FLEXBEAN
Flexibility for Energy Transition PROJECT

Flexibility potentials and user Behaviour Analysis

Residential Flexibility Supply

13.02.2026

Joachim Geske, Rawan Akkouch, Boris Moreno, Laura Andolfi

creos
LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY | LIST
uni.lu | SnT

Project acronym	FlexBeAn
Full title	Flexibility potentials and user behaviour analysis
Project start date	2022-05-01
Project duration	36 months
Work package 3	Title of work package
Deliverable lead organisation	LIST / SNT / CREOS
Authors	Joachim Geske (SNT) Rawan Akkouch (SNT) Boris Moreno (SNT) Laura Andolfi (SNT)
Version	01
Status	Final
Dissemination level	PU: Public
How to cite this report	Geske, J.; Akkouch, R.; Moreno, B.; Andolfi, L.; (2026) Flexibility Potential and User Behaviour Analysis: Residential Flexibility Supply (WP3)

This deliverable contains a report with a detailed description of the approach the methods and the results of the work package.

Executive Summary

1. Objective

This Work Package 3 (WP3) report, part of the FLEXBEAN project developed in collaboration with the Luxembourgish grid operator CREOS and the Luxembourg Institute of Science and Technology (LIST) investigates the role of residential flexibility in supporting the energy transition at the distribution grid level. As the country moves toward decarbonization - driven by EU climate targets and national commitments - electrification of heating, mobility, and decentralized renewable energy generation is accelerating. This transformation poses significant challenges to grid infrastructure.

The study aims to assess whether households equipped with flexible technologies (e.g., PV systems, electric vehicles, batteries, heat pumps, and building insulation) can help alleviate grid bottlenecks or exacerbate them. It also evaluates the effectiveness of policy interventions - specifically grid tariffs and curtailment mechanisms - in mitigating transformer overloads and ensuring secure grid operation. The analysis is grounded in a welfare-based approach, balancing grid investment costs against household energy revenues.

2. Methodology and Approach

The study employs a simulation-based modelling framework to analyse household electricity demand and flexibility provision for the years 2030 and 2040. It models 166 representative households connected to a single transformer, reflecting Luxembourg's socio-demographic and technological characteristics. Households are categorized into three types: non-technological, technological but non-flexible and fully flexible.

Flexible households are assumed to operate their energy assets (EVs, batteries, heat pumps, and thermal storage) to minimize electricity costs by responding to hourly wholesale market prices. This includes arbitrage behaviour - charging during low-price periods and discharging or exporting during high-price periods. Nonflexible households minimize their energy consumption and charge their EVs as fast as possible.

The model incorporates detailed constraints such as battery degradation, thermal inertia, and EV availability, and assumes perfect foresight of prices and weather conditions. Scenarios vary by the share of flexible households (0%, 50%, 100%) and are tested under three policy environments:

- No policy (unregulated market behaviour)
- Grid tariffs (on imports only, and on both imports and exports)
- Curtailment (1-hour and 3-hour windows around transformer overloads)

Transformer load profiles are evaluated against capacity thresholds to determine overloads and the need for grid expansion. Investment costs are calculated based on transformer equipment and infrastructure and translated into annual household costs. Welfare is assessed by combining grid enforcement costs with household electricity revenues.

3. Key Results

Flexibility Potential and Grid Impact: Flexible households behave like electricity traders, leveraging storage and thermal assets to exploit price fluctuations. This inverts the traditional "duck curve" to a “turtle”-curve leading to midday import peaks and evening export spikes. In 2030, transformer overloads occur only under extreme flexibility (100%), requiring modest grid expansion (0.57 transformers per site). By 2040, even with 0% flexibility, overloads become prevalent due to increased technology adoption. At 100% flexibility, transformer capacity needs rise to 2-4 times current levels, requiring up to 3 new transformers per site. The impact of parameters on aggregate load is highly nonlinear – making an accurate load forecast a challenging task.

Economic Behaviour and Efficiency: Flexible households increase heating and hot water consumption by 15% due to pre-conditioning and thermal storage use, slightly reducing energy efficiency. EV charging can shift strongly between external and home-based charging – depending on the incentives. Annual household revenues from electricity trading range from €500 to €800 in 2030 and 2040.

Policy Evaluation: Grid Tariffs on Imports only flatten import peaks but fail to address export overloads. Investment needs remain high. Grid Tariffs on Imports and Exports proof most effective. They reduce transformer overloads significantly, requiring only 0.71 new transformers per site at 100% flexibility. Curtailment of 1h and 3h around a transformer overload is moderately effective. It reduces overloads slightly but introduces rebound effects and fails to prevent capacity violations consistently.

Welfare Analysis: The symmetric grid tariff (on both imports and exports) offers the best cost-benefit ratio. It increases household electricity bills by only marginally while reducing grid investment costs by up to €110 per household compared to the second-best option. Curtailment policies are less effective and more disruptive, especially at high flexibility levels. Welfare outcomes improve with higher investment costs (e.g., higher interest rates), further favouring the symmetric grid tariff.

4. Conclusion

Residential flexibility can play a pivotal role in the energy transition, but its unregulated deployment risks destabilizing the distribution grid. By 2040, widespread adoption of flexible technologies will necessitate significant grid reinforcement unless effective mitigation strategies are implemented.

The study finds that a symmetric grid tariff - charging for both imports and exports - is the most efficient and economically viable solution. It discourages excessive arbitrage behaviour, flattens load profiles, and reduces grid investment needs without significantly impacting household revenues.

Future research should refine policy parameters, incorporate dynamic price feedback, and explore additional mitigation strategies such as local storage and voltage-based controls. The findings provide actionable insights for grid operators, policymakers, and energy stakeholders seeking to balance flexibility, efficiency, and infrastructure resilience in a decarbonized energy system.

1. Introduction

The energy transition in Luxembourg is rapidly advancing, driven by ambitious Luxembourgish climate targets and European Union commitments to decarbonize the energy sector. As outlined in the National Energy and Climate Plan (NECP), the country aims to increase the share of renewable energy in final energy consumption from 11% in 2024 to 37% by 2030 - an effort that entails not only expanding supply-side capacity through renewable generation but also the electrification of key areas like the heating and mobility sector.

In this context also the electrical distribution grid - like power generation and the transmission network - is undergoing a profound transformation - into a decentralized controlled system increasingly shaped by storage technologies and renewable energy sources. To ensure this transition is implemented efficiently also at the distribution level, a paradigm shift is currently underway: moving away from a blind, purely peak-load-driven, static grid design towards a monitored economically optimized operation and design that systematically weighs costs against benefits.[1]

This shift is far from trivial, as ensuring complete protection of the infrastructure against overloads in all conceivable scenarios will become unpayable. To avoid faults and blackouts flexibility becomes essential. In detail: industries and households do not only consume more electricity but also participate actively, by shifting their consumption patterns, storing electricity, and even feeding energy back into the grid according to dynamic tariffs - aligned with wholesale market prices.

The latter are available to almost all European households as the EU has steadily advanced its market liberalisation agenda in the energy sector, aiming to foster competition, increase efficiency, and empower consumers. Central to this approach is the principle that prices should reflect real-time supply and demand conditions, turning them into key signals that guide investment, consumption, and production decisions. By promoting price responsiveness, the EU positions prices as the primary mechanism for balancing supply and demand in an increasingly decentralised and dynamic energy system.

However, if households' incentives do not align with the needs of the distribution grid, it raises the question of how to effectively promote grid-beneficial behaviour. Rather than simply expanding grid capacity, future efforts should focus on designing incentives or market structures that encourage households to adjust their consumption based on the grid's real-time needs. Thus, the challenge for grid operators lies in ensuring a sufficiently secure and efficient grid operation through a combination of improved grid management, grid enhancement (also including grid level storage options), tariff and market design and targeted regulatory measures in an environment of

---

[1] This is conceivable in a discussion about the appropriateness of the classical N-1 design and operation criterium of grid security vs. a risk-based assessment of grid security based on the Value of Lost Load.

information and communication technologies, change in behavioural patterns and various energy storage solutions.

This challenge will be of critical importance to grid operators in the coming decades - even though many influencing factors remain highly uncertain today. Long planning and implementation timelines (typically more than 5 years) also require a forward-looking anticipation of what will be possible or necessary in the future. However, the answer is an economic one: only extend the grid if this is beneficial for the society.

As part of Work Package 3 of the FLEXBEAN project, conducted in collaboration with the Luxembourgish distribution system operator CREOS, we investigated the challenges posed by the energy transition to the low-voltage grid. Specifically, we examined whether residential demand-side flexibility can alleviate these challenges or potentially exacerbate them and explored strategies to mitigate any resulting issues through tariff design, rule-based policies or grid expansion. We evaluated these based on a welfare analysis.

Our analysis therefore deliberately starts with grid performance: we examine how it is expected to evolve over the coming decades and how it can be influenced through market-based and regulatory instruments (curtailment). In detail we simulate the responsiveness of households 1. in an unregulated environment, 2. to a grid tariff and 3. a curtailment policy. We model electricity consumption and flexibility supply at the transformer level with 166 representative households in Luxembourg, under different technological adoption and flexibility participation scenarios for the years 2030 and 2040. Using an empirical modeling framework, rational households' reactions are simulated, and their impact on transformer loading and grid congestion is evaluated.

We find that future unmitigated flexibility provision triggers trading responses - ping-pong flexibility - at high adoption levels of storage and electric mobility technologies by 2030 and generally by 2040. This flexibility inverts the typical duck-curve to a turtle-curve with eventually critical levels - requiring mitigation mechanisms for secure operation. While curtailment spread consumption more evenly throughout the day, it alone was insufficient to prevent transformer overload significantly. Grid tariffs reduced peaks gradually depending on their extend and achieved a more efficient peak reduction.

The remainder of this report is as follows: In section 3 the theoretical model of flexible households is introduced including a description of our empirical approach, simulated household load profiles for various scenarios and years, the data and methodology used for this simulation and the identification of bottlenecks based on these profiles. In section 4 the model is presented formally. In section 5 the results of the policy free scenarios are presented. In the following two sections the results of the policy experiments curtailment (section 6) and grid tariffs (section 7) are presented. Finally, in Section 8, we compare the policies in a cost benefit analysis and provide conclusions in section 9.

2. Project Context

The ongoing energy transition is increasingly driven by additional renewable generation and the electrification of mobility and heating. As part of political initiatives, wholesale electricity market-based tariffs are accessible to residential customers and industry. This development introduces new opportunities for households to actively participate in the electricity system by adjusting their consumption patterns in response to price signals. The flexibility that emerges from this behaviour is anticipated to play a crucial role in supporting the stability and efficiency of the future electricity grid.

In this context, the grid operator CREOS has raised several important questions:

1. How will typical load curves of flexible residential customers look like in the future.
2. How will this flexibility help alleviate existing grid bottlenecks or, conversely, create new ones.
3. What are the costs associated with resolving such bottlenecks via rule respectively market-based mechanisms.

To address these questions, in work package 3 of the FLEXBEAN project energy consumption of a population of cost-minimizing flexibility supplying households[2] has been simulated over the course of an entire year, focusing on the years 2030 and 2040. The active buildings are equipped with technologies such as PV, electric vehicles, heat pumps, battery storage, and thermal storage systems. The simulation assumes that a share of households acts as smart flexibility provider, responding dynamically to electricity tariffs, grid constraints and curtailment.

The objective of this modelling effort is to assess whether the flexible behaviour of these households can effectively prevent overloading the distribution grid and whether CREOS's newly designed grid tariff or loadshedding mechanisms are sufficient to address these challenges. Additionally, the simulation provides insights into the economic implications of different flexibility scenarios, helping to estimate the investment and operational costs required to ensure reliable grid operation in a more electrified and decentralized energy system.

---

[2] We will call these households synonymously "active buildings", referring to the automatically controlled nature of the flexibility supply.

3. Approach of the Analysis

The first goal of this analysis is to determine the electricity consumption of households in hourly resolution over one year[3] under the climatic, technical, economic, and sociodemographic conditions expected in the future, specifically in 2030 and 2040. We assume that electricity tariffs reflecting wholesale market prices will be accessible to all households[4]. If this is the case, households can make use of a range of storage technologies, which can be bundled with electric vehicles and heating systems (e.g., hot water storage) or acquired separately as electric battery storage. In addition, high-insulated buildings of the future, with very low heat losses, can also store heat. All these storage systems can be operated independently by households, subject to performance and capacity constraints.

For flexible households, we assume that storage systems are operated in a way that minimizes the net electricity supply costs. This means electricity is purchased at low prices and sold at high prices. At first glance, one might wonder: What electricity can households sell? First, the electricity they generate themselves via PV systems and second, the electricity they purchased cheaply and stored. Thus, flexible households become not only electricity producers but also electricity traders - even more: Electric vehicles can serve as "transporters" of electricity as they may be charged and eventually discharged over the day outside the residential site[5].

