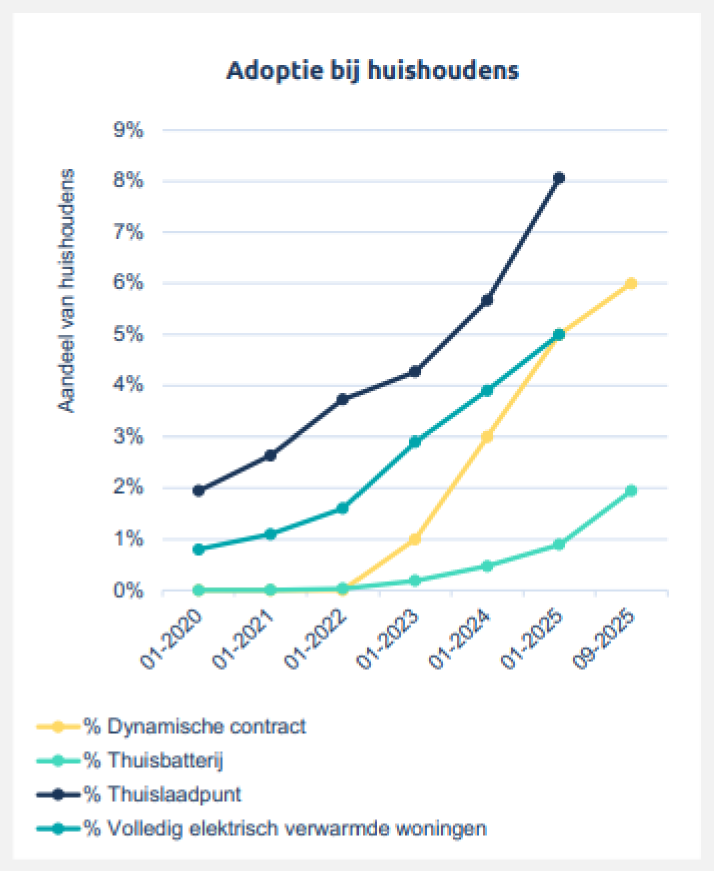
Household **adoption of solar PV** is high with over 35% of households having PV panels. 50% of owner-occupied houses has PV installed and over 20% of social rental housing (DNE, 2025a). Self-consumption is estimated at 25% for households with average electricity use, 60-70% for those with a home battery (Quax, 2025). Since 2024, adoption rate has slightly declined.

The household **adoption of heat pumps** is increasing. Most heat pumps are not automatically controlled yet. In 2025, 129.000 heat pumps were put in use (DNE, 2026), bringing the total to 823.000 (excl. ACs), including 189.000 hybrids (ibid.). Since 2022, air conditioners have been used for space heating by majority (85%) of households with an AC, with steady adoption (ibid.). Most heat pumps are not yet automated for incentive-based control. However, many are 'connected' (able to send and receive data over the internet), allowing for control (estimated at 17% in 2021) or connectable (estimated at 77% in 2021) (FAN, 2023). The main barrier to automation is interoperability.

In December 2025 there were 680.605 private (battery) **electric vehicles adopted** in the Netherlands and about 395.000 **home charge points** (Elaad, 2026). Grid friendly charging and bi-directional charging can potentially reduce the peak demand of charging by 44% and thereby increase the flexible capacity of households with charge points significantly (Refa et al, 2023; Van Sambeek et al., 2024).

The **adoption of home battery systems** also increases flexible capacity of households due to their high flexibility and controllability. In 2024, more than 75.000 home batteries were installed. They are used for increasing self-consumption or controlled by energy suppliers or aggregators to use their flexibility on various energy markets. The number of installed home battery systems is increasing exponentially since 2020 (RVO, 2025; DNE, 2025b) and the ending of the net metering for solar PV is expected to increase the interest of households with solar PV in home battery systems.

Home energy management systems (HEMS) are not yet broadly adopted. There are several suppliers of home EMS. However, home EMS are still in a phase of early adoption, mainly by enthusiasts (DNE, 2025b).



Adoption of assets in households.
Source image: Van Dijk & Treurniet, 2026. pg. 21

Developments behind the meter – 2 of 2

Development of price incentives for households

7% of households in the Netherlands have an energy contract with dynamic prices. Respectively 39% and 54% of households in the Netherlands have a variable or fixed price contract. The percentage of households with a dynamic contract is increasing (maandelijkse Energiemonitor ACM, 2026). Especially for households with flexible assets, dynamic price contracts are of interest. 41% of people with a home charge point have a dynamic contract (Wolterman et al., 2025)

Based on an expert interview with a dynamic supplier and a recent publication of Van Dijk & Treurniet (2026), we observe that over time energy suppliers are planning to offer contracts with elements of both fixed and dynamic contracts, providing price incentives in combination with insurances for high energy prices (interview; Van Dijk & Treurniet, 2026).

In the future, grid tariffs will change. The grid operators, ACM and Ministry of Economic Affairs and Climate are exploring a time of use grid tariff with five time-blocks and four kWh tariffs, to be implemented in 2029. This will provide an additional incentive next to energy prices.

Development of flexibility services for households

Adoption of automated home assets and the offering of flexibility services are important for increasing flexibility of households. Think of smart charging, smart thermostats, and curtailment of PV. These services can relieve households and increase economic benefits while maintaining comfort. Economic benefits of flexibility should be high enough for market parties to develop these services (Van Cappellen et al., 2026). Providing transparency about the economic benefits is a point of attention (ibid.), as well as safeguarding privacy.

Standardisation in communication protocols

Energy management systems (EMS) help households by automating the response to signals and incentives. A barrier to adoption of EMS is a lack of interoperability. Interoperability between assets and EMS, and between the EMS external parties is important for automation and integration. In 2025, the development of technical agreements for smart home assets has started, for heat pumps, solar converters, home batteries and home energy management systems (LAN, 2026), which aims to increase the interoperability.

Social & ethical considerations

Several social barriers and ethical considerations exist about flexibility of household energy consumption.

- A large proportion of people is willing to change their energy consumption patterns (Kort et al., 2024), but people need **action perspective** to realise the potential. For example, being able to adopt electric assets and energy management.
- Financial **incentives** are an important motivation, but the absolute height of the incentive is not (Kort et al., 2024; Van Cappelen et al., 2026)
- Experienced friction (**hassle**) is a behavioural barrier.
- People need to **trust** assets and flexibility services to adopt these. Transparency about data use and safeguarding privacy are necessary.
- The adoption of automatable and automated assets in households is low and unevenly distributed among different income groups.
- Household routines and capabilities differ. Rigid routines, digital literacy and energy literacy can translate into barriers for households to benefit from demand side flexibility (Dudka et al., 2026).

Service models and flex incentives

Consumer values and services – 1 of 3

Values of consumers have an effect on the adoption of assets. Also, they influence how households responds to (implicit) flex **incentives**. Implicit flexibility, contrary to explicit flexibility, is not traded on markets but results from responses to incentives (signals or information) such as energy prices or grid contracts. A response can be manually e.g. by changing behaviour, or it can be automated, e.g. with a HEMS.

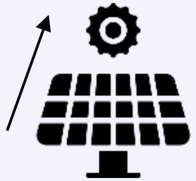
Below is an overview of the types of **values,** optimisation goals and the **incentives** that can influence the management of household assets.

The values are derived from Langley et al. (2020) and play a role in sustainable behaviour. The selection of value types is based on previous research (Kort, et al., 2024), which indicated that the following values motivate people to change their electricity consumption (or ‘deliver’ flexibility):

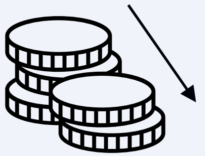
- Egoistic value: financial motivations
- Biospheric value: reward in sustainability, e.g. less fossil fuels used.
- Altruistic value: doing something for the community; contributing to the grid or preventing the street/neighbourhood from lack of electricity.

We found that most people (about 80%) are willing to change assets operation based on cost incentives (egoistic value) and prefer to use or store PV production for self-consumption (Kort et al., 2024). The altruistic and biospheric values are drivers for a smaller proportion of the households. A fourth type of values, hedonistic, translates to comfort and mainly forms the preconditions for when and how much flexibility households are willing to offer.

values
goals

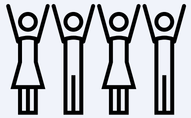


egoistic, biospheric
optimisation for self-consumption



egoistic
optimisation for cost

biospheric
optimisation for sustainability



altruistic
contribution to grid

incentives

Use energy at times of own PV-production

Within fixed contract, assets will respond to:
- ToU grid tariffs*
- Saving energy settings

Within dynamic contract, assets will respond to:
- Energy prices (day-ahead)
- ToU grid tariffs*
- Saving energy settings

- Energy saving settings
- Information on moments with high share of renewables in the energy mix

- Saving energy settings
- ToU grid tariffs*
- Peak shaving*.
- Time. To avoid use of energy between 16.00 – 21.00

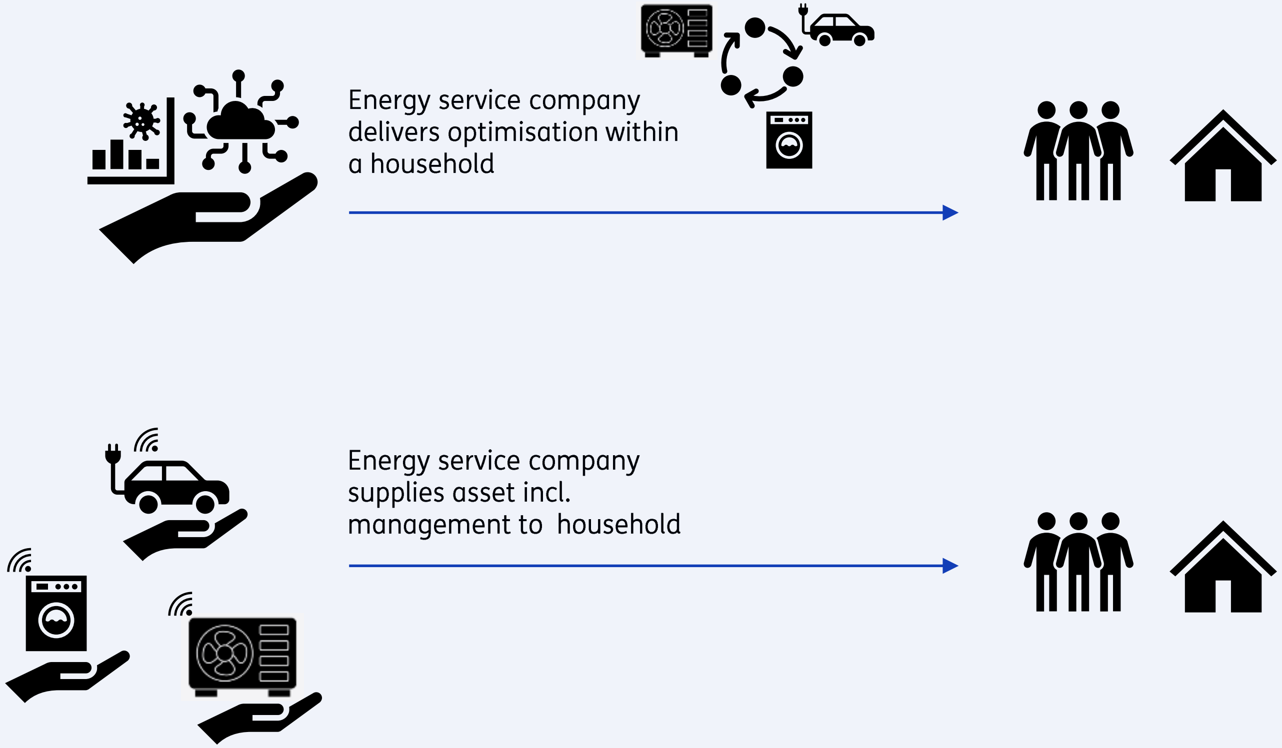
* These incentives do not exist (yet) for households