The question is to what extent? This is precisely what we aim to answer with our approach. The extent to which this is possible is not easy to determine in detail, since all these storage systems are primarily acquired and used not for trading but to ensure a comfortable daily life: the car battery for mobility, building insulation to reduce heating costs, and hot water storage to ensure a continuous supply of hot water. So, how much room is left for electricity trading?

We therefore model in detail over the course of an entire year which electricity demand must absolutely be "fulfilled" as shown in Figure 1. For direct electricity demand, we refer to standard household load profiles (1) today and scale them according to future household sizes. Furthermore, we project hot water demand based on standard load profiles (1) to 20% of annual electricity demand (2). Mobility needs are derived from synthetic mobility time series, which indicate when a vehicle is "at home" i.e., can be charged or discharged, and how much electricity the vehicle consumes (3). This is particularly complex, as off-site vehicle charging must also be tracked. As long as the vehicle can be sufficiently charged to meet all upcoming trips, we assume the battery can also be used for electricity trading. Heat demand is indirectly derived from a

---

[3] Aside from goal to conduct annual load flow analyses based on load profiles we preferred the hourly simulation over a year the computationally less "expensive" and in the view of foreseeability more accurate representative weeks approach to fully cover the dynamics of highly renewable systems in 2030/2040. Even though we do not believe in a continuous seasonal storage pattern - which would have required an annual approach - intermittent renewables would still have made it hard to identify representative weeks for annual household behaviour.

[4] To focus the analysis on a comparison mitigation policy the model excludes supplier margin and taxes.

[5] The conditions to charge and discharge „off-home" adds a further level of opportunities for the flexible households as they can make use of fast charging capacities and eventually cheaper external grid tariffs if the cars are parked at an office. They could - during lunchtime charge cheap electricity that can be sold expensively during the high-price evening hours of a day at home. Currently this is not profitable, but economies of scale could play a role in future.

comfort temperature range: we calculate the electricity needed for heating based on the energy required to keep the building within a comfortable temperature range of 20-30°C, though this range can vary by season and time of day (4). It is important to consider thermal inertia, which helps prevent sudden temperature shifts within a building, making it easier to maintain a consistent comfortable environment. This required energy is derived from the building envelope's heat losses, depending on insulation and outside temperature, and the current indoor temperature.

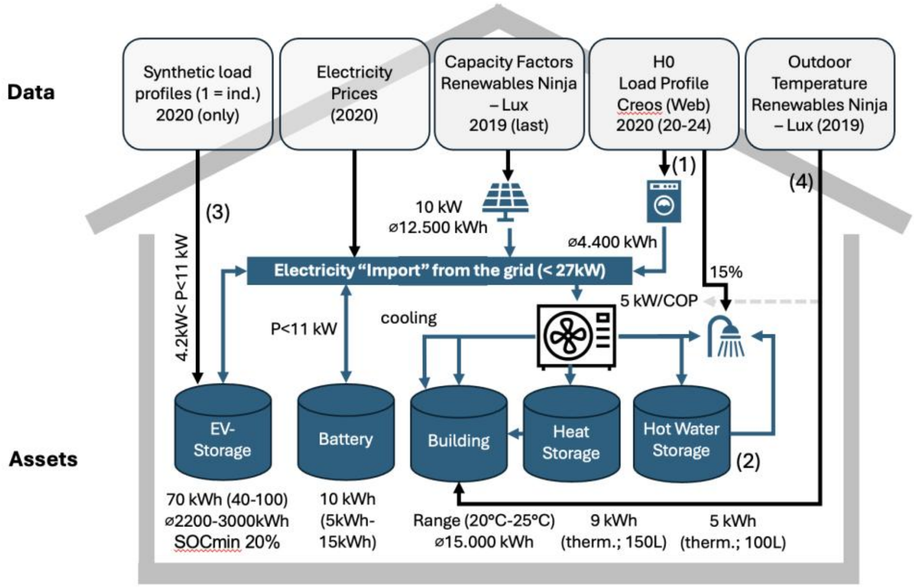


Figure 1: Household/Active building technologies

Matching this electricity demand and the flexibility provided by storage systems - within capacity limits of power lines, heat pumps, and EVs considering degradation of electrical storage systems and regulatory implemented constraints (11 kW for EV charging) - with favourable electricity trading times requires significant effort, including time. We assume that home energy management systems (HEMS; as automatic controllers), which handle this task, are available to all flexible households. For simplicity, we assume that EV usage profiles, appliance's demand, outdoor temperature, capacity factors of PV generation and electricity prices are perfectly foreseeable and available to the controller.

As this is an idealistic assumption, our estimate of the potential of flexibility needs to be considered as an upper bound. However, it clarifies how flexible households can be expected to behave. We will synonymously call this setting an active building. To simplify our analysis, we only consider fully flexible and fully inflexible households (figure 2). Non-flexible (technological) households use an automatic heating energy minimizing controller and plug in their EVs immediately once a charging point is reached. They do not respond to price dynamics, similar to a fixed-price tariff.

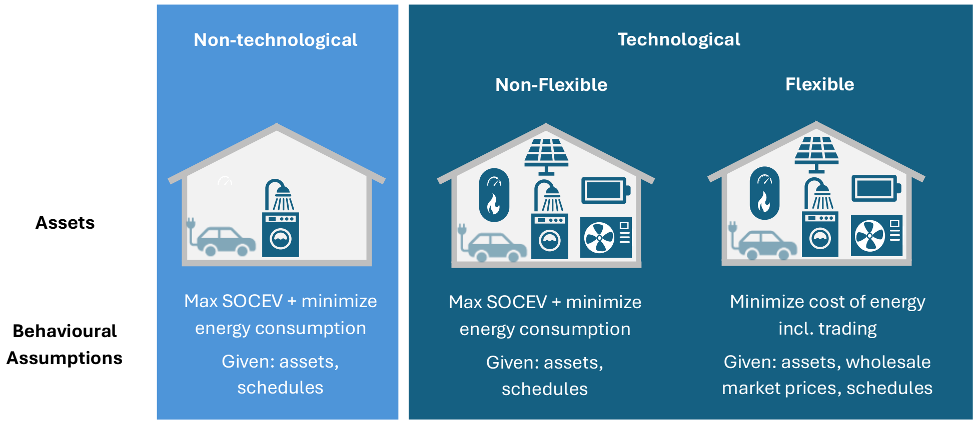


Figure 2: Household classification

In our study, we examine the impact of flexibility on the utilization of the distribution grid. To identify it, we vary the share of flexible households without simultaneously changing the equipment of households with the described assets. This requires us to consider household equipment separately. Again, for simplicity, we distinguish only between households that are technically equipped with storage systems and those that are not (figure 2). Only technically equipped households can offer flexibility. Technical equipment includes the installation of a heat pump, improved insulation, and storage systems. A nontechnically equipped household, on the other hand, has a nonelectric heating system. Temperature is not considered for such households. The only exception to technical equipment is electric vehicles.

We are not directly interested in individual households, but the aggregate of multiple households within the distribution grid, specifically at the low-voltage level with a transformer. Ideally, we want to study the entire low-voltage grid, but previous studies have shown that transformer capacity is typically the main bottleneck (Ministère de l'Économie, 2024, p. 46). We therefore examine the typical service area of a transformer - 166 connected households in a rural area by summing their net electricity demand over a year in 2030 and 2040 (figure 3).

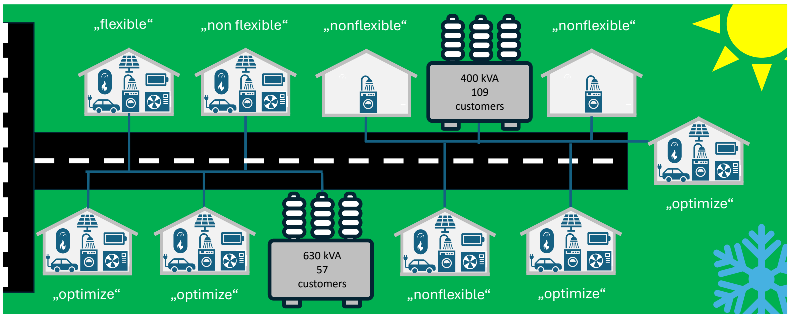


Figure 3: Topology of 166 households and transformers

For simplicity we assume the households represent Luxembourgish sociodemographic characteristics (e.g. mobility demand). This will likely underestimate energy demand from transportation, as rural regions typically have higher driving distances. We randomly draw household compositions from given distributions based on scenario data for 2030 and 2040, determine the annual load profile for each household, sum across households, and compare it to transformer capacities.

To determine the impact of the share of flexible households, we calculate transformer load for shares of 0%, 50%, and 100% flexible households - representing 0%, 15% and 30% in 2030 and 0%, 30% and 60% in 2040. Each of these simulations will be applied to policy scenarios: no policy in 2030 and 2040, 2040 with grid tariffs and curtailment. In the following section the modeling details will be exposed.

4. Simulating Households Electricity Demand/Supply

4.1. Model Description

In the Active Building Model, household energy behaviour is modeled through a linear optimization framework. The model operates on an hourly resolution and simulates how households manage their energy assets, such as EVs, batteries, and heat pumps to minimize their objectives while meeting comfort and technical constraints. Two objectives are considered: for flexible households electricity cost and for non-flexible households a combination of electricity consumption and electric vehicle's state of charge.

The flexible households minimize costs of energy used or produced over a year in an active building. They consider CREOS' grid tariff, which consists of a costly allowance to consume electricity up to a volume of k**.** The extent to which imports or exports exceed the threshold k defines the variable excess_t, representing the surplus at time t. Households need to pay a penalty p_{pt} per unit of excess. The idea is that households balance the penalty and the allowance level of k optimally. Furthermore, the household considers the cost for charging EVs outside with an extra fee of 0.2€/kWh for external charging equipment usage[6].

The objective function of the flexible households includes total electricity-related costs while accounting for penalties when import or export levels exceed defined grid thresholds. It is to be minimized:

$$\begin{aligned} \min -p_k^{\text{threshold}}\, k + \sum_{t=1}^{365\cdot 24} p_t \Big((1+\varepsilon)\, \text{Import}_t^+ - \text{Import}_t^- \\ + (1+0.2)\cdot (s_t^{EV+} - s_t^{EV-})|_{if\ not\ at\ home} \Big) + p_{pt} \cdot \text{excess}_t \end{aligned} \tag{1}$$

where p_t represents the electricity price at hour *t*, ε is the grid tariff to be paid only for electricity consumption, Import_t^+, and Import_t^-[7] are imports and exports, respectively, and excess_t captures any excess consumption or export above tariff threshold k. We distinguish positive and negative imports as the grid fee is on imports only.

In contrast, non-flexible households are agnostic towards the cost. Their objective is to maximize the SOC of the vehicles (S_t^{EV}; once they are connected) and minimizes the energy to meet demand for hot water (e_t^{Water}), space heating (e_t^{Heat}), and cooling (e_t^{cool}):

$$\min -\sum_{EV,t=1,\ldots 365\cdot 24} S_t^{EV} + e_t^{Water} + e_t^{Heat} + e_t^{cool} \tag{2}$$

These goals are set to operate the building with all its assets: The model is constrained by a resource balance which ensures that all energy demand is met through imports ($\text{Import}_t^+, \text{Import}_t^- \geq 0$), PV generation, battery and EV storage, and thermal loads:

$$\text{Import}_t^+ - \text{Import}_t^- = \text{LOAD}_t - \text{PV}_t + (s_t^{EV+} - s_t^{EV-})|_{ifin} + s_t^{Bat+} - s_t^{Bat-} + e_t^{Heat} + e_t^{Water} + e_t^{cool} \tag{3}$$

---

[6] https://today.rtl.lu/news/luxembourg/a/2268421.html

[7] Superscript plus and minus symbols indicate the direction of a flow of positive variables. E.g. Import_t^+ is the positive import, while Import_t^- is an export.

where LOAD_t is the household's electricity demand for appliances (the household size scaled version of the standard load profile H0), PV_t is the generation, and the terms $s_t^{x+/-}$ refer to charging and discharging of different storage technologies. Charging and discharging of vehicles is only accounted for in the resource balance if the vehicle is at home ("in").

The state of charge evolves over time according to:

$$S_t^x = (1-\delta^x)S_{t-1}^x + s_t^{x+} - s_t^{x-} - c_t^{EV}|_{x=EV} - \alpha \cdot LOAD_t|_{x=Water} \\ x \in \{Bat, EV1, EV2, EV3, Heat, Water\} \tag{4}$$

This ensures that losses (δ^x), charging (s_t^{x+}), discharging (s_t^{x-}), and direct usage for EV driving ($c_t^{EV}|_{x=EV}$) and hot water demand $\alpha \cdot LOAD_t$ are reflected in the battery and EV charge levels. Here it does not matter, if the EVs are at home the energy balance of the EVs changes anyway. Charging and discharging are further constrained by technical and operational limits:

$$\underline{P}^x y^{x+/-} chargeable_t \le s_t^{x+/-} \le chargeable_t y^{x+/-} \overline{P}^x \quad x \in \{Bat, EV1, EV2. EV3, Heat, Water\} \tag{5}$$

The technical constraint limits the power at which assets can be charged/discharged ($\underline{P}^x, \overline{P}^x$), and the operational ensures that no more than 11kW for charging or discharge EVs simultaneously with a maximum number of three EVs. $y^{x+/-} \in \{0,1\}$ indicates the availability of charging power for an EV - e.g. it is not available during trips.

$$\sum\nolimits_{x\in \mathrm{EV1,EV2,EV3}} (S_t^{x+} + S_t^{x-}) \le 11 \tag{6}$$

Degradation is modelled via a an upper bound on charging cycles. The idea is that 200 full cycles ($\mathrm{MaxAnnualCycle}^x$) per year are in line with a 10-year lifetime of a Lithium-Ion battery[8], the typical length of a warranty supplied by manufacturers, so that additional battery operation by vehicle to grid does not affect the choice of the driving technology. This idea is approximated by summing up all charging and discharging $s_t^{x+} + s_t^{x-}$ dividing it by twice the storage capacity $\bar{S}^x$ to end up with the number of full cycles:

$$\sum\nolimits_t s_t^{x+} + s_t^{x-} \le 2 \cdot \bar{S}^x \cdot MaxAnualCyc^x \quad x \in \{Bat, EV1, EV2, EV3\} \tag{7}$$

which limits annual cycling of batteries and EVs. We could have introduced monetary charging costs only. However, these calculations are based on an overall maximum number of charging cycles. To preserve these, we decided to limit our battery charging cycles directly and stick to the capital costs calculations based on the maximum number of cycles.

In addition to electrical energy dynamics, the model captures the building's thermal dynamics:

---

[8] "The standard battery warranty in Europe is typically 8 years or 160.000Km…". Some manufacturers offer 10 years like Hyundai. (https://ekoenergetyka.com/blog/electric-vehicle-battery-lifespan-and-replacement-what-european-drivers-need-to-know/); "Most lithium-ion batteries will hold their charge capacity through 1,500 to 2,000 complete charge cycles - that is, running down to 0% and recharging to 100%." https://www.midtronics.com/blog/the-end-to-end-lifecycle-of-an-electric-vehicle-battery/.

$$T_{t+1} = T_t + \frac{1}{C}\left(\mathrm{Heat}_t - \mathrm{COP}_t \cdot e_t^{\mathrm{Cool}} - U \cdot A \cdot (T_t - T_t^{\mathrm{out}})\right) \qquad (8)$$

where the indoor temperature T_t evolves based on heating input Heat_t, cooling output e_t^{Cool} (multiplied with the coefficient of performance COP_t[9] for the heating energy balance), and thermal losses to the environment $U \cdot A \cdot (T_t - T_t^{\mathrm{out}})$[10].

If the building is technologically equipped it is heated respectively cooled by an air source heat pump. Its operation is modeled to meet both space-, water-heating and cooling needs separately - to reflect thermodynamics of different temperature levels (40° Celsius for the heating system and 60° for hot water supply). Electricity e_t^{Heat} required to meet heat demand at 40°C Heat_t is "produced" from a heat pump with coefficient of performance COP_t or from discharging the heat storage $s_t^{Heat+} - s_t^{Heat-}$:

$$COP_t \cdot e_t^{Heat} = s_t^{Heat+} - s_t^{Heat-} + Heat_t \qquad (9)$$

The 60° C hot water demand is equivalent to the linearly scaled electricity demand H0. This $\alpha \cdot \mathrm{LOAD}_t$ is met by the heat pump's electricity consumption e_t^{Water} and net discharging of the hot water storage $s_t^{Water+} - s_t^{Water-}$

$$COP_t \cdot e_t^{Water} = s_t^{Water+} - s_t^{Water-} + \alpha \cdot Load_t \qquad (10)$$

To align electricity demand for hot water e_t^{Water}, heating e_t^{Heat} and eventually cooling e_t^{Cool} with the heat pump capacity total heat-related power usage is limited by the power of the heat pump $\mathrm{HP}_{\mathrm{Power}}$:

$$e_t^{\mathrm{Water}} + e_t^{\mathrm{Heat}} + e_t^{\mathrm{Cool}} \leq \mathrm{HP}_{\mathrm{Power}} \qquad (11)$$

Finally, CREOS' grid tariff's capacity k is designed to minimize the costs of electricity consumption of each customer. The volumes for which the excess fee must be paid $excess_t$ is defined by the next two inequalities:

$$excess_t \geq Import_t^{+} - k \text{ and } excess_t \geq Import_t^{-} - k \qquad (12, 13)$$

The combination of these objectives and constraints forms the household optimization model, which captures the behavioural[11], economic and technical aspects of residential flexibility provision. The model captures the complex interactions between household assets, comfort needs, electricity prices, and grid constraints. By integrating detailed representations of storage dynamics,

---

[9] Equation (8) is expressed in terms of heating energy. Thermodynamically, this energy is supplied by an electric heat pump, which converts electrical energy into thermal energy with an amplification factor defined by the coefficient of performance (COP).

[10] The idea behind this equation is that a change in temperature stems from an energy injection - via a heating system - reduced by losses of the building. These losses are determined by the U Values (see Appendix B), the area of the outer hull of the building A and the difference of indoor to outdoor temperature $T_t - T_t^{\mathrm{out}}$. The change in temperature due to a net heating is scaled by thermal mass C of the building. Both parameters depend on building size and used materials respectively the construction year (Appendix B)

[11] A behavioural component is e.g. the immediate charging preference of the non-flexible households.

heating behavior, and tariff structures, it allows for the simulation of realistic flexibility provision scenarios.

4.2. Data

To determine household load profiles, we integrated key household characteristics such as EV ownership, PV system capacity, battery storage availability and size, heat pump ownership, and building insulation or energy efficiency ratings. Understanding household flexibility provision required an analysis of electricity pricing variations throughout the day. We extracted future electricity prices from the ACER's Ten-Year Network Development Plan (TYNDP), which provide a long-term perspective on the development of the European energy system. TYNDP scenarios support infrastructure planning in alignment with European climate and energy policy objectives, making them essential for identifying key future time frames for analysis, such as 2030 and 2040. Especially, we chose as particularly representative the Scenario Distributed energy with weather year 2009 (Table 1).

Annual Time Series	**Description**	**Source**
Synthetic EV profiles	Electricity consumption kWh, charging power kW, location in 15min intervals	Gaete-Morales et al., 2021[12]
Electricity Prices	Hourly Wholesale market prices €/MWh	ACER, TYNDP (2035, 2040, Weather Year - 2009, DE), Link
Solar Capacity Factors	Hourly country wide average	Renewables Ninja, Luxembourg 2009, Link
Outdoor Temperature	°C country wide	
Residential Load Profile	Hourly distribution normalized to 1000	Creos, H0 2020, Link

Table 1: Sources of the annual hourly time series used to simulate households' electricity demand/supply.

To capture the impact of environmental conditions, we incorporated PV capacity factors and outdoor temperatures for the year 2009[13] (according to the TYNDP weather year underlying the price data) from Renewable Ninja (Table1).

Household consumption patterns were provided by CREOS through standardized synthetic profiles (H0 profiles, Table 1), which denote load profiles defined by the grid operator for customers without metering. These profiles, based on statistical averages from actual measurements, enable suppliers to forecast daily consumption and estimate individual load curves by applying the customer's projected annual consumption to a normalized ¼-hourly profile. By integrating these data sources, we ensured that the load profiles are robust, adaptable, and representative of different household configurations.

Additionally, parameters are compiled in Table 2. These include, U-values, indicating heat transfer rates across different building components, which are essential for evaluating thermal efficiency

---

[12] Gaete-Morales, Carlos; Kramer, Hendrik; Schill, Wolf-Peter (2021) : An open tool for creating battery-electric vehicle time series from empirical data, emobpy, Scientific Data, ISSN 2052-4463, Springer, Berlin, Heidelberg, Vol. 8, https://doi.org/10.1038/s41597-021-00932-9 , https://www.nature.com/articles/s41597-021-00932-9#Abs1.

[13] These years are selected within the TYNDP framework to represent varying climatic conditions: 1995 is a cold year, testing the system's resilience under high heating demand; 2008 is a dry year, characterized by lower precipitation and reduced hydroelectric generation; and 2009 is a typical year, serving as a baseline with average weather conditions. This comprehensive approach ensures that both extreme and normal climatic variations are accounted for in the scenario analysis.

and the thermal mass, representing the ability of building materials to store heat, impacting indoor temperature stability. The limit of 27 kW reflects the maximum permissible power import from and export to the grid. Also, electric vehicles contribute to household energy demand, with EV possession - and therefore consumption - depending on household size. Total electricity consumption follows a linear relationship depending on the household size based on data of the German Federal Statistical Office (Statistisches Bundesamt). Correspondingly, hot water consumption is modeled as 20% of total electricity usage (H0 profile). Further technological, socio demographic, behavioural and tariff related parameters have been compiled in table 2 and Appendix C.

Technical Parameters	**Unit**	**Value**	**Source**
Home Battery Storage Capacity	kWh	10	Own assumption
Battery lifetime	cycles	5000-10000	
EV Storage Capacity	kWh	70	Own assumption
EV NMC/NCA	Cycles	1000-2000	
Hot Water Storage Capacity	kWh	5	100 Liter
Heating Storage	kWh	9	150 Liter
U-Values / building age(n/m/o)	kW/K	New: 0.10/medium: 0.19/old: 0.40	Building data Link, own calculations
Thermal Mass	kW/K	40	Building data Link, own calculations
Heat Pump Power (n/m/o)	kW_e	2.5/4.5/8	
Building Temperature Range	°C	[20, 30]	Own assumptions
Electricity Import Limit	kW	±27	CREOS
Solar PV Capacity	kW	10	CREOS
Power in House	kW	Total d/charg. power EVs ≤ 11	CREOS
Coefficient of Performance (COP) Heat Pump	-	2.5	CREOS
Household Electricity consumption.	kWh	1150kWh+950kWh/pers·#Pers	Stat. Bundesamt
Hot water consumption (α)	kWh	0.20 · Electricity Consumption	Stat. Bundesamt
Nr. of EVs/household size distr.		Appendix C	

Table 2: Sources of technical parameters

4.3. Household Classification

To derive load profiles at the transformer level, we randomly draw the characteristics of 166 households with respect to sociodemographic and building parameters. These profiles aim to reflect the heterogeneity of the sample population while closely representing local load patterns associated with specific transformer capacities projected into the future.

The 166 households consist of three categories (figure 2). The first category contains non-technological households that do not possess advanced energy technologies; rather, they may own an EV, operated without consideration of price signals or grid conditions. This category serves as a baseline without assets and load shifting opportunities. The second category involves technological but non-flexible households, which own a bundle of technologies including heat pumps, EVs, PV systems, and batteries but do not optimize their energy usage according to electricity costs based on wholesale market prices. For instance, households with PV systems directly sell excess PV production to the grid without engaging in energy storage. Finally, the third category includes technological and flexible households, which are fully equipped with the same bundle of technologies as the second category. However, these households actively participate in demand-side flexibility by adjusting their energy usage to reduce their energy bills or even make profits out of electricity trading.

4.4. Scenarios

Our Scenarios are designed to identify the impact of household's technology adoption and flexibility on transformer load - in policy environments of no intervention, grid tariffs and curtailment. Therefore, we vary the level of flexibility provision across the scenarios, depending on household technological equipment. The aim of this approach is to isolate the effect of flexibility behavior, allowing for a clearer understanding of how varying levels of demand-side participation influence transformer load. These scenarios focus on rural and semi-urban households connected to transformers representing the capacities available in Luxembourg's distribution grid. Table 3 outlines six scenarios for the years 2030 and 2040, each designed to analyze how different levels of technology adoption and flexibility provision affect transformers.