Consumer values and services – 2 of 3

Depending on the service suppliers that supply services to a household, assets within the household will be managed differently. Examples of service suppliers are energy suppliers, aggregators, that use the flexibility of the household to balance their own portfolio or offer flexibility on the market. Other service supplier operate the assets only for optimisation behind the meter. See right upper picture.

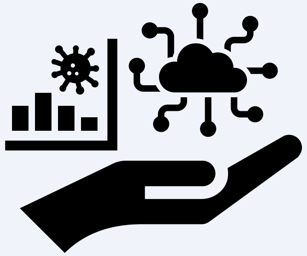
Others deliver one asset and the optimisation of that specific asset. See right under picture. Energy suppliers have also started to include the sales of assets like solar PV and home batteries and provide management of these assets as a service, and at the same time minimise the imbalance costs of their portfolio.

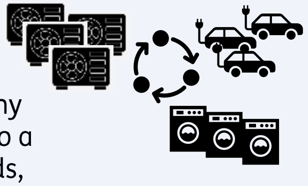
For the second part of the study, we assume that the assets are managed with a home energy management system to optimise for a specific objective, but that the flexibility is not traded on markets. So, we look only at implicit flexibility.



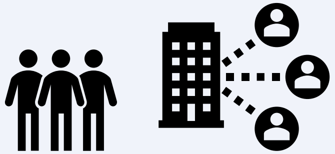
Consumer values and services – 3 of 3

If a household is part of an energy community, such as a cooperative with a collective production facility and/or a connection for large volumes, an individual household might also respond to implicit flexibility incentives that sprout from the collective goals and agreements within the collective. For example, to optimise for collective self-consumption, for a collective kW-max grid agreement or collective self-balancing purposes that stem from the collective energy contract. The community can also help to optimise for individual goals such as cost optimisation. In the second part of this study, households in energy communities are out of scope.



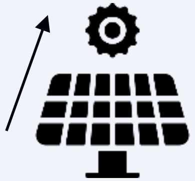


Energy service company delivers optimisation to a collective of households, operating some or all assets of households

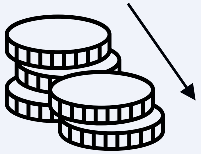


Household in energy community

values
goals

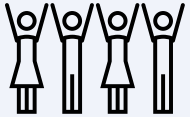


optimisation for self-consumption



optimisation for cost

optimisation for sustainability



contribution to grid

incentives

Optimisation for self-consumption:

Use energy at times of collective production

Optimisation for cost:

Within fixed contract, assets will respond to:
- Collective kW-max contract
- Collective self-balancing
- ToU grid tariffs*

With dynamic contract, assets will respond to:
- Collective kW-max contract
- Collective self-balancing
- Energy prices (day-ahead)
- ToU grid tariffs

Optimisation for sustainability:

- Saving energy settings
- Information about share of renewables in the energy mix

Contribution to grid:

Saving energy
- Coll. kW-max contract / peak shaving.
- Coll. self-consumption information
- ToU grid tariffs*
- Avoid use of energy between 16.00 – 21.00

Effects on the grid connection and energy bill

Methodology

The effect of on the household grid profile and energy bill has been simulated with an optimisation model. The model optimises the flexible behaviour of different assets in a single house (like a HEMS does). Optimisation of a collective of houses has not been done given limited scope of the study. Three optimisation objectives have been applied and compared. Implicit flexibility incentives were energy prices and own production. Note that in the previous section more incentives have been identified, however not all could be modelled in the scope of this study. Here we give more information on the model, the assets and the optimisation objectives used.

- Linear programming optimization model, using the Artifical load profile generator (Hoogsteen, 2016) as profile generation engine and an additional Home Energy Management System
- Flexible and controllable assets: EV charging, hybrid heat pump (heating/cooling), battery storage
- Uncontrollable assets: fixed load (e.g., cooking, washing, lighting) and PV generation
- Thermal house model for heat buffering. A typical Dutch terraced house (Terraced house) with energy label C was assumed. A typical household composition and energy usage profile was assumed.
- Electricity contracts: fixed or dynamic prices. Net metering (salderingsregeling) has not been applied (situation from 2027).
- Grid contract: fixed price

Three optimisation objectives were applied and compared. The first two (energy cost and self-consumption) align with the dominant value orientations identified earlier in the GO-e project, the third one (grid-friendly) has been chosen to show the potential of household flexibility in mitigating grid congestion and thereby inform current policy making.

- **Energy cost**: minimizes the total energy bill (electricity + gas) over the optimization horizon by shifting flexible demand to low-price periods by using local generation or storage to avoid expensive energy import from the grid. The controller prefers charging, running assets, or preheating when prices are low and reduces grid consumption when prices are high.
- **Self-consumption**: maximizes the share of on-site renewable generation (typically PV) that is used directly within the home instead of being exported to the grid. It encourages matching local demand to local production, e.g., by running flexible loads or charging a battery during sunny hours, thereby increasing energy autonomy and reducing reliance on an external electricity supply.
- **Grid-friendly (Peak)** : minimizes the peak, i.e. the highest power import and export over the day by flattening the load profile and avoiding short high-power spikes. This leads to smoother grid interaction, reduce network stress, and improve system friendliness by spreading flexible consumption more evenly across time. Currently, no financial incentives exist for households to be grid-friendly. Future grid tariffs like a time-of-use tariff will change this.

Model and assumptions - Types of houses

House identifier	1	H3	H4
Building archetype	**Terraced house - A (reference)**	**Terraced house – B**	**Terraced house – C**
Assets			
Solar PV	X	X	X
Home battery		X	X
Heat pump (hybrid)		X	X
Home charging point			X
hEMS		X	X
Gas boiler	X		
Type of energy contract	Fixed	Dynamic	Dynamic

Fixed energy tariff:
€0.30/kWh (constant, all hours)
Decomposed components:
Implied Spot: €0.120/kWh (ex-VAT)
Supplier Markup: €0.020/kWh (ex-VAT)
Energy Tax: €0.12286/kWh (incl-VAT)
VAT Rate: 21%
Network Fee: €455.74/year
Monthly Fee: €6.00/month
Annual Tax Credit: €635.19

Gas price:
Fixed flat rate of €0.14/kWh ~ 1.27 €/m3.

Dynamic energy tariff:
Decomposed components:
Spot price: from day-ahead market
Supplier Markup: €0.020/kWh (ex-VAT)
Energy Tax: €0.12286/kWh (incl-VAT)
VAT Rate: 21%
Network Fee: €455.74/year
Monthly Fee: €6.00/month
Annual Tax Credit: €635.19

Assets assumption:
PV: 18m2, ~3 kWp, 17% efficiency
Battery: 5 kWh / 3.7 kW
EV: 50 kWh / 11 kW
Hybrid heat pump: 4 kW (elec) / 10 kW (gas), COP variable with temperature

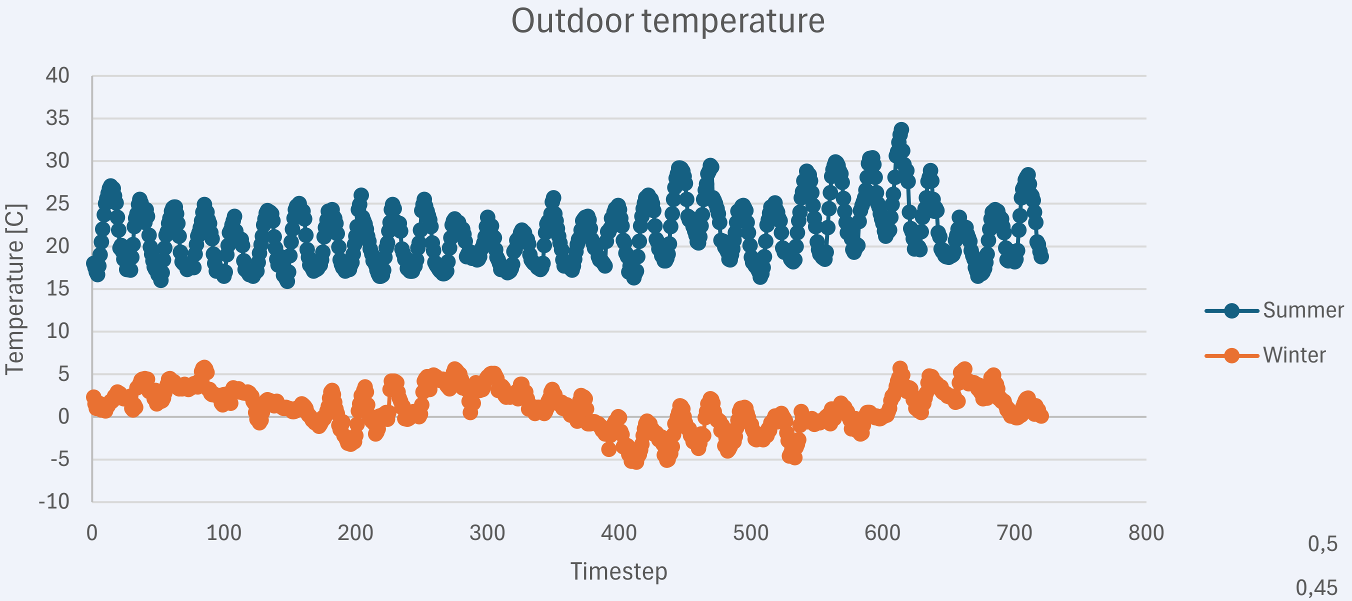
Export compensation:
Fixed at 50% of *kale leveringstarief.*
Kale Leveringstarief Components:
Spot price + supplier markup + VAT
No Hourly Variation.
Spot Price Assumption: €0.10/kWh
Supplier Markup: €0.02/kWh ex-VAT
VAT Rate: 21%
Effective Compensation Range: ~€0.04-0.06/kWh