Parameters	**2030 Base**			**2040 Base**		
	0%	50%	100%	0%	50%	100%
Share of Technological HHs		30%			60%	
Share of flexible (absolute) households	0%	15%	30%	0%	30%	60%
Cars (# of cars per HH)	0.75	0.75	0.75	1.5 (1.0)	1.5 (1.0)	1.5 (1.0)
Share of Heat Pumps, PV, Battery		30%			60%	

Table 3: Description of the Base scenarios

In Scenario Base 2030 - 0%, (table 3) 30% of households are "technological", yet, none of these households is flexible in their energy usage, meaning they do not provide any flexibility to align with electricity costs. Scenario Base 2030 - 50% maintains the same 30% share of technological households but introduces flexibility, with 15% of all households acting flexibly by shifting consumption toward periods of lower prices (figure 4). Scenario Base 2030 - 100% extends scenario Base 2030 - 50% by increasing the share of flexible households to 30%, meaning that all technological households now fully participate in flexibility provision. This scenario explores the impact of a higher share of flexible households on transformer load, with all three scenarios having the same technological appliances, including average car ownership and the absence of a grid tariff.

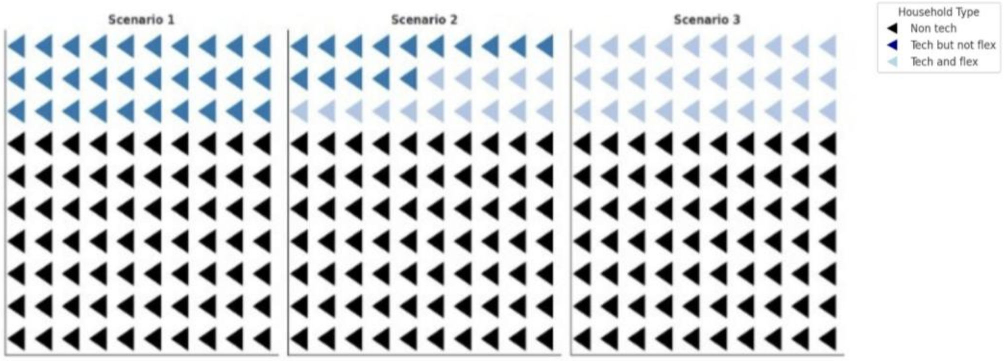


Figure 4: Household Classification in 2030 Scenarios

For the 2040 scenarios (Table 3), also shown in figure 5, the share of technological households increases to 60%. Starting with scenario Base 2040 - 0%, none of the households provide flexibility. Scenario Base 2040 - 50% introduces 30% flexibility among technological households, which corresponds to 50% of the technological households engaging in flexible behaviour, while maintaining the same technology adoption rates and EV ownership as scenario Base 2040 - 0%. scenario Base 2040 - 100% builds on the previous scenario by increasing the percentage of flexible households to 60%, meaning again that all technological households act flexibly.

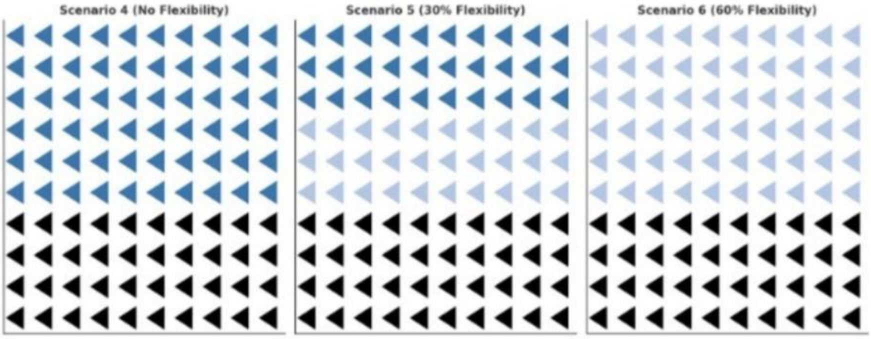


Figure 5: Household Classification in 2040 Scenario

Each of the 0-50-100% flexibility scenarios is exposed to six policy experiments: 2030 no policy, 2040 no policy, 2040 grid tariff on imports, 2040 grid tariff on imports and exports, 2040 curtailment ± 1 hour around the hours that violate reference transformer capacities in 2040 no policy scenarios and 2040 curtailment ± 3 hours. So, in a second step we can hold flexibility levels constant and analyze the impact of the policies on transformer load levels and the necessity to expand the respective capacities with welfare implications. To this end, we solved the optimization problem (1) - (16) with CPLEX for 166 households, configured as described in section 4.3 and exposed to the respective policies - details will be explained in the following sections. This analysis is conducted for each transformer separately. Therefore, we describe the details of the transformer heterogeneity in the next section.

4.5. Infrastructure: Transformers

After deriving aggregated load profiles at the transformer level for each scenario, we evaluate how transformers are affected. This assessment will provide insights into the extent to which varying levels of household flexibility in the future will require additional transformer capacity to operate safely, according to a - assumed representative - distribution of transformer capacities. Our dataset includes 7 transformers (aggregated from 14 smaller units; table 4) - 4 in rural and 3 semi-urban areas - with aggregated consumption capacities ranging from 504 kW to 1008 kW (453,6 kW to 907.2 kW for production).

Aggregated Topology	Type	Number of Households	Consumption kW	Production kW	Consumption kW/HH	Index
1	Rural	166	824	741.6	5.0	1.00
	a	109	504	288	2.9	
	b	57	320	453,6	8.8	
2	Rural	174	840	756.0	4.8	0.97
	a	80	320	288	4.0	
	b	54	200	180	3.7	
	c	40	320	288	8.0	
3	Rural	239	824	741.6	3.4	0.69
	a	157	504	453,6	3.2	
	b	82	320	288	3.9	
4	Rural	231	640	576.0	2.8	0.56
	a	106	320	288	3.0	
	b	125	320	288	2.6	
5	Semi-urban	170	504	453.6	3.0	0.60
6	Semi-urban	133	704	633.6	5.3	1.07
	a	87	200	180	2.3	
	b	46	504	453,6	11.0	
7	Semi-urban	252	1008	907.2	4.0	0.81
	a	143	504	453,6	3.5	
	b	109	504	453,6	4.6	

Table 4: distribution of transformer capacities and connected number of households; We will call transformer nr1. Reference transformer. Grey shaded transformers represent the aggregate of real transformers.

We use transformer topology 1 as reference and simulate the loads of these 166 households. To relate this special case to the other 6 transformer topologies and estimate the transformer utilization and investment requirements, we could recalculate the load curves for the respective household numbers per transformer as in table 4. Instead, to reduce the computational burden we simulate only the load curves for the 166 households and scale the transformer capacities to the same consumption capacity per household equipment as the reference case of 5,0 kW/household. We can then conclude the utilization of the other transformers.

As a reference of the current situation, we present in figure 6 transformer load duration for 5 of the 7 transformers in 2024 (data received from CREOS). There is currently little injection and transformer capacities are barely used with peaks leaving at least 20% until the capacity limits of the transformers. We will in the next section see how this is expected to change in 2030 and 2040 with more technological respectively flexible households. To make the limitations of transformers more transparent we will develop a reinvestment indicator in the next section.

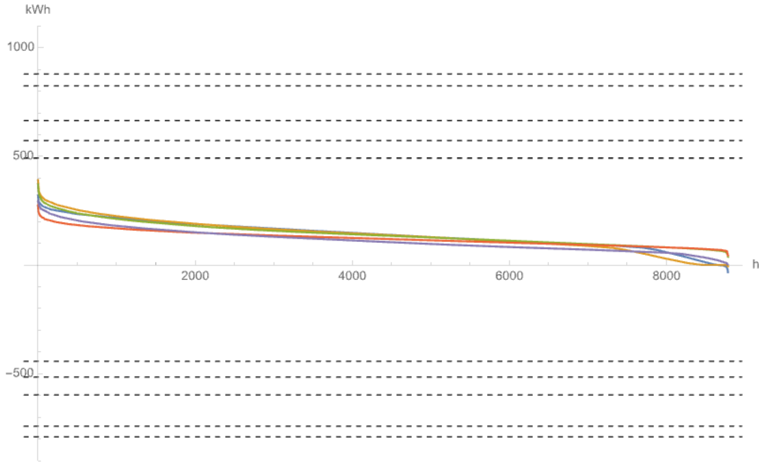


Figure 6: 2024 transformer load duration: This figure shows the load duration curve of a transformer over one year, illustrating different load levels across various scenarios. Data source: CREOS.

As we assume the grid operator needs to take care for safe operation of the low voltage grid, he will have to invest into new capacities once installed transformer capacities reach their limit - if further approaches fail like curtailment and incentives to shift load. Transformers are considered overloaded if the load reaches 100% of the capacity at least for one hour. In this case an additional transformer will have to be added to the grid until no transfer is overloaded any more - consider that the equipment per household varies significantly - meaning that once transformer nr 1 needs to be extended by one unit transformer nr 4 needs an update of two units of the installed capacities already. We will now determine the capacity utilization and investment needs for each of the policy experiments.

5. Base Scenarios: Energy transition without policy

When the energy transition proceeds, we expect more households to acquire assets to reduce their environmental impact. In our terms more households become technological. We now derive aggregate transformer load over a year in 2030 and 2040 and whether transformer capacities are sufficient to meet this demand. Thus, we present load profiles in relation to price variations, and we examine how these profiles under different levels of flexibility provision contribute to transformer overload as defined in the last section.

5.1. Base scenario 2030

Figure 7 displays households' net electricity imports on the transformer level for an average weekday in 2030 with varying shares of flexible households. The x-axis represents the hour of the day, while the y-axis denotes power imports (kW). The blue line depicts scaled TYNDP electricity prices of 2030. The red lines represent scenarios of household consumption patterns - dotted curves 0% dashed 50% and solid curves 100% of flexible households.

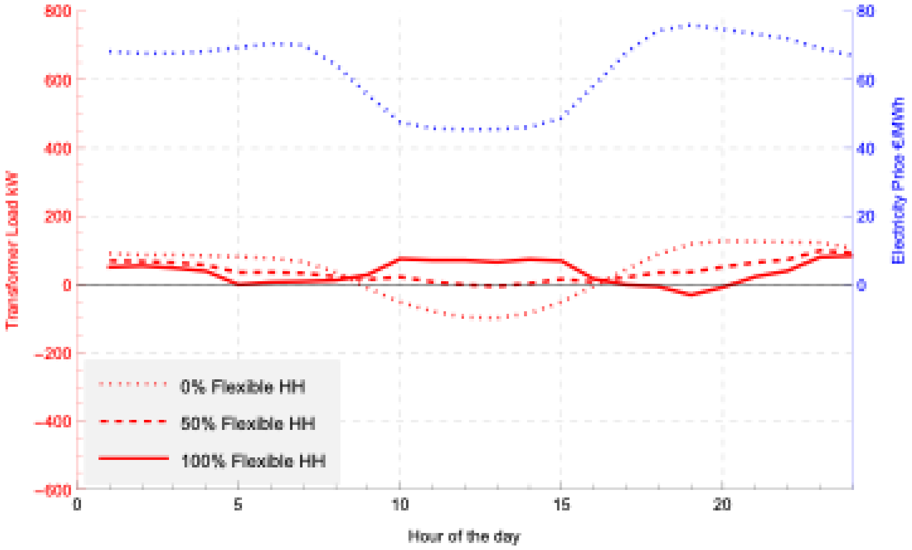


Figure 7: Average Weekday Load Duration in 2030.

In the baseline scenario - without flexibility - household’s load follows a (flat) classical duck curve with electricity exports during the day due to PV generation and a strong increase to imports at 6pm, peaking at 8 pm, staying constant until 9 am and then decreasing to net exports until a peak at 3 pm and so forth. This pattern is well explainable from the perspective of the equipment of households with PV delivering exports during the day and EVs charging once household members return from work adding imports to the standard load profile (H0).

However, when flexibility is gradually introduced, as shown by the dashed and solid lines, clear shifts in consumption behavior become apparent. Now, during low-price periods, particularly from around 9:00 to 16:00, flexible households reduce their exports to charge EVs or batteries and operate heating devices at cheaper rates. This leads to visible dips in the red curves, indicating increased demand. Conversely, when prices rise in the evening (after 17:00), the flexible households reduce their imports relying on stored energy - also exporting to take advantage of the higher prices. This behavior is evident in the flattened and lower evening import levels shown in the solid red curve - the duck curve inverts.

The overall relationship illustrates the intended effect of price signals, encouraging households to shift their demand to off-peak, low-price hours. However, the solid red curve also highlights a potential challenge associated with high levels of flexibility. As flexibility provision increases to 100%, the import pattern becomes more extreme and synchronized. While this consumption pattern reduces load in the evening, it creates new peaks in the middle of the day when many households simultaneously increase imports. This phenomenon, commonly referred to as overcorrection or market-based arbitrage (“ping-pong flexibility”), presents the risk that poorly coordinated flexibility can destabilize grid operations rather than smooth demand patterns.