EV assumptions:
Charging sessions are composed of arrival time, departure time, and the required energy to be full.
It is assumed an efficiency of ~5.5 km/kWh and a 16.6% correction during winter

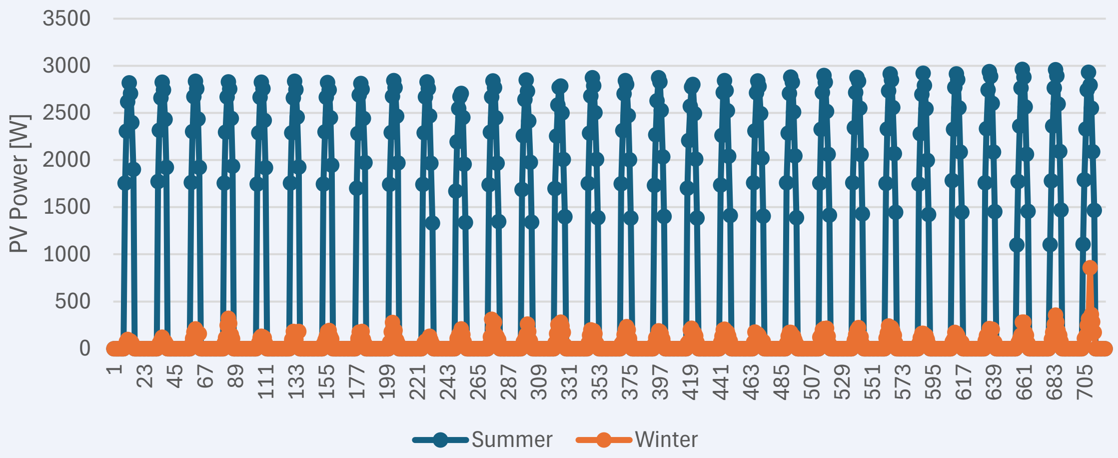
Temperature set-points:
Comfort bounds assumed at 19 °C and 22 °C at all times (summer, winter)

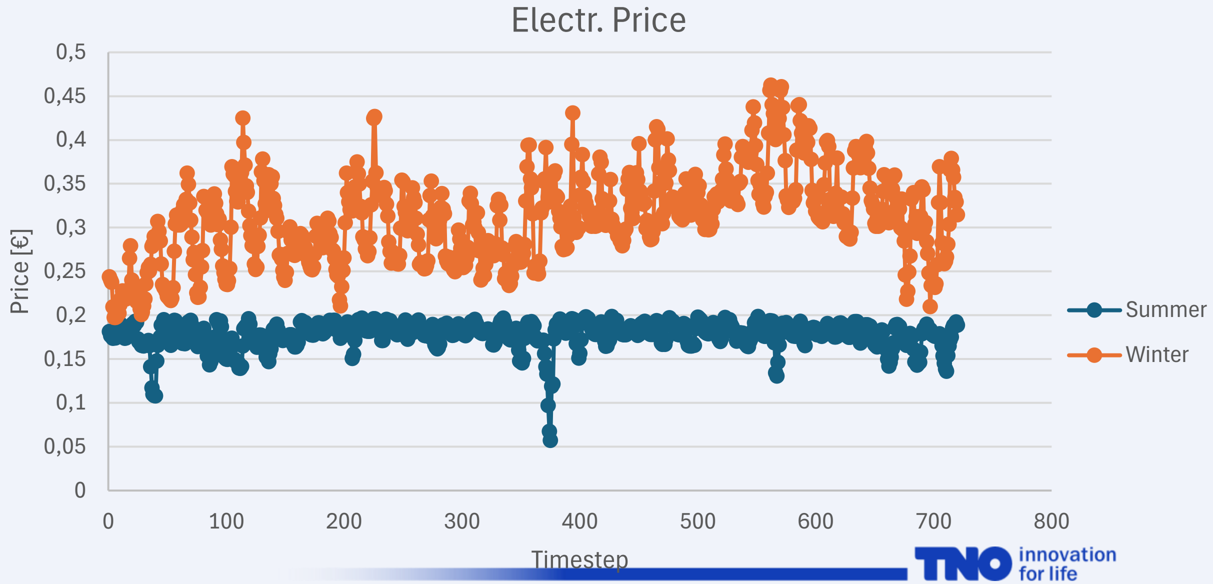
Heating is disabled when ambient temperature is higher than 20 °C

Model and assumptions -- Weather



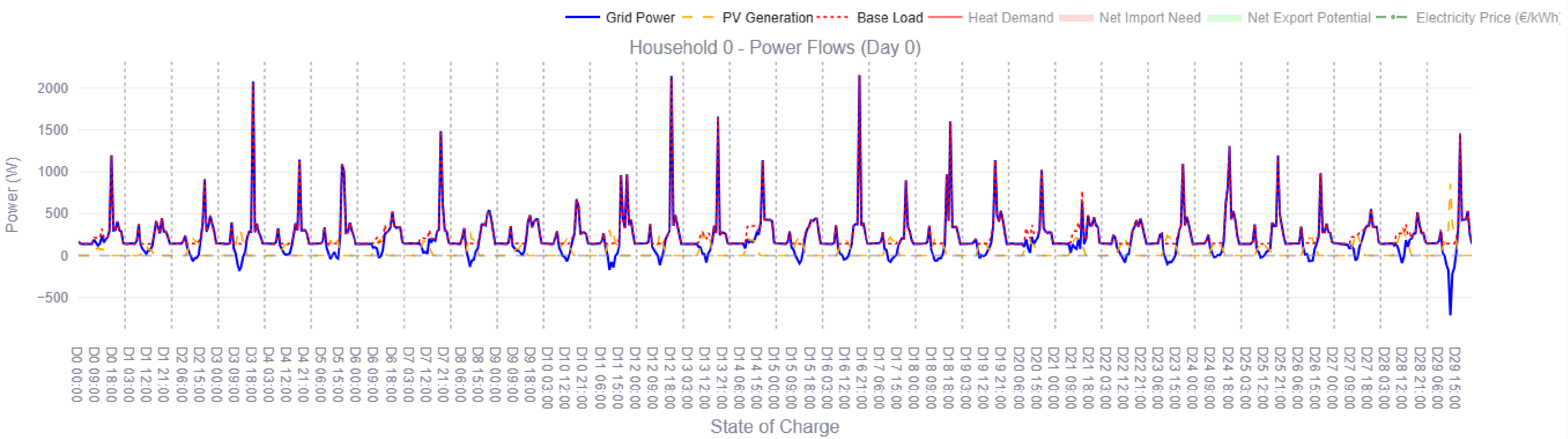
- For weather data and day-ahead prices we have taken percentile 95 per timestep over the last 10 years for the periods of **Jan-Feb (winter)** and **Jul-Aug (summer)** for temperature, price, and solar irradiation
- 30 days window – 1 hour resolution
- Sources: KNMI, Day-ahead prices





Results Winter -- Terraced house - A

House identifier	1
Buidling archetype	Rijtjeshuis - A (reference)
Energy label	C
Assets	
ZonPV	x
Thuisbatterij	
Warmtepomp (hybrid)	
Laadpaal (prive)	
hEMS	
gas CV ketel / warmtenet	x
Salderingsregeling	nee
Type of energy contract	Fixed



- No controllable devices
- Most PV generation can be consumed locally, but it’s not much since solar irradiance is low
- Peak power from import and export is not controlled

Total Cost
€409.60

Grid Import
154.47 kWh

Grid Export
4.81 kWh

Net Grid
149.67 kWh

Electricity Cost
€45.62

Gas Cost
€363.98

PV Generation
31.81 kWh

Self-Consumption
84.9%

Self-Sufficiency
14.9%

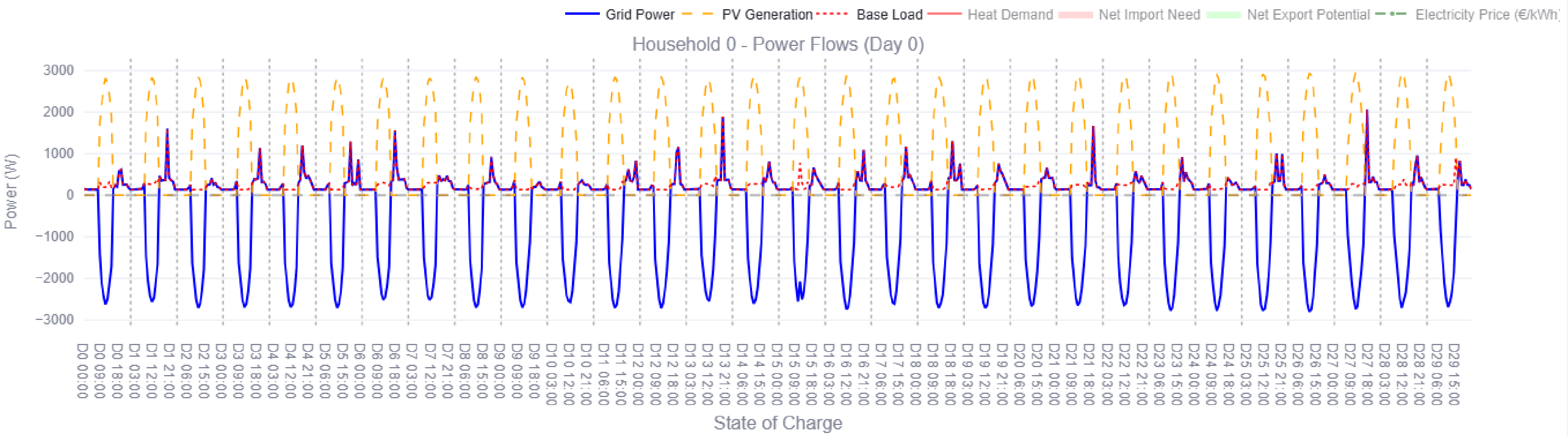
Peak Import
2.15 kW

Peak Export
0.71 kW

PV Installed
3.06 kWp

Results Summer -- Terraced house - A

House identifier	1
Buidling archetype	Rijtjeshuis - A (reference)
Energy label	C
Assets	
ZonPV	x
Thuisbatterij	
Warmtepomp (hybrid)	
Laadpaal (prive)	
hEMS	
gas CV ketel / warmtenet	x
Salderingsregeling	nee
Type of energy contract	Fixed

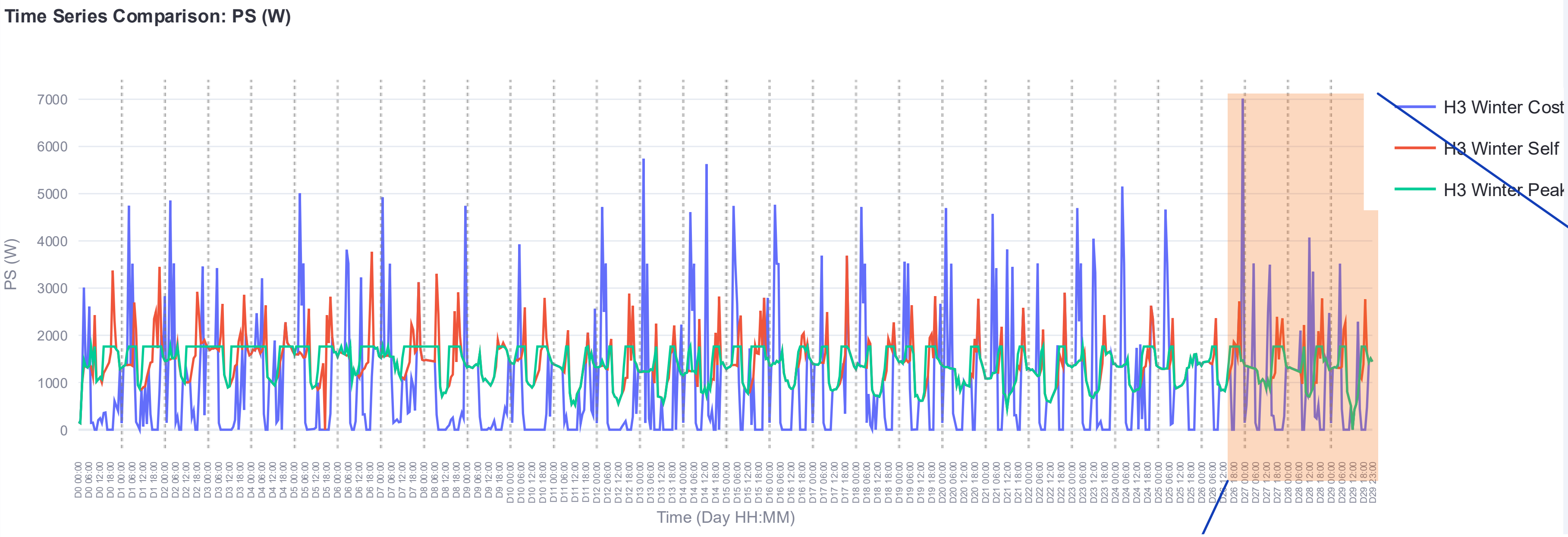


Total Cost €-32.82	Grid Import 136.05 kWh	Grid Export 490.90 kWh	Net Grid -354.85 kWh
Electricity Cost €-32.82	Gas Cost €0.00		
PV Generation 538.79 kWh	Self-Consumption 8.9%	Self-Sufficiency 26.0%	Peak Import 2.06 kW
Peak Export 2.80 kW	PV Installed 3.06 kWp		

- No controllable devices
- Most PV generation is injected back to the grid (~91%) since load and local generation are not synchronized
- Peak power from import and export is not controlled

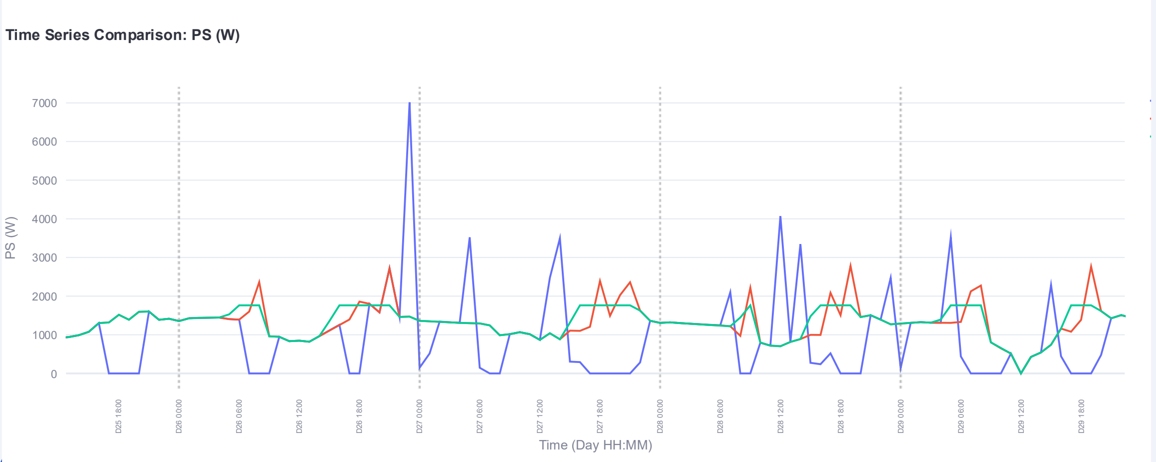
Results Winter -- Terraced house - B

Power at the smart meter (PS)



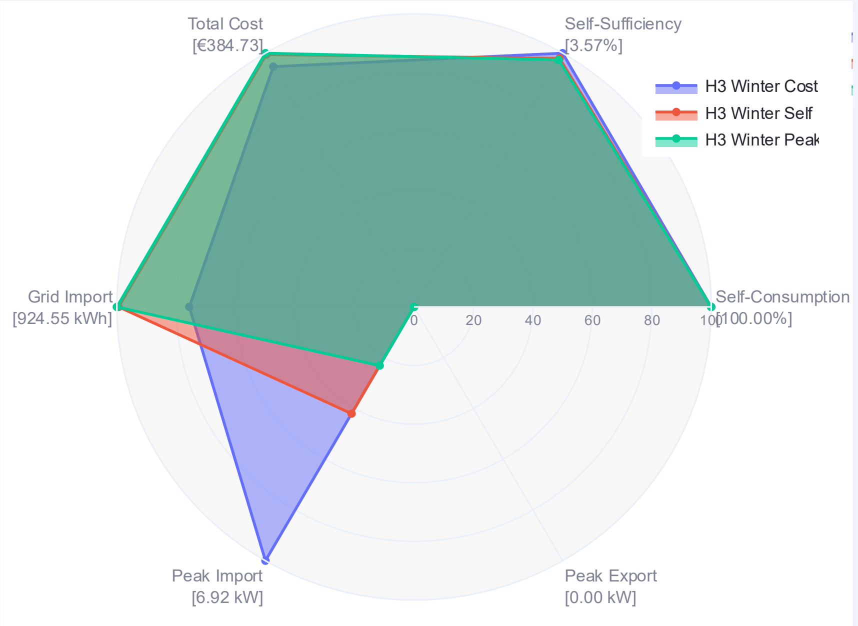
House identifier	3
Buidling archetype	Rijtjeshuis - B
Energy label	C
Assets	
ZonPV	x
Thuisbatterij	x
Warmtepomp (hybrid)	x
Laadpaal (prive)	
hEMS	x
gas CV ketel / warmtenet	
Salderingsregeling	nee
Type of energy contract	Dynamic

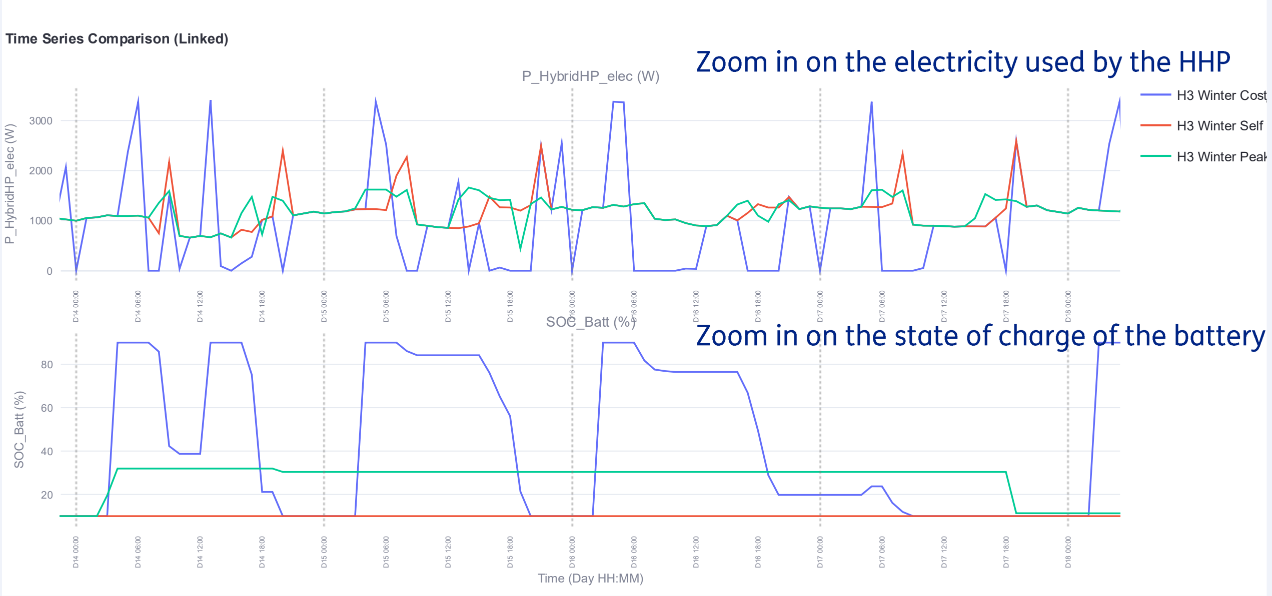
- The highest peaks of power imported from the grid occur when energy costs are minimised
- Maximising Self consumption and minimizing Peak power follow a similar path most of the time, with differences in some periods with high demand



Results Winter -- Terraced house - B

- The highest peak is reduced by ~75% when minimizing the Peak power compared to the Cost optimal solution (7 kW). However in Peak mode, the total cost increases ~6% compared to the optimal Cost (€364.4), as well as the grid imports due to a smoother use of the heat pump.
- This is related to differences in the electricity use profile of the hybrid heat pump for heating and the operation of the battery (abrupt changes vs more constant which uses more electricity). The abrupt changes are related to electricity price opportunities (low day-ahead prices) and highest peaks related to charging the battery.