This pattern is overlayed with seasonal and short-term effects like price peaks due to intermittent renewable generation or temperature changes leading eventually to peaks in consumption and generation - offering trading opportunities. To get a more comprehensive picture of the transformer load we analyze in Figure 8 load duration over a year - comparing for 0-, 50 and 100% flexibility provision in 2030. The x-axis represents the number of hours (from 0 up to approximately 8760, which covers all hours of the year), while the y-axis shows the power levels (in kW) that transformers experience (on average) during these hours. Meanwhile, the black horizontal dashed lines represent the scaled transformer capacity limits.

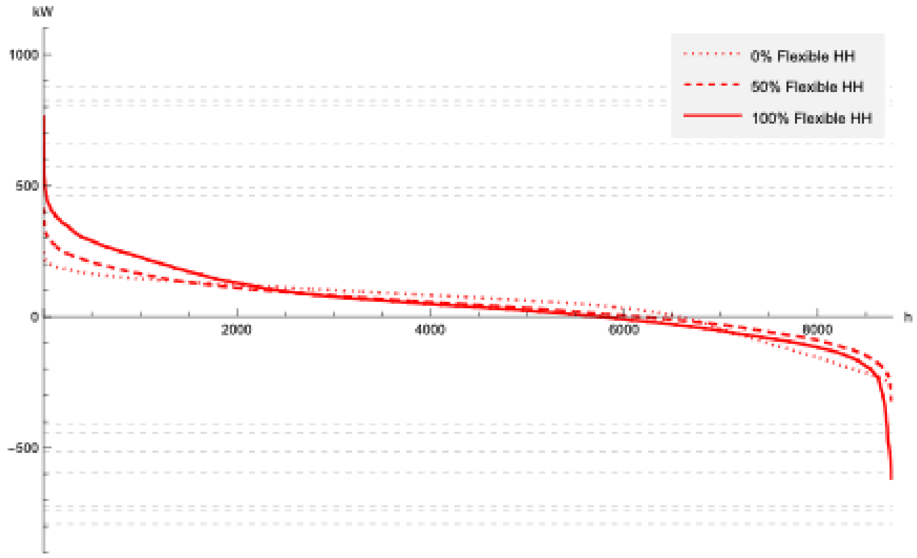


Figure 8: Load duration on transformer level 2030.

Most of the year, particularly under no flexibility and limited flexibility scenarios (dotted and dashed red lines), transformer load levels remain well within the capacity limits, as indicated by the horizontal dashed black lines. However, a notable issue emerges under the maximum flexibility scenario (solid red line). In this case, the load curve exceeds some transformer capacities, particularly for transformers with capacities below 1000 kW. These exceedances occur at the leftmost part of the curve, which represents the coldest periods of the year when household heating demand is at its highest.

These findings are confirmed by the analysis of the analysis of transformer overload (table 5). While there is no overload in the scenarios with 0% and 50% flexible Households, transformers 1-4 reach the transformer capacities for 3 to 74 hours, requiring an extension of the respective capacities by 4 transformers - on average 0.57 transformers required per site.

2030 Base Scenario

Transformer load (h) relative to capacity (100%)	**100% Flexibles** Transformers						
	1	2	3	4	5	6	7
X > 100%	74	54	23	3			
# Transformer required	1	1	1	1	0	0	0
Av. Transformers re.	4/7 = 0.57						

Table 5: 2030 Base Scenario For each of the 7 transformers we show how long the indicators violate the respective limits and conclude the investment requirements for each transformer; The new transformer will never be overloaded.

We conclude that until 2030 only in the high flexibility scenario there is already so much trading activity to risk transformer overload and requiring investment in four (out of seven) transformers. Therefore, although the problem is not yet systemic in 2030, it is already evident at the local level and signals that targeted interventions and tariff designs will become essential as household flexibility increases.

5.2. Base Scenario 2040

We would expect that the ping-pong flexibility leads to even more investment requirements in 2040 as the share of technological households in the 166 households increases and therefore the absolute number of flexible households (even if the share of flexibles remains constant) - while prices decline slightly on average.

Indeed, in figure 9 the weekday average load profiles for the year 2040, show a more expressed duck curve for the non-flexible scenario with exports of around 300 kWh at 12:00 and imports of 200 kWh at 19:00 - twice the values of 150 and 100kWh in 2030. With increasing share of flexible households - again - ping-pong flexibility sets in inverting the duck curve to imports of 400 kWh at 2pm and exports of 300 kWh at 7pm up from 50 kWh in 2030.

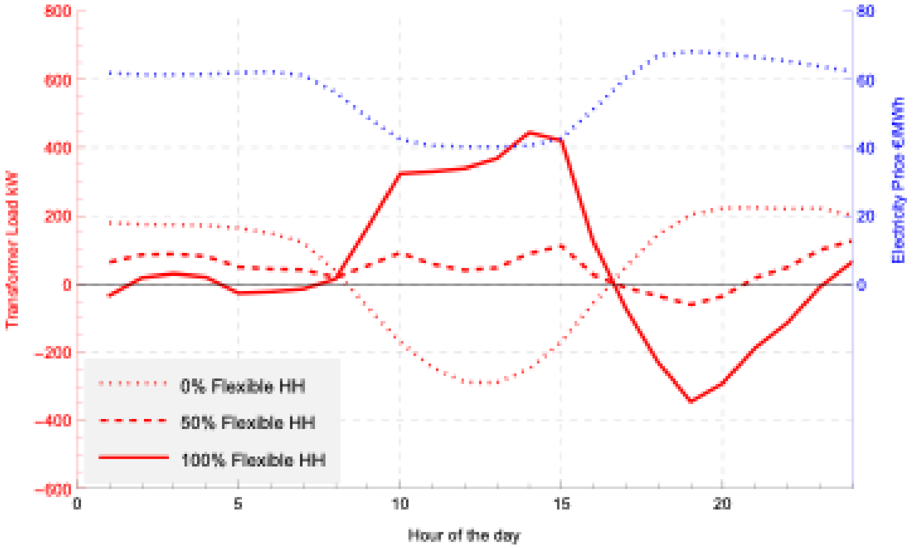


Figure 9: Average Weekday Load Duration Base scenario 2040

Thus, during hours of low electricity prices, particularly between 12:00 and 15:00, household imports surge as users charge storage assets such as EVs or batteries. When prices rise sharply in the evening hours, households significantly reduce imports, sometimes resulting in negative net demand, which reflects exports to the grid. This creates a highly inverse relationship between prices and imports, with consumption peaks occurring when prices are low and valleys or even export peaks when prices are high. This behavior aligns perfectly with arbitrage logic: buy cheap (charge/store/import) and sell/avoid consumption when expensive. Figure 9 shows that market-based arbitrage can, increase grid volatility. It is no longer system-friendly flexibility, which without control mechanisms, requires grid investment.

On top of this more expressed duck curve inversion (turtle curve) from increased flexibility rare events will now offer even more trading violating the transformer capacities. This can be deduced from load duration in figure 10. In the case of no flexibility (red-dotted line), overload conditions are present however, overloading emerges only towards the far-right of the load duration curve, specifically after hour 7500 of the year, where the dotted red line crosses the transformer capacity threshold. The pattern changes significantly when flexibility is introduced. In the limited flexibility scenario (50%), the dashed red line crosses the transformer operates above the capacity threshold for an increased number of hours compared to the 'No flex' scenario. Also, it operates below the lower scaled capacity threshold for a more extended number of hours, indicating increased periods of negative overloading.

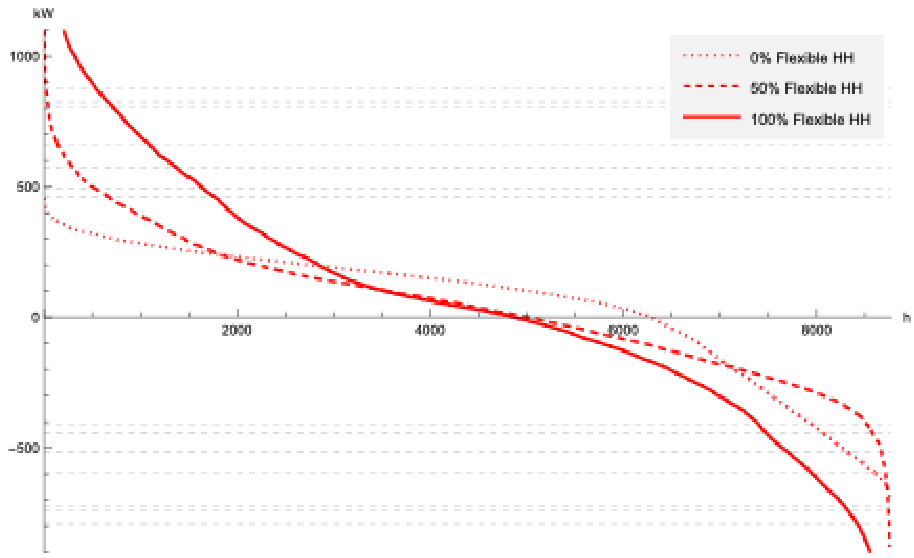


Figure 10: Load Duration on Transformers Base scenario 2040

The situation becomes even more serious under the maximum flexibility scenario (100%), represented by the solid red line. In this case, the transformer operates above the scaled capacity thresholds for more hours compared to other scenarios. Additionally, it operates below the lower scaled capacity threshold for a longer duration, indicating prolonged periods of households feeding electricity back into the grid due to coordinated consumption patterns driven by price signals. Thus, showing how transformer overload can be heavily driven by widespread market arbitrage.

Which pattern causes capacity violations? The set of histograms shown in figure 11 breaks down import and export overloading hours per year across scenarios. In each row, the left graph depicts the distribution of overloading hours across the year, while the right graph shows the distribution over a typical day. In the 50% flexibility case (top row), while overloading hours are relatively limited, they still show noticeable occurrences, especially around winter hours (later in the year and during evening time). However, in the maximum flexibility case (bottom row), import-related overload hours become widely spread across the year, amounting to an estimated 500-700 hours annually, while export-related overloading becomes even more pronounced, with approximately 900-1000 hours per year. Notably, export overloading is highly concentrated during evening peak price periods (roughly between 16:00 and 22:00) and import overloading occurs when prices are low (between 10:00 and 15:00), which aligns with typical household energy arbitrage strategies.

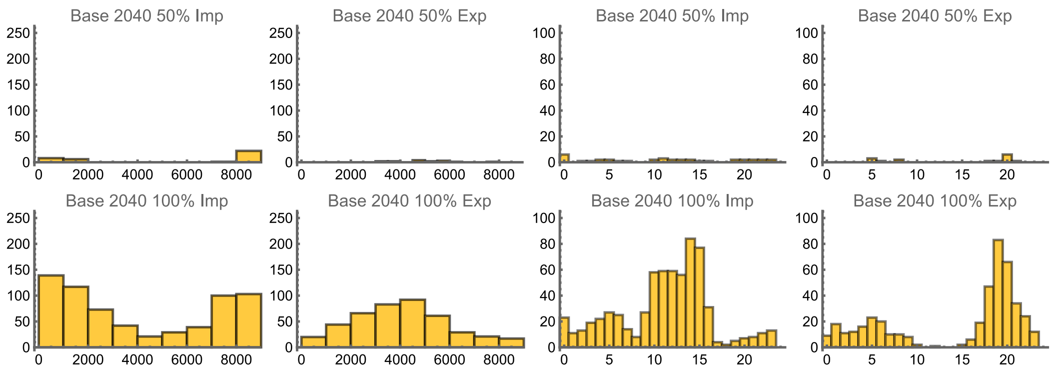


Figure 11: Distribution of the hours of transformer overloads in 2040 by: imports and exports, over the year and over the day and 50 and 100% flexibles in the base 2040 scenario.

A closer look (table 6) into the transformer utilization in table 6 confirms the pattern: the 4 smallest transformers now reach their 100% limit for 788 hours a year - requiring 4 new transformers even in the 0% flexibility case.

2040 Base Scenario

Transformer load (h) relative to capacity (100%)	**0% Flexibles** Transformers 1	2	3	4	5	6	7
X > 100%	788	689	463	142			
# Transformer required	1	1	1	1	0	0	0
Av. Transformers re.	4/7 = 0.57						

Table 6: 2040 scenario: For each of the 7 transformers we show how long the indicators violate the respective limits and conclude the investment requirements for each transformer; empty cells are 0.

With 50% flexible households all transformers are overloaded with three transformers even requiring a second transformer for less than 15 hours a year - barely an economic investment, which leaves out room for policies reducing the load during these hours at least. On average 1.43 new transformers are required. These numbers almost scale to the 100% flexibility case: on three sites 4 new transformers a required to avoid overloading, with at least 2 transformers per site. On average three new transformers are required per site.