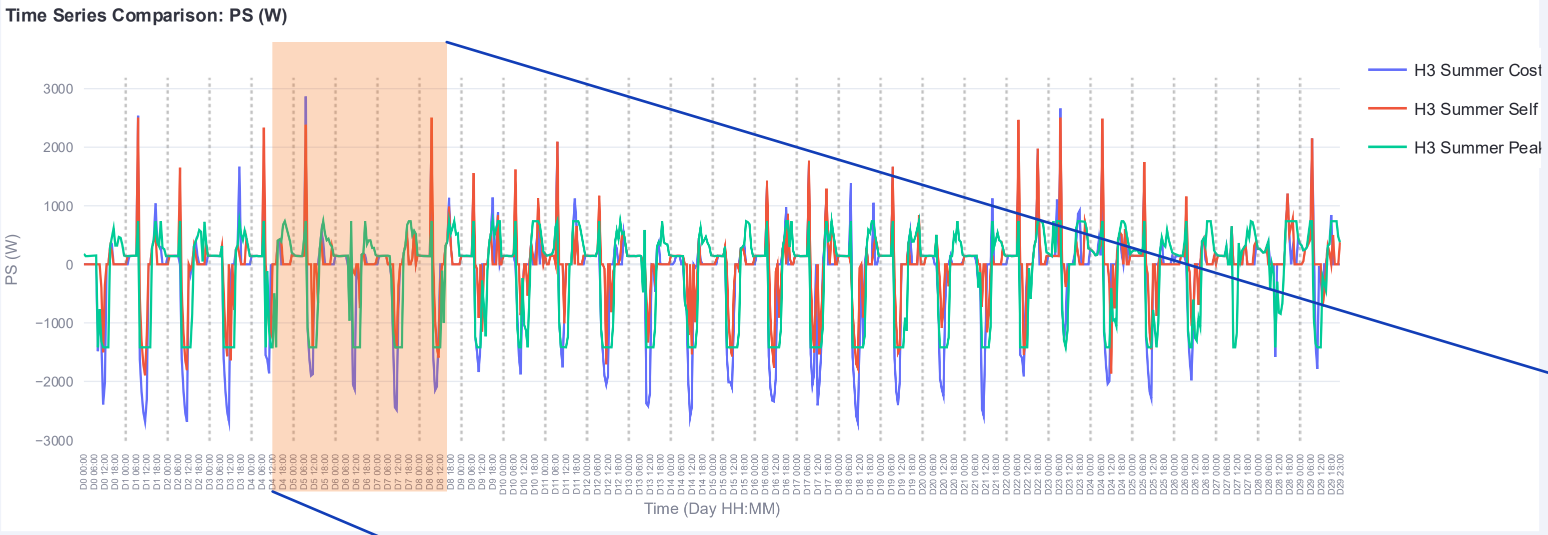




H3 Winter Cost	H3 Winter Self	H3 Winter Peak
Household 0 | Tussenwoning	Household 0 | Tussenwoning	Household 0 | Tussenwoning
PV Installed 3.06 kWp	**PV Installed** 3.06 kWp	**PV Installed** 3.06 kWp
Total Cost €364.35 (266.06€/98.29€)	**Total Cost** €382.56 (382.56€/0.00€)	**Total Cost** €384.73 (384.73€/0.00€)
Grid Import 699.16 kWh	**Grid Import** 918.98 kWh	**Grid Import** 924.55 kWh
Self-Consumption 100.00%	**Self-Consumption** 100.00%	**Self-Consumption** 100.00%
Self-Sufficiency 3.57%	**Self-Sufficiency** 3.50%	**Self-Sufficiency** 3.48%
Peak Import 6.92 kW	**Peak Import** 2.91 kW	**Peak Import** 1.60 kW
Peak Export 0.00 kW	**Peak Export** 0.00 kW	**Peak Export** 0.00 kW

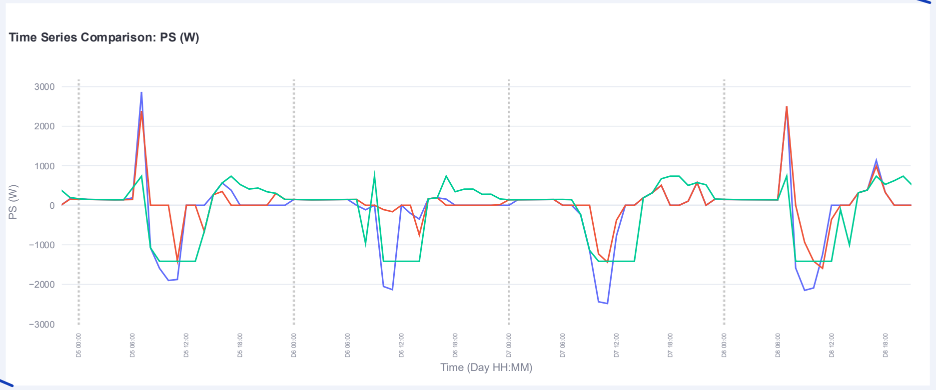
Results Summer -- Terraced house - B

Power at the smart meter (PS)



House identifier	3
Buidling archetype	Rijtjeshuis - B
Energy label	C
Assets	
ZonPV	x
Thuisbatterij	x
Warmtepomp (hybrid)	x
Laadpaal (prive)	
hEMS	x
gas CV ketel / warmtenet	
Salderingsregeling	nee
Type of energy contract	Dynamic

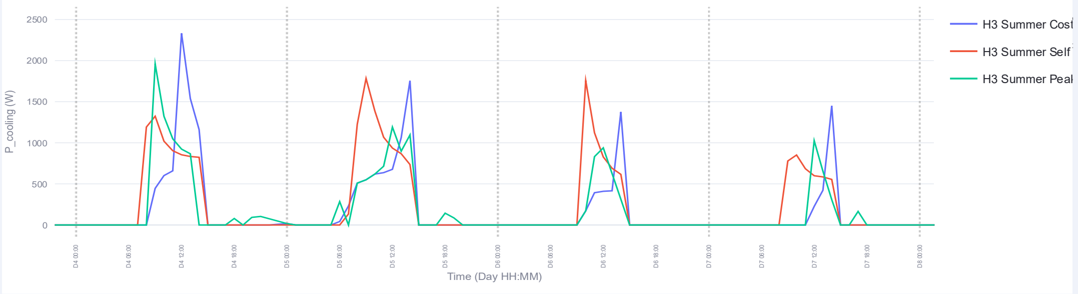
- The highest peaks of power **exported/imported** to/from the grid occur when optimizing for the energy cost objective.
- Exported energy is minimized when Self consumption is the driver since the HEMS tries to use the power from PV as much as possible, e.g., charging the battery or using it for cooling



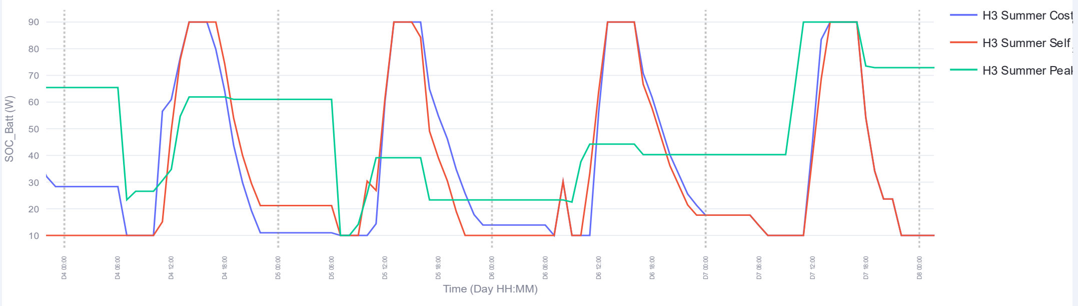
TNO innovation for life

Results Summer -- Terraced house - B

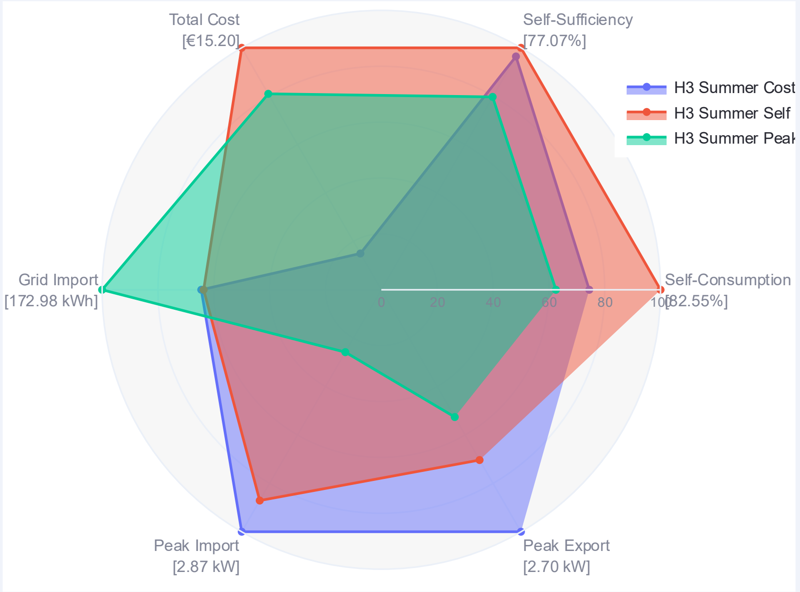
- Energy imports from the grid are bigger in the Peak reduction mode since it uses flexibility from the battery and the heat pump to reduce the peaks at critical hours (~80%) at the expense of reducing its self-consumption.
- The Self-consumption objective results in a higher cost for the household (~6x) compared to the optimal cost at the expense of using the energy from the PV to supply its demand. This cost difference is related to charging the battery during high PV production periods, reducing the energy injected back to the grid in the Self-consumption objective
- In the figure below, it can be seen that the **hybrid heat pump (HHP) for cooling is used for more time** by the Self-consumption driver during high PV hours, while the battery is used to a lower extent by the Peak reduction approach.



Zoom in of the electricity used by the HHP for cooling



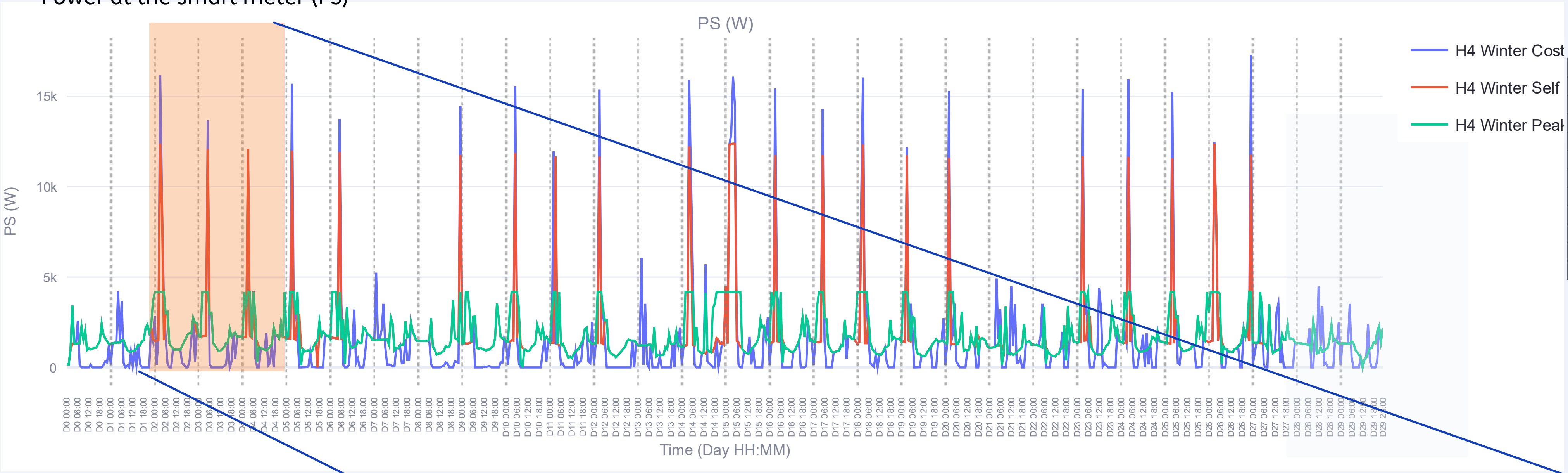
Zoom in on the state of charge of the battery



H3 Summer Cost	H3 Summer Self	H3 Summer Peak
Household 0 | Tussenwoning	Household 0 | Tussenwoning	Household 0 | Tussenwoning
PV Installed 3.06 kWp	**PV Installed** 3.06 kWp	**PV Installed** 3.06 kWp
Total Cost €2.28	**Total Cost** €15.20	**Total Cost** €12.31
Grid Import 111.56 kWh	**Grid Import** 110.09 kWh	**Grid Import** 172.98 kWh
Self-Consumption 61.48%	**Self-Consumption** 82.55%	**Self-Consumption** 51.62%
Self-Sufficiency 74.32%	**Self-Sufficiency** 77.07%	**Self-Sufficiency** 61.44%
Peak Import 2.87 kW	**Peak Import** 2.50 kW	**Peak Import** 0.74 kW
Peak Export 2.70 kW	**Peak Export** 1.90 kW	**Peak Export** 1.42 kW

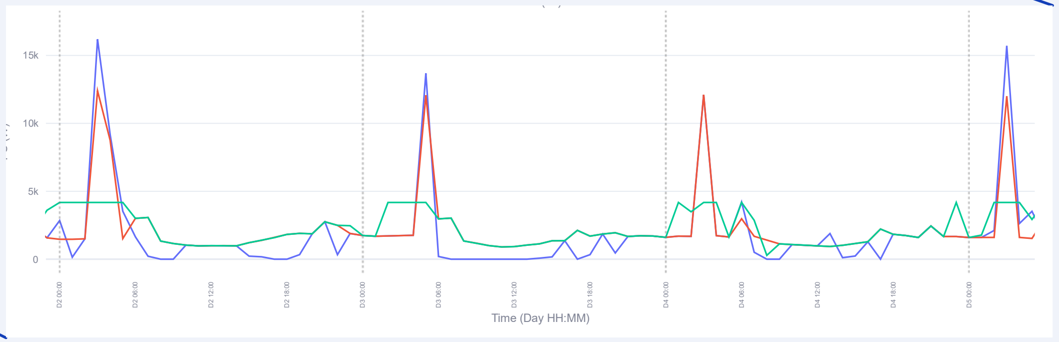
Results Winter -- Terraced house - C

Power at the smart meter (PS)



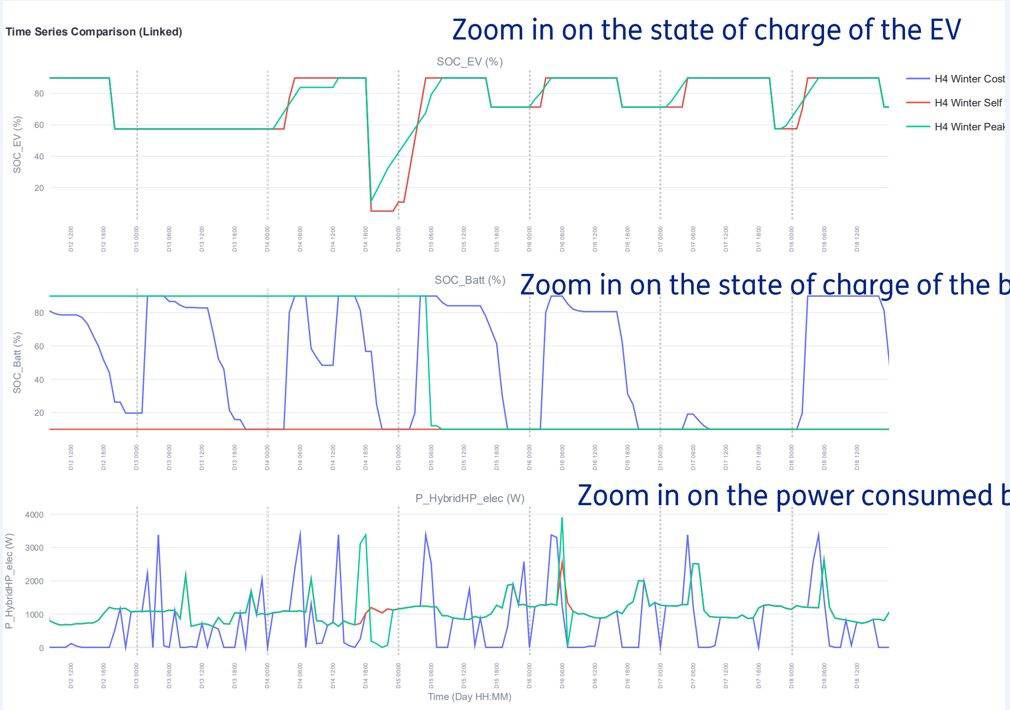
House identifier	4
Buidling archetype	Rijtjeshuis - C
Energy label	C
Assets	
ZonPV	x
Thuisbatterij	x
Warmtepomp (hybrid)	x
Laadpaal (prive)	x
hEMS	x
gas CV ketel / warmtenet	
Salderingsregeling	nee
Type of energy contract	Dynamic

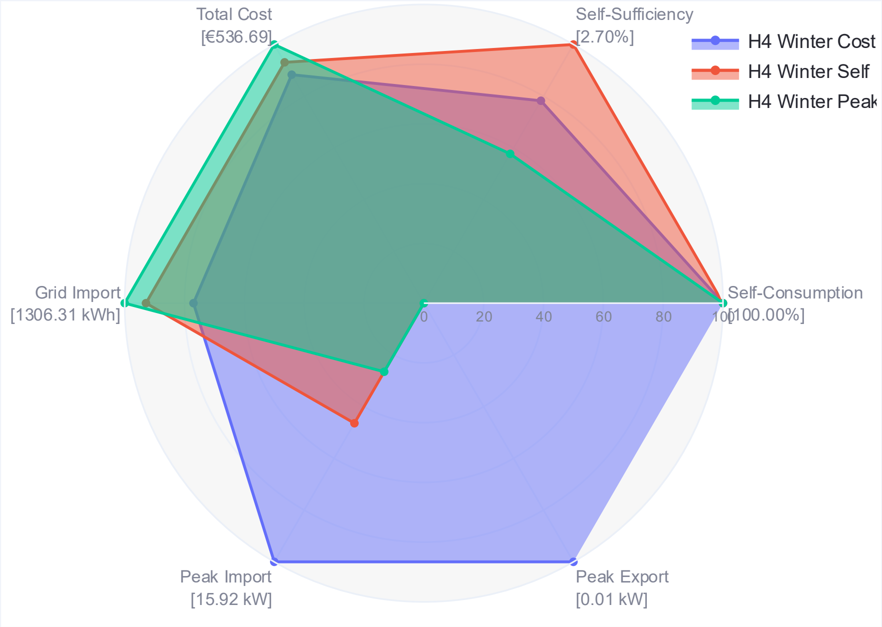
- Power peaks present a substantial **increase when the EV is added** to the household (~3x), when comparing the Cost driver objective results.
- The imported energy from the grid increases (~42%), and the total cost (~26%) increases compared to the case with only HHP.



Results Winter -- Terraced house - C

- Compared to the cost-optimal case, the peak-oriented strategy reduces peak import from 15.9 kW to 4.2 kW (~73%), while total cost increases only from €474.1 to €536.7 (13%); however, grid import rises from 1006kWh to 1306 kWh (~30%).
- In winter, all strategies achieve 100% self-consumption, so the key difference is peak management rather than PV utilisation.
- In the figure below, it can be seen that the hybrid heat pump for heating is used more statically by the Peak-reduction driver, and the energy required to charge the EV is spread over a longer period of time. Also, the battery is not actively used to reduce peaks or increase self-consumption during winter.