2040 Base scenario

Transformer load duration (h) relative to capacity (100%)	**50% Flexibles** Transformers 1	2	3	4	5	6	7	**100% Flexibles** Transformers 1	2	3	4	5	6	7
200% > X > 100%	876	696	388	180	65	52	25	2383	2373	2144	1732	1149	1051	837
300% > X > 200%	15	9	5					611	478	271	142	51	45	30
400% > X > 300%								104	69	37	4			
X > 400%								13	6	1				
# Transformer required	2	2	2	1	1	1	1	4	4	4	3	2	2	2
Av. Transformers re.	10/7 = 1.43							21/7 = 3						

Table 7: 2040 scenario: For each of the 7 transformers we show how long the indicators violate the respective limits and conclude the investment requirements for each transformer; empty cells are 0.

What is the reason for these effects? The analysis of electricity consumption over the year by purpose and household type (table 8) reveals a lot: In the 0% flexibility scenario shown, the values reflect household behaviour that is entirely unresponsive to price signals meaning that EVs are charged and appliances are used according to static routines, without any attempt to optimize for electricity costs. For general electricity load (appliances, light, etc.), households consume around 3.300 kWh.

	2040 0% flexibles		2040 50% flexibles			2040 100% flexibles	
Electricity consumption:	Non-tech.	Tech. non-flexible	Non-tech	Tech. non-flexible	Flexible	Tech. non-flexible	Flex.
Load	3.358	3.181	3.282	3.013	3.390	3.344	3.197
Heating	0	8.432	0	8.466	9.704	0	9.740
Hot Water	0	254	0	240	303	0	284
EV	1.014	928	944	922	313	1.013	698
PV	0	-11.556	0	-11.556	-11.556	0	-11.556
Losses	-11	-11	-11	-10	-11	-11	-11
Net Import	4.361	1.228	4.216	1.075	2143	4.346	2352

Table 8: Average annual energy consumption in kWh by purpose and household type.

Non-technical households have no electric heating or hot water consumption, reflecting the absence of relevant technologies. In contrast, technical but non-flexible households consume 8.432 kWh for heating and 254 kWh for water heating. EV consumption is moderate, with non-technical households using 1.014 kWh and technological but non-flexible households using 928 kWh. As there is no price responsiveness, charging follows static patterns. PV generation is not available in non-technological households, while technical but non-flexible households produce 11.556 kWh from rooftop PV systems, although this energy is not used flexibly. As a result, net electricity imports remain high, at 4.361 kWh for non-technological households and 1.228 kWh for technological but not flexible households.

Interestingly, by heating flexibly electricity consumption increases by 15% (from 8.466 kWh to 9.740 kWh) due to an increase of the indoor temperature by 1.7°C from 20.04°C (technological nonflexible) to 21.76°C (flexibles). Thus, flexible households increase indoor temperature to take advantage of the building as energy storage that enables a reduction in energy consumption during low-price periods. The building temperature serves as a state of charge to make use of the building as storage, thereby accepting an increase in energy consumption (higher temperature) and losses (also apparent in other heat storages). Similarly, hot water consumption increases for flexible households to 284 kWh respectively 303 kWh from 240-254 kWh for the same reason. This behaviour shows that while households respond economically to price signals, the resulting increase in total energy use makes heating demand effectively price-elastic, due to an increase in energy consumption, as storage becomes profitable. Superficially, energy efficiency decreases due to acting flexibly.

EV consumption from home charging differs only slightly for technological but nonflexible households (around 1000 kWh). However, in flexible households it decreases to 300 kWh in the 50% flexibility case as the flexible households do not maximize their SOC, instead they take advantage of arbitrage and cheaper inhouse charging opportunities (20Cents/kWh usage fee on charging not at home).

PV production is unaffected at 11.556 kWh for all households. However, the net electricity import shows a significant shift: technological but non-flexible households reduce their imports from 4.000 kWh to 1.000 kWh due to PV generation. Flexible households consume additional 1000 kWh as they refrain from expensive charging outside. This transition highlights the combined benefits of PV generation, load shifting, and V2G technologies in flexible energy management.

As household flexibility increases, energy consumption patterns shift significantly, with more consumption occurring during low-price periods and greater reliance on technologies such as preheating and thermal storage. This behavior enables households to engage in economic arbitrage by aligning usage with favorable electricity prices, particularly evident through increased PV utilization and vehicle-to-grid (V2G) discharge during peak-price hours. While flexible households consume slightly more energy for heating and hot water due to storage losses and pre-conditioning. Ultimately, full flexibility transforms households from passive consumers into less energy efficient active market participants, enabling cost savings and revenues from trade.

As outlined in the previous chapters, household electricity demand and supply are influenced by technical equipment, market conditions (wholesale prices), climatic variables (temperature and solar capacity factor), and behavioral factors (H0). The climatic factors, in turn, affect wholesale prices. However, all of these interactions occur in a highly nonlinear manner. Therefore, a simple relationship between transformer load and a linear combination of these parameters is not to be expected. And indeed, the model calculations cannot be successfully approximated linearly.

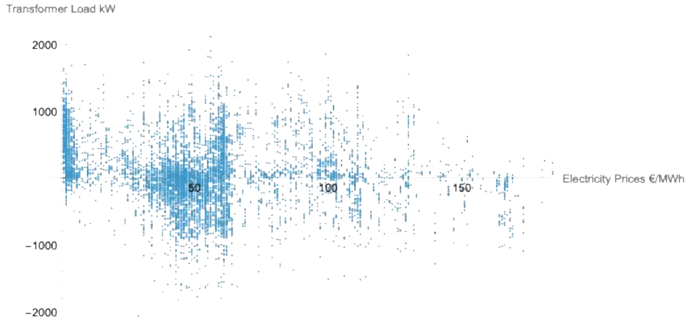


Figure 11a: Transforer Load vs. electricity prices 2040 DE Weather year 2009

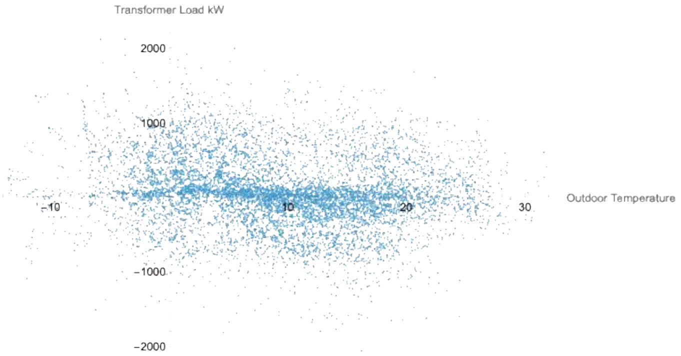


Figure 11a: Transforer Load vs. outdoor temperatures

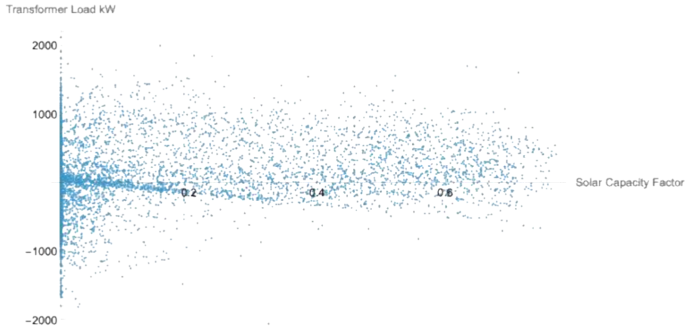


Figure 11a: Transforer Load vs. solar capacity factors

In the following three figures (11 a-c), we compare transformer load and wholesale prices (11a), temperatures (11b), and solar capacity factors (11c) for a scenario with 100% flexibility in 2040. None of the figures suggest a global linear relationship. At negative prices, we observe high export levels (11a), but in the price range between €25 and €75, the data forms an indeterminate cloud of import and export levels. No clear relationship is observable with temperature, while low PV generation tends to coincide with higher import levels.

Therefore, the correlation coefficients are low: -0.16 (prices), -0.14 (temperature), and 0.23 (capacity factor). A linear regression of transformer load using all three parameters yields a similarly modest r-squared of 0.3 - insufficient to build a reliable load forecast upon. The inclusion of more parameters could show better results especially if combined with nonlinear regression approaches.

One more comment on the flexibles' ability to generate revenues: Non-flexible households pay about €600 per year (Appendix A), while technologically flexible households receive around €177. In other words, by being flexible they gain roughly €800. In today's context, that sounds like a surprisingly large amount. The explanation is that non-flexible households charge their vehicles immediately whenever a charging station is available — which often means charging in the evening, when electricity prices can be high. Flexible households, on the other hand, make optimal use of their assets. They may manage up to three cars, charging them at midday and discharging in the evening, take advantage of longer-term temperature fluctuations, and generate PV electricity that they can likely sell at higher prices in the evening.

In addition, electricity price peaks in the 2040 TYNDP scenario are far higher than today. With the massive share of renewables expected in 2040, the system is no longer driven simply by "time of day" pricing — it becomes heavily dependent on renewable generation patterns. In short: this is a fundamentally different world, and the €800 figure cannot be compared to what €800 means today.

6. Mitigation Strategies I - Grid Tariffs

In the previous section we have seen that in 1/3 of the less well-equipped regions transformer capacities are insufficient by 2030 (with 100% flexibility) already and that this issue extends to on average three new transformers per site by 2040 - in case of maximal flexibility. So, the question arises what can be done to safe the transformers from overloading. We will in the next three sections introduce policies to mitigate the increased willingness to trade and reduce ping pong flexibility: The first approach involves a grid tariff structure designed to regulate household electricity consumption and exports.

Luxembourg's network usage tariff came into effect on January 1, 2025. We have already introduced our interpretation of this tariff in the model description; however, it is worth mentioning the original details: The tariff introduces a power (consumption)-based component. Residential and business customers are assigned a discrete reference power level (in kW) {1,2,4,7,12,17,27,43,70,100} based on their past 12 months' consumption patterns. The network fees include the fixed monthly charge tied to this reference power, the volumetric fee based on actual consumption, and the exceedance fee for consumption beyond the reference power. The reference level is chosen to minimize the customer's bill. In our model approach we chose the subscription level, exceedance and consumption simultaneously. That enables us to choose in a consistent (long run) way.

Grid Tariff			
Penalty	€/kWh		0.1139
Grid Base	€/HH		60
		Old	New
Capacity	€/kWy	0.01	24.46
Consumption markup	€/kWh	0.0759	0

Table 9: Sources of Parameters Included in the Model; data based on CREOS

We now check whether this - already in place tariff - resolves the need to extend transformer capacities - even though it also discourages e.g. charging batteries to serve the electricity markets. In figure 12 we see the load duration curve of the import grid tariff. Indeed, imports are now a lot flatter than under unconstrained consumption in 2040. However, the tariff does not restrict electricity exports, but that's precisely its drawback: the unrestricted export overloads the transformers, so the need for new investments remains almost as high as in the base scenario (see table 10).

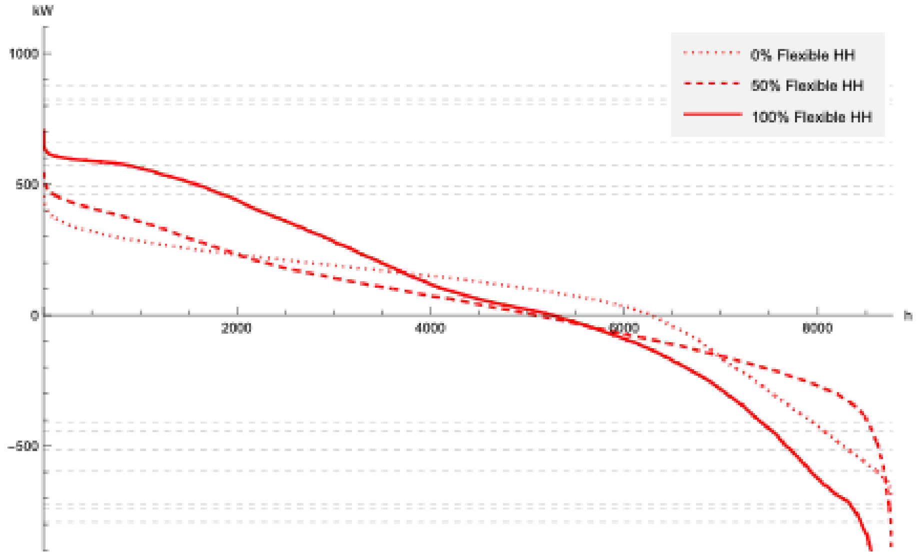


Figure 12: Load duration of transformers under export grid tariff.

2040 Export Grid Tariff

Transformer load duration (h) relative to capacity (100%)	**50% Flexibles**							**100% Flexibles**						
	Transformers							Transformers						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
200% > X > 100%	336	219	131	71	26	18	8	2896	2628	1813	719	393	359	292
300% > X > 200%	3	2	1					175	154	132	103	43	35	21
400% > X > 300%								85	62	28	2			
X > 400%								7	3	1				
# Transformer required	2	2	2	1	1	1	1	4	4	4	3	2	2	2
Av. Transformers re.							10/7 = 1.43							21/7 = 3

Table 10: 2040 Grid Tariff - For each of the 7 transformers we show how long the indicators violate the respective limits and conclude the investment requirements for each transformer.

The success of the import grid tariff to limit import peaks provides the intuition, that also imposing it on exports will finally provide a suitable reduction in transformer load. Indeed, table 11 shows a massive reduction in overload. Only 4 new transformers are required in the 50% flexibility case and 5 in the 100% case. So overall only 0.57 respectively 0.71 new transformers are required per site.

2040 Import and Export Grid Tariff

Transformer load duration (h) relative to capacity (100%)	**50% Flexibles**							**100% Flexibles**						
	Transformers							Transformers						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
X > 100%	421	174	18	2				3518	3134	2214	770	1		
# Transformer required	1	1	1	1	0	0	0	1	1	1	1	1	0	0
Av. Transformers re.							4/7 = 0.57							5/7 = 0.71

Table 11: 2040 Grid Tariff - For each of the 7 transformers we show how long the indicators violate the respective limits and conclude the investment requirements for each transformer.

The export tariff discourages effectively exports aimed solely at maximizing financial gains and ensures that grid usage remains balanced throughout the day. Figure 13 presents the household load profiles for 2040 after the introduction of the new grid tariff mechanism.

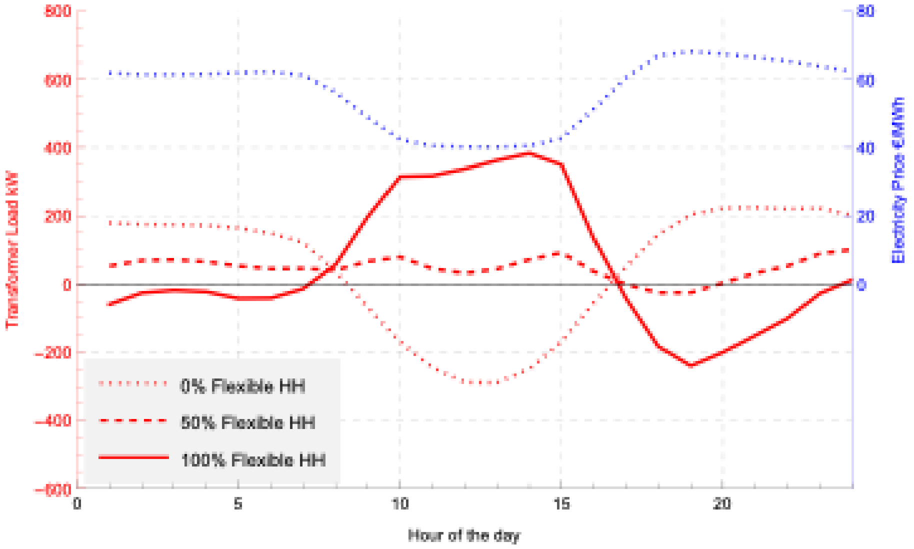


Figure 13: Average weekday after implementing an import and export grid tariff in 2040; blue curve average electricity prices 2040.

The key observation is that unlike the basic tariff scenario of 2040, the load curves are flatter after the introduction of the new tariff schemes. Notably, during peak price periods (around 19:00-21:00), when high prices would incentivize bulk exports, the applied tariffs successfully suppress export spike by 100 kW. Likewise, imports during midday low-price periods (around 9:00-16:00) remain slightly elevated. Overall, the grid tariff discourages extreme and synchronized household responses to price signals, effectively moderating both imports and exports. This also reflects in the load duration curve that does not show large load peaks compered to figure 14.

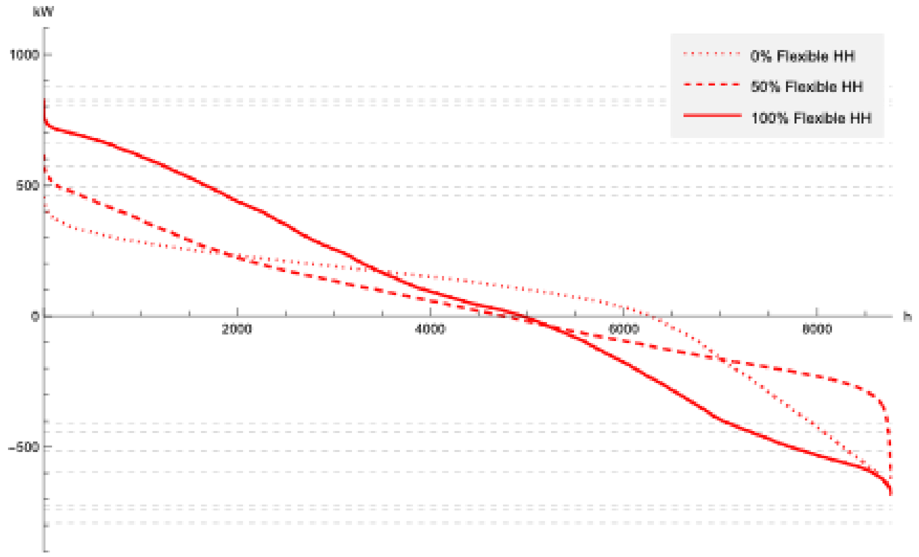


Figure 14: Load duration of transformers for import and export grid tariff.

How is the reduction in peaks achieved? We answer this question with a comparison of a specific day (hours 168 to 192) from our simulation time series of Base 2040 and import-export grid tariff in figure 15. In the base case scenario, the load curve (blue curve) hits the transformer capacity of transformer 1 from 11:00-17:00. During these hours a penalty needs to be paid for exceeding the subscription capacity k. Only flexible households react to this threshold and reduce imports, so that final consumption (orange curve) just underscores the capacities of transformer 1. So, the penalty is sufficiently high to prevent an overload of the whole transformer (including unchanged imports of non-flexible households). Implicitly as the excess fee is constant for individual capacity (k) excess, the households reduce imports proportionally to the excess - ending up with an import plateau just below the transformer capacity. Additionally, we see that a rebound occurs from 18:00 till 24:00, increasing imports.

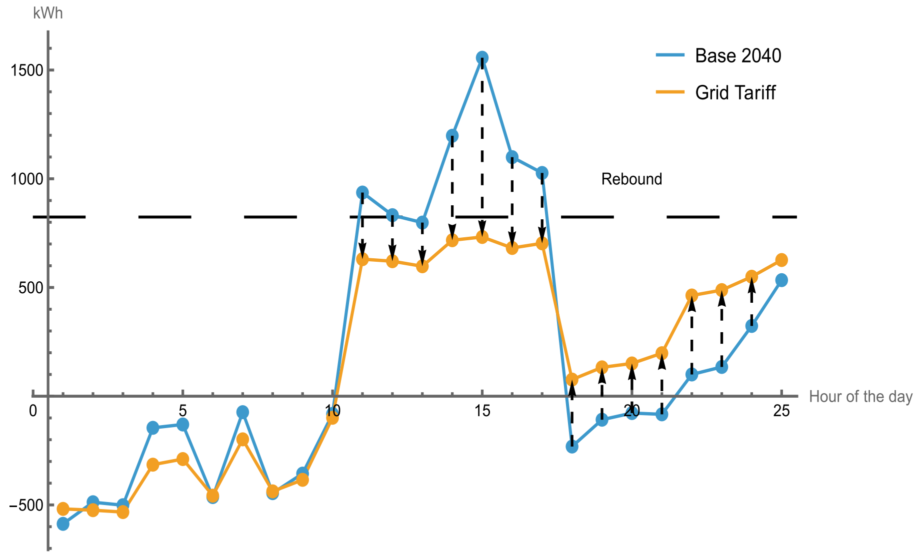


Figure 15: Comparison of the transformer load curves for hours 168-192 of the year with scenarios base 2040 and import and export grid tariff 2040. The dashed line indicates the capacity of the reference transformer nr 1.

It is worth noting that this result has been achieved with the actual parameters of the grid tariff. Principally the parameters of the grid tariff could be adjusted and even spatially be individualized to stay within local capacity constraints.

7. Mitigation Strategies II - Curtailment

The second mitigation mechanism we analyze is curtailment, which involves the controlled reduction of electricity production or consumption in response specific hours of transformer overload according to the German regulation (EEV/§14a EnWG). We implemented this strategy by reducing EV charging during curtailment hours to 5.5. kW, heat pump usage to 4.2kW and PV generation to 30% of installed capacity (Table 12). Curtailment hours are all the hours violating the transformer capacity of our reference transformer 1 in 2040 ± 1 hour - so for each hour with a capacity excess at maximum three hours are curtailed. Two consecutive hours of excess would result in 4 hours of curtailment.

Curtailment conditions		
EV	kW_e	5.5
Heat Pump	kW_e	4.2
PV		30% of capacity

Table 12: Sources of Parameters Included in the Model; Data from CREOS

With this curtailment strategy the average weekday profile does not change significantly compared to 2040 base scenario (Figure 9). This suggests that targeting curtailment only during the specific hours when transformer overloading occurs does not fundamentally alter the average consumption pattern.

The transformer overload statistic in table 13 reveals that curtailment reduces the need of new transformer from 7 to 4 with 50% flexibles from 1.43 to 1.29 and for 100% from 3 to 2.86. the policy is barely effective - based on the overload definition based on transformer nr1 capacity.

2040 Curtailment ± 1 (hour around capacity violations in the base scenario 2040)

Transformer load duration (h) relative to capacity (100%)	**50% Flexibles**							**100% Flexibles**						
	Transformers							Transformers						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
200% > X > 100%	886	707	407	162	39	26	11	2635	2522	2168	1586	816	690	496
300% > X > 200%	5	2						344	240	139	75	34	31	21
400% > X > 300%								52	44	26	1			
X > 400%								7	3					
# Transformer required	2	2	1	1	1	1	1	4	4	3	3	2	2	2
Av. Transformers re.	9/7 = 1.29							20/7 = 2.86						

Table 13: 2040 Curtailment - For each of the 7 transformers we show how long the indicators violate the respective limits and conclude the investment requirements for each transformer

To better understand the underlying drivers, Figure 16 compares the case illustration for hours 168-192 of simulated year with the load curves of the 2040 base and curtailment scenarios. Under the curtailment scheme, load reductions occur at all curtailment times (09:00-19:00) by an approximately constant amount. However, this uniform reduction is insufficient to prevent capacity exceedance, as it does not account for the magnitude of the overload. This suggests that either the curtailment windows, calibrated to transformer 1 (with a relatively high household capacity), were too generous, or the overall load reduction was inadequate. In any case, this form of curtailment represents a less targeted intervention than the grid tariff. Following curtailment, a rebound comparable to that observed under the grid tariff emerges, accompanied by a slight "prebound" (increased imports prior to curtailment to replenish electrical or thermal storage). These pre- and post-curtailment effects may overlap, potentially creating new capacity constraints.

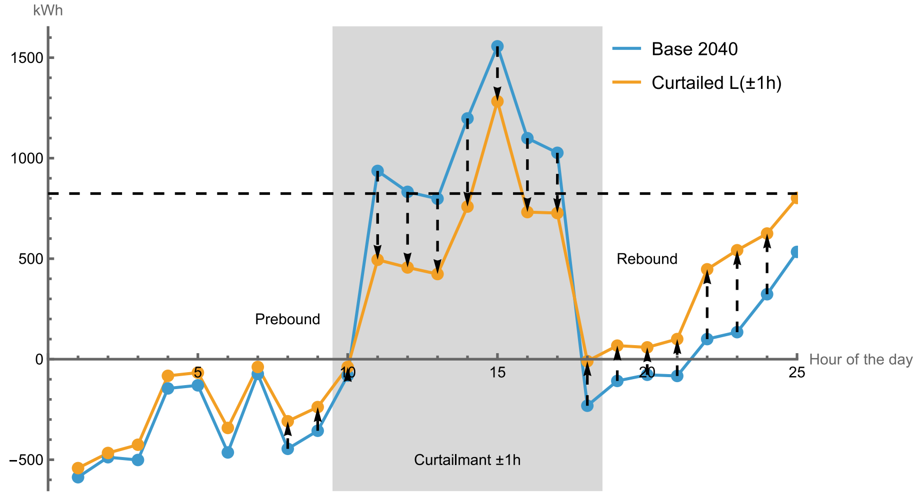


Figure 16: Comparison of the transformer load curves for hours 168-192 with scenarios Base 2040 and curtailment ±1 2040. The dashed line indicates the capacity of the reference transformer nr 1 – indicative for curtailment.