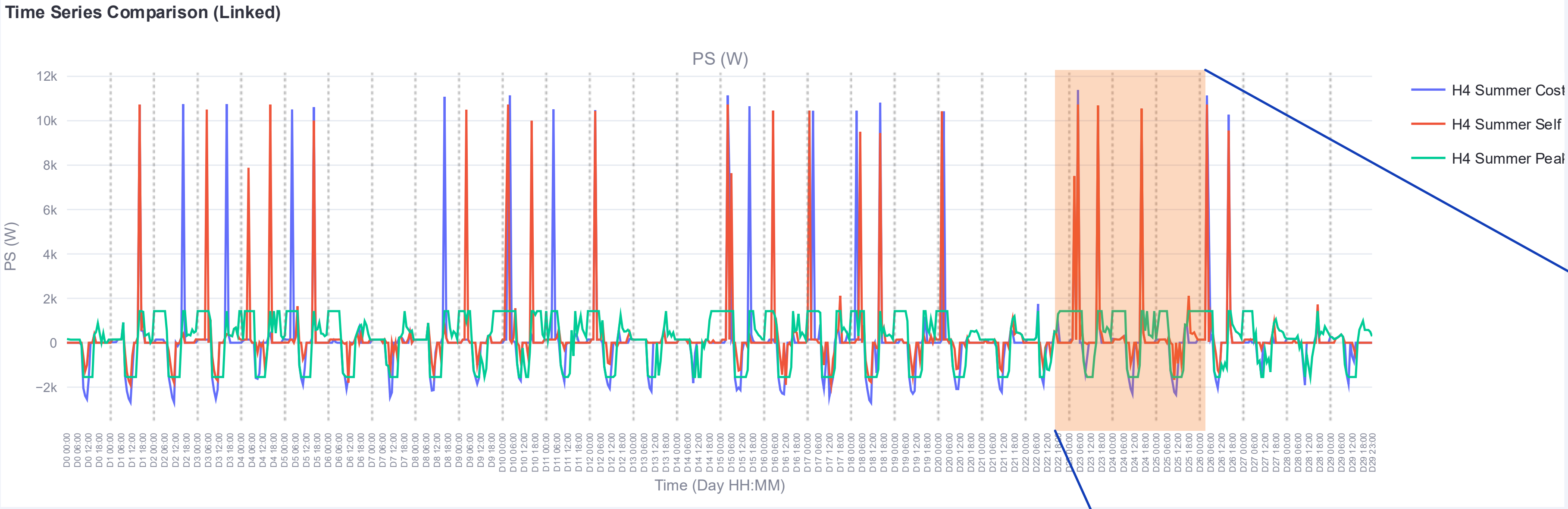




H4 Winter Cost	H4 Winter Self	H4 Winter Peak
Household 0 | Tussenwoning	Household 0 | Tussenwoning	Household 0 | Tussenwoning
PV Installed	**PV Installed**	**PV Installed**
3.06 kWp	3.06 kWp	3.06 kWp
Total Cost	**Total Cost**	**Total Cost**
€474.06 (376.27€/97.79€)	€499.69 (499.46€/0.24€)	€536.69 (536.53€/0.16€)
Grid Import	**Grid Import**	**Grid Import**
1005.98 kWh	1213.41 kWh	1306.31 kWh
Self-Consumption	**Self-Consumption**	**Self-Consumption**
99.98%	100.00%	100.00%
Self-Sufficiency	**Self-Sufficiency**	**Self-Sufficiency**
2.11%	2.70%	1.56%
Peak Import	**Peak Import**	**Peak Import**
15.92 kW	7.39 kW	4.22 kW
Peak Export	**Peak Export**	**Peak Export**
0.01 kW	0.00 kW	0.00 kW

Results Summer -- Terraced house - C

Power at the smart meter (PS)

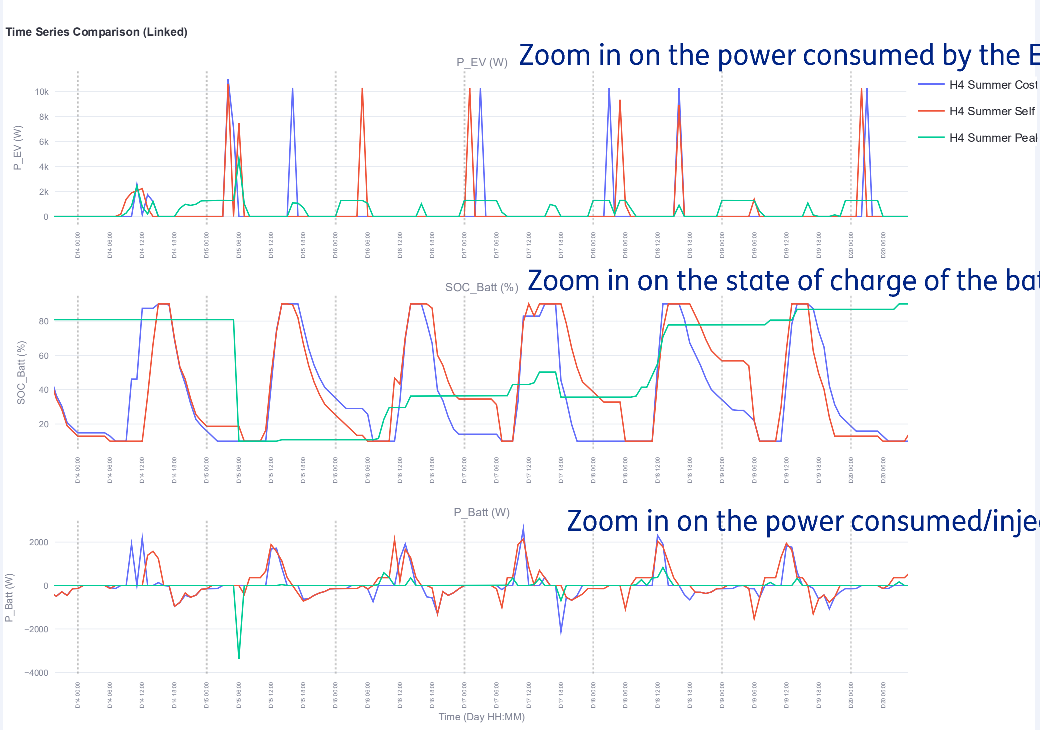


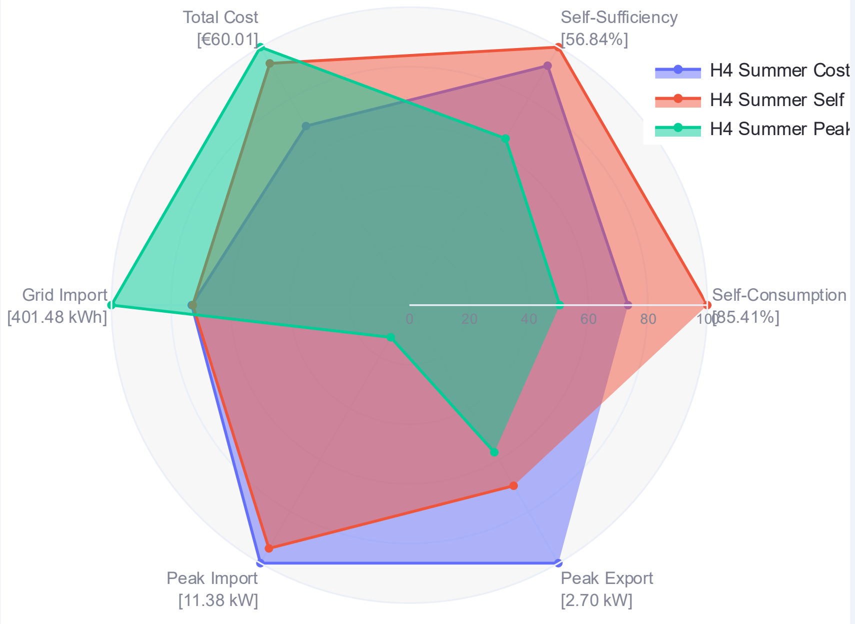
House identifier	4
Buidling archetype	Rijtjeshuis - C
Energy label	C
Assets	
ZonPV	x
Thuisbatterij	x
Warmtepomp (hybrid)	x
Laadpaal (prive)	x
hEMS	x
gas CV ketel / warmtenet	
Salderingsregeling	nee
Type of energy contract	Dynamic

- Power peaks present a substantial increase when the EV is added to the household (~3x), when comparing the Cost driver objective results in the case with only HHP.
- The imported energy from the grid increases (~2.6x), and the total cost (~17x) compared to the case with only HHP.

Results Summer -- Terraced house - C

- The cost-driven objective gives the lowest operating cost (€41.66), while the self-consumption-driven strategy increases PV self-consumption from 62.7% to 85.4% with a moderate cost increase to €56.23 (~35%).
- The peak-minimization strategy reduces peak grid import from 11.38 kW to 1.42 kW (about 88% lower), but at the expense of a higher total cost (~44%) and grid energy import (~37%).
- In the figure below, it can be seen that the power used by the battery to charge/discharge and the power to charge the EV are the main drivers to reduce peaks during summer.

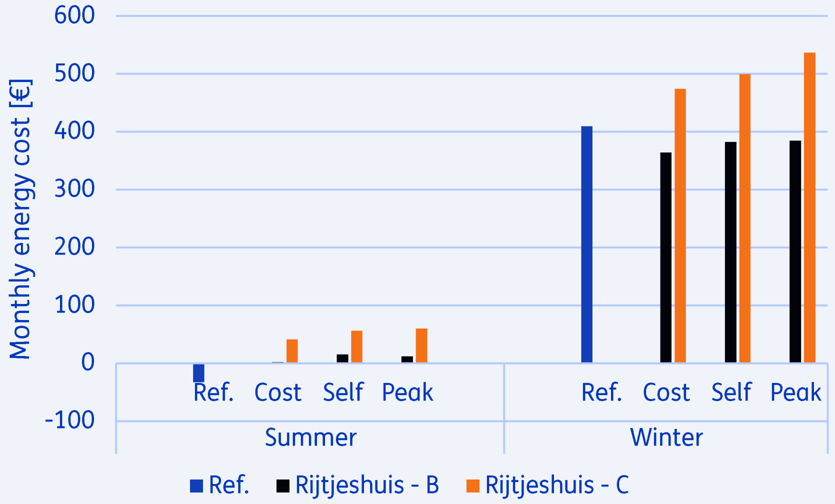


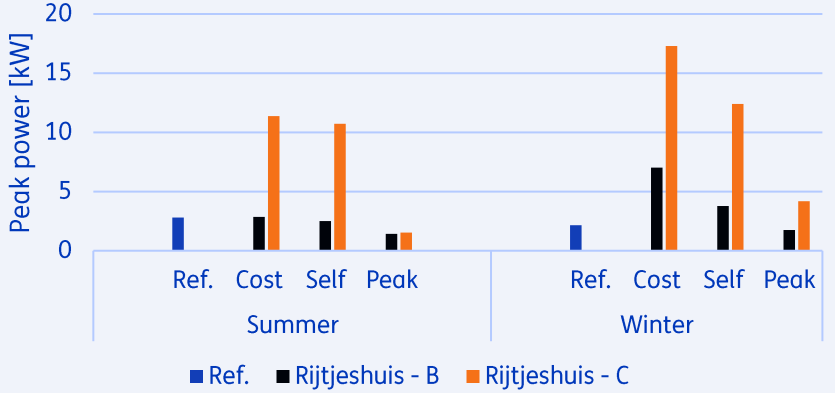


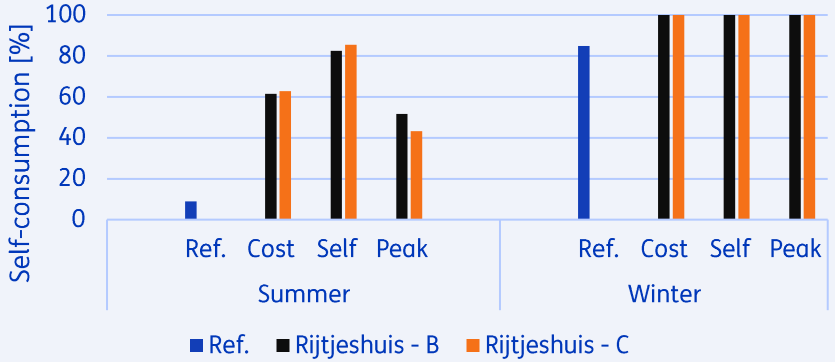
H4 Summer Cost	H4 Summer Self	H4 Summer Peak
Household 0 | Tussenwoning	Household 0 | Tussenwoning	Household 0 | Tussenwoning
PV Installed 3.06 kWp	**PV Installed** 3.06 kWp	**PV Installed** 3.06 kWp
Total Cost €41.66	**Total Cost** €56.23	**Total Cost** €60.01
Grid Import 293.29 kWh	**Grid Import** 291.93 kWh	**Grid Import** 401.48 kWh
Self-Consumption 62.68%	**Self-Consumption** 85.41%	**Self-Consumption** 43.12%
Self-Sufficiency 52.75%	**Self-Sufficiency** 56.84%	**Self-Sufficiency** 36.70%
Peak Import 11.38 kW	**Peak Import** 10.73 kW	**Peak Import** 1.42 kW
Peak Export 2.70 kW	**Peak Export** 1.89 kW	**Peak Export** 1.54 kW

Summary of results

- Across all configurations, the cost-driven objective gives the lowest operating cost, but it also tends to create the largest grid peaks. The reason is that flexible use is shifted toward low-price periods. As the lowest cost is an important driver for households and price incentives are national and thus simultaneous, the risk is that with growing adoption of flexible assets, the grid impact will further increase.
- The self-consumption objective mainly improves local PV utilisation and reduces exports. At the same time, power peaks are reduced compared to the cases optimized for cost, but the operating cost is slightly higher. However, the costs are usually lower than the peak shaving objective ones.
- The peak objective gives the most grid-friendly profile, usually at the expense of (slightly) higher cost and higher grid imports compared to the other two objectives. The peak reduction is mainly driven by a smoother operation of the heat pump and a spread charging profile for the EV. Reflection: These results confirm the flex potential of households to mitigate grid congestion. However, currently no financial incentive exists for households to take the grid effect into account in the optimization.
- The main differences between the three strategies are driven by the operation of the hybrid heat pump and the battery: in winter through heating demand (for example, pre-heating and using the thermal buffer of the house), and in summer through PV self-consumption, either being used for additional cooling, and/or for battery charging.
- The addition of an EV makes these trade-offs much stronger (grid impact vs cost), especially for peak demand and total imports. Overall, we see that that smart-charging for self-consumption or peak shaving smooths out the demand profile and reduces the maximum peak import power.
- Overall, the additional costs of choosing 'Self-consumption' or 'Peak shaving' as objectives instead of 'Cost minimization' for the household in this study are between €25 and €62 per month during a cold month in winter and between €10 and €18 per month during a hot month in summer. The ranges include the impact of an EV and the chosen objective. These results give an indication of the minimum financial effect that would be required from a new grid tariff to make the peak-shaving objective financially attractive for households and thereby utilize the flex potential of households to mitigate grid congestion.







Conclusions & Recommendations

Conclusions, reflection and recommendations

Adoption of net-intensive assets at households is growing, especially EV charging, heat pumps and home batteries. We see different concepts emerging for operating these flexible assets, with different parties in control. Various optimisation goals can be applied with different impacts on cost, grid impact and self consumption. In this research we have investigated the effect of currently existing financial incentives (energy pricing and self-consumption) and different optimisation objectives on the grid profile and energy bill of a typical Dutch household.

We see adoption rates of dynamic contracts and flexible assets steadily increasing, while adoption of PV already being high. From earlier research we learn that financial incentives are an important motivation for households. This study shows that optimising for cost indeed leads to a lower energy bill compared to the other optimisation objectives. Therefore, we expect that energy behaviour for a typical 'terraced house' with automated and controlled assets responding to implicit incentives will align with the results of the cost-driven objective in our analysis.

Our results show that households with an EMS, controlled heat pumps, EV charge points and a dynamic energy price contract that optimise for costs, will significantly increase their peaks demands. As dynamic energy prices follow the national day-ahead energy market, household behaviour will be largely simultaneous thereby increasing grid impact on system level. This may be a smaller problem if energy prices are low outside the grid peak hours, but with a growing share of renewables (especially wind) in the system, price patterns might change in the future.

Furthermore, results confirm that households can lower their grid impact significantly by optimising for a grid-friendly profile. However, we conclude that this requires financial incentives that compensate households for deviating from pure cost optimisation. In other words, the economic attractiveness of grid-friendly behaviour depends fundamentally on the design of future energy and network tariffs.

Currently there is no financial incentive for the household to do so. A time-of-use grid tariff is currently in development by the grid operators aiming for introduction in 2029. Our quantitative results give an indication of the minimum financial effect that would be required from this new grid tariff to make the peak-shaving objective financially attractive for households and utilize the flex potential of households to mitigate grid congestion. For the specific household simulated in this study, the difference in energy cost between cost-optimisation and peak optimisation are between €25 and €62 during a cold month in winter and between €10 and €18 during a hot month in summer.

We recommend to investigate the expected effect of the envisioned time-of-use grid tariff on the grid profiles and analyse time-of-use prices schemes in combination with existing financial incentives such as dynamic energy pricing. This can be done with the optimisation model used in this study. In addition, it would we be relevant to extend the analysis to different household types and to simulate the effect of multiple houses on neighbourhood level to assess the effect on the low voltage grid.

Limitations and suggestions for further work

Given the limited time and budget available limitations had to be made to the scope of this study. As the analysis gives relevant results, and the simulation and optimisation model applied allows for a broader scope, we have suggestions for further work.

- **Only one type of house has been simulated** → Future work can include different house types like appartement, hoekwoning, vrijstaande woning, and apply different energy labels.
- **Central optimization (HEMS) has been assumed**→ Future work can assess the effect of individual asset optimization (no centralized control), which is the case if assets are not interoperable.
- **A single household has been simulated** → Future work can include multiple households to analyse the effect on neighbourhood level and calculate the effect of different configurations behind the meter on the low voltage transformer and even joined optimization / coordination.
- **Fixed network tariffs** → Future work can assess the impact of alternative network tariffs, e.g., time-of-use, kW-max, and assess the effect of different pricing schemes on the asset behavior and grid effects.
- **Results are based on models. Are findings recognised in practice?** -> It would be interesting to reflect with stakeholders on the findings and compare them with insights obtained from practice.

References

DNE Research (2025a). *Nationaal Solar Trendrapport.* Dutch New Energy Research & Solar365

DNE Research (2025b). *Nationaal Smart Storage Trendrapport 24/25.* Dutch New Energy Research & Solar365

DNE Research (2026). *Nationaal Warmtepomp Trendrapport.* Dutch New Energy Research en Warmte365

DNV (2024). *Assessing the risk of undesired effects and interactions of large scale implementation of control and optimization algorithms in power systems.* Deliverable of TKI project GO-e. 2024.

Cappellen, L. van, Bongaerts, M., Hesselink, F., Nauta, M. & Scheers, J. (2026). *Zoveel kan met lokale flex!* CE Delft: Delft.

Hoogsteen, G., Molderink, A., Hurink, J. L., & Smit, G. J. (2016). *Generation of flexible domestic load profiles to evaluate demand side management approaches.* In 2016 IEEE International Energy Conference (ENERGYCON) (pp. 1-6). IEEE.

Dijk, M. van & W. Treurniet. (2026). Onderzoek naar vraagrespons in het kader van leveringszekerheid. Magnus Energy.

Refa, N., Hammer, D. & Slobben, T. (2023). *Regulier en netbewust laden. Outlook Laadprofielen Personenauto's.* ElaadNL.

ElaadNL (2026). *Interactief dashboard met prognoses.* Beschikbaar via Outlook dashboard.

Kort, J., de Koning, N., van Stokkum, R., Zweers, N., Sixma, A., Melli, A. (2024) De bereidheid van consumenten om flexibiliteit te leveren in het energiesysteem in de gebouwde omgeving. Deliverable of TKI project GO-e. TNO: Amsterdam.

LAN Landelijk actieprogramma netcongestie (2026). *Derde voortgangsrapportage*. Beschikbaar via Voortgangsrapportage LAN - voorjaar 2026'

Langley, M. G., Bouman, T., & Steg, L. (2020). De waarden achter klimaatgedrag: Hoe persoonlijke waarden en waargenomen groepswaarden klimaatgedrag motiveren en versterken, *Mens en Maatschappij, 95*(3), 175-196.

Sambeek, H. van, Westerga, R., Wijbrandi, W., Konsman, M., Magan, I. & Taminiau, F. (2024). De rol van slimme apparaten bij netcongestie op het laagspanningsnet. Een analyse van flexibiliteitsmogelijkheden, interoperabiliteit en beleidsopties. TNO: Amsterdam.

Quax, R. (2025) presentatie: zonnestroom goedkope bron zoekt waardevolle toepassing. TKI Urban Energy. Gegeven door Robin Quax op 12 februari 2025.

RVO (2025). Monitor Verduurzaming Gebouwde Omgeving 2025.

Wolterman, B., Hiep, E., van Biezen, M., Zweistra, M. (2025) Laden van elektrische auto's n Nederland. Ervaringen en meningen van EV-rijders. Nationaal Laadonderzoek 2025.