We repeated the analysis for curtailment around ± 3 hours of capacity violations of the reference transformer in the 2040 base scenario - so in total 7 hours of curtailment for a single hour of capacity violation (in contrast to three hours in the ± 1 hour case). This policy changed results only marginally with no effect on replacement requirements (table 14).

2040 Curtailment ± 3 (hour around capacity violations in the base scenario 2040)

Transformer load duration (h) relative to capacity (100%)	**50% Flexibles**							**100% Flexibles**						
	Transformers							Transformers						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
200% > X > 100%	897	718	393	159	34	26	9	2604	2446	2042	1492	754	645	466
300% > X > 200%	6	2						293	226	139	79	34	30	19
400% > X > 300%								59	44	24	1			
X > 400%								7	3					
# Transformer required	2	2	1	1	1	1	1	4	4	3	3	2	2	2
Av. Transformers re.	9/7 = 1.29							20/7 = 2.86						

Table 14: 2040 Grid Tariff - For each of the 7 transformers we show how long the indicators violate the respective limits and conclude the investment requirements for each transformer.

The case analysis in figure 17 demonstrates, that during the curtailment period from 8:00 till 20:00 the load exceeds capacity limits only between 11:00 till 17:00. While the reaction under curtailment is like the 1-hour curtailment case, the prebound is significantly higher.

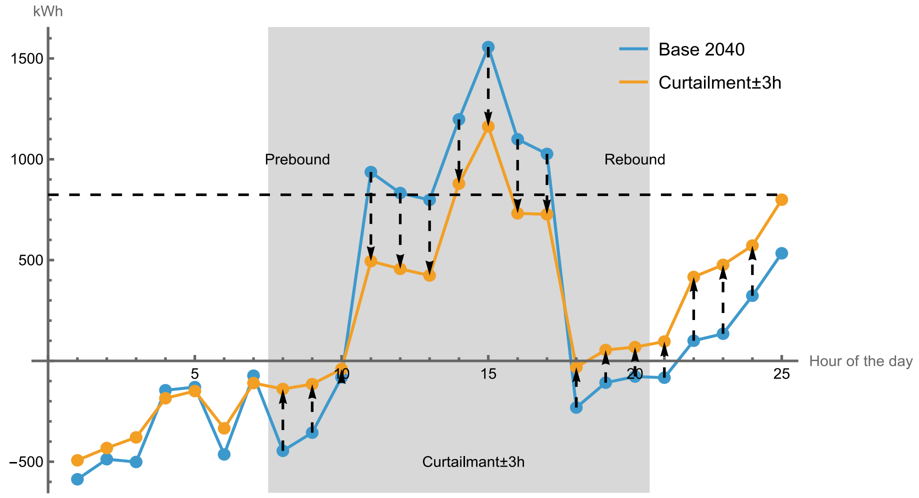


Figure 17: Comparison of the transformer load curves for hours 168-192 with scenarios Base 2040 and curtailment ±3 2040. The dashed line indicates the capacity of the reference transformer nr 1 – indicative for curtailment.

8. Cost-Benefit Analysis of Mitigation Strategies

In our scenario analyses we have already determined the required grid expansion for each scenario based on transformer overload statistics. An expansion must be carried out by the grid operator whenever a transformer is overloaded. We now deduce the costs associated with this replacement and combine them with the consumer's cost/revenues of electricity purchase to determine the cost-benefit ratio of the policy measures we examined for the households. The best cost-benefit ratio provides insights into the suitability and effectiveness of the policy measures.

Although we only simulated the electricity consumption and flexible behaviour of 166 representative households in Luxembourg, we still aim to make representative statements about Luxembourg, particularly regarding its infrastructure. We achieve this by evaluating the grid expansion based on a representative distribution of transformer capacities in Luxembourg. In this context, we scale the transformer capacity to our 166 households and evaluate each scenario's load duration curve for potential overloads.

Once the necessity has been identified to invest in new capacities, the cost of the extension needs to be determined. As we account the costs of grid extension in terms of additional transformer capacities we list only the costs of this extension - typically also the old equipment would be renewed, however, these elements are not considered as related to grid extension. In detail, the addition of a transformer to the grid would include the costs of the transformer itself, low and mid voltage equipment and if the new transformer would not fit into the old station, a new building. For simplicity we assume that each new transformer requires a new building. For the comparison of annual electricity costs/revenues and annual fixed costs we translate the overnight costs to annuities with respective lifetime of T years according to tariff regulation and an interest rate of r = 3%, using the formula: $A = P_0 \frac{(1+r)^T r}{(1+r)^T - 1}$. We find costs of 59 €/Household per year for additional transformer capacities (table 15). For 5% interest rate annuity rises to 70€/household and year.

Components	**Cost k€**	**Lifetime years**	**Annuities €**	**Annuity €/HH**
Transformer	40	35	3351	
Low Voltage equipment	20	15	1675	
Mid Voltage equipment	35	15	2932	
Building	45	45	1835	
Total	140		9793	59

Table 15: cost data of grid expansion (new transformers) in a 166-household low-voltage grid; Based on average data provided by CREOS.

We have in recent sections determined the number of additional transformers required to satisfy demand without violating transformer capacities. In table 16 these results are summarized. We can derive the grid enforcement costs in terms of an annual bill per household by multiplying the expected number of transformers with the annuity - just calculated.

Average number of transformers required to avoid overloading

	Policy experiment					
Share of flexible households	2030	2040				
	No policy		Grid tariff		Curtailment	
			Imports	Imp+exp	±1h	±3h
0%	0	0.57				
50%	0	1.43	1.43	0.57	1.29	1.29
100%	0.57	3	3	0.71	2.86	2.86

Table 16: Average number of transformers required per site to avoid overloading.

However, this does not mean that the most effective policy is also favourable in terms of welfare, as the policies reduce the ability of the households to make proper use of their assets and trade optimally according to wholesale market prices.

To consider these effects we derive average electricity supply costs from the scenarios as a further component of the welfare. To focus solely on the incentive or 'steering' effects of policy measures like tariffs or curtailment, we exclude the payments of the grid tariff but only consider its effect on via the purchase-price on the objective to minimize costs. This may sound strange at first glance, but it enables a fair evaluation of policies: guess we would wish to compare a grid tariff with a curtailment policy in terms of welfare, and we would not redistribute the payments for the grid tariff, the grid tariff would have a natural disadvantage as the revenues from the grid tariff would accumulate at the grid operators balance sheet - in contrast to curtailment. As the grid operator is not allowed to make profits the revenues need to be refunded to the customers, which justifies the approach.

Based on this approach the impact of policies for each household type are presented in table 17. We see that the difference is less than 37 €/year for 50% flexibles in 2040 and 44€/year for 100% flexibles in 2040.[14]

Average household electricity bill

	Policy experiment					
Share of flexible households	2030	2040				
	No policy		Grid tariff		Curtailment	
			Imports	Imp+exp	±1h	±3h
0%	-284	-478				
50%	-203	-229	-227	-240	-229	-231
100%	-138	-5	-3	-26	-24	-47

Table 17: Average bill at each transformer site

With the impact on grid extension and household revenues, we can net the benefits of the policies - reducing the investment requirements - with their costs - the reduced ability to trade unrestrictedly. The results of the welfare analysis are summarized in table 18.

---

[14] It becomes clear that the grid tariff needs to be considered as redistributed because otherwise it would increase the households bill, but the money will be on the grid operators balance sheet. However, the latter one must be equilibrated and redistributed to customers.

Average welfare

	Policy experiment					
Share of flexible households	2030	2040				
	No policy		Grid tariff		Curtailment	
			Imports	Imp+exp	±1h	±3h
0%	-284	-512				
50%	-203	-313	-311	-274	-305	-307
100%	-172	-182	-180	-68	-193	-216

Table 18: Average welfare at each transformer site; row maxima indicated grey - with annuity of the equipment of 59€ (3% interest rate).

The symmetric grid tariff discourages trading but increases the average bill by only 11€ (50% flexibility) and 21€ (100% flexibility) compared to no policies. However, it reduces investment cost to at most one third giving it the best cost-utility ratio of the alternatives analysed. Thus, the costs savings exceed the reduction of revenues increasing the net welfare.

The asymmetric grid tariff is not as efficient as the reduction in capacities is smaller making it only slightly better than the no policy option. Curtailment works slightly better than the asymmetric grid tariff for 50% flexibility and the worst option for 100% flexibility. Thus, the symmetric grid tariff in the parameterization provides a better balance than any other analysed policy between discouraging trade in rare cases to discard underutilized grid capacities.

Higher investment costs (e.g. induced by higher interest rate of 5%) foster the positive effect of the import and export grid tariff (table 19).

Average welfare

	Policy experiment					
Share of flexible households	2030	2040				
	No policy		Grid tariff		Curtailment	
			Imports	Imp+exp	±1h	±3h
0%	-284	-518				
50%	-203	-329	-327	-280	-319	-321
100%	-178	-215	-213	-76	-224	-247

Table 19: Average welfare at each transformer site; row maxima indicated grey. With annuity of 70€ (5% interest rate)

9. Conclusion

In recent years, European energy regulations have increasingly promoted demand-side flexibility, encouraging households to adopt technologies that respond to wholesale electricity market dynamics. This study investigates whether such flexibility is beneficial or detrimental to transmission grid stability.

Using simulations based on current socio-demographic trends and technology adoption patterns, we model household electricity demand under future wholesale market price scenarios. Our findings indicate that flexible households, equipped with control technologies can effectively act as electricity traders. They have sufficient storage capacity such that their aggregated behaviour inverts the duck curve into a turtle curve, exceeding existing transformer capacities during intermittent peaks. While these grid bottlenecks will occur only under extremely high flexibility rates in 2030, they become prevalent by 2040, with required transformer capacities reaching 2-4 times current levels, albeit for only a few hours annually.

This phenomenon is driven by revenue-optimizing households, leveraging electric vehicles and thermal storage - including building envelopes - to exploit intraday price fluctuations. This strategy results in lower EV state-of-charge and higher thermal storage levels, reducing heating efficiency by more than 15%. Nevertheless, households can generate annual revenues of €500-€800 in 2030 and 2040, respectively.

Assuming grid operators expand transformer capacity to ensure safe operation and accommodate flexible demand - financed at €60 per household annually - we evaluate grid tariffs and curtailment policies aimed at mitigating peak loads. Our analysis reveals that a symmetric grid tariff on both imports and exports, as currently applied only to imports in Luxembourg, outperforms alternatives such as unrestricted trading or curtailment as practiced in Germany in terms of welfare – consisting of grid enforcement costs plus revenues from electricity trading. This approach can yield savings of up to €110 per household annually compared to the second-best option.

While policy parameters warrant further optimization, the symmetric tariff effectively flattens peak loads to align with virtual capacity constraints (at best equal to the transformer capacity), whereas sudden curtailment merely shifts demand by a constant, mostly insufficient to prevent overloads framed by significant pre- and rebounds.

To enhance the robustness of our flexibility simulations, future research will incorporate rebound effects of flexible demand on electricity prices. As current price scenarios already reflect some degree of flexibility - evident in persistently high early-morning prices - significant deviations from our results are not anticipated. Further value could be unlocked by refining grid tariff and curtailment parameters, expanding the investment portfolio to include local storage, time-of-use tariffs, and voltage-based strategies, and integrating an extended transformer database.

10. References

Al-Ani, B., Trainer, E., Ripley, R., Sarma, A., Van Der Hoek, A., Redmiles, D. 2008. Continuous coordination within the context of cooperative and human aspects of software engineering. In Proceedings of 2008 International Workshop on Cooperative and Human Aspects of Software Engineering, pp. 1-4.

Appendix A: Detailed parameters and results by household type

Scenario 2030 Base

	2030 0				2030 50				2030 100			
	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All
HH	2.2	2.27		2.22	2.2	1.81	2.7	2.22	2.2		2.27	2.22
EV	0.45	0.55		0.48	0.45	0.43	0.65	0.48	0.45		0.55	0.48
o/m/n	0.07	0.67		0.23	0.07	0.67	0.67	0.23	0.07		0.67	0.23
tech	0.	1.		0.27	0.	1.	1.	0.27	0.		1.	0.27
flex	0.	0.		0.	0.	0.	1.	0.14	0.		1.	0.27
ID	85.02	79.3		83.5	85.02	80.48	78.22	83.5	85.02		79.3	83.5
EV1Prf	32.34	46.02		35.96	32.68	28.	42.74	33.48	31.83		29.86	31.31
EV2Prf	4.15	6.95		4.89	3.54	5.95	5.83	4.16	3.07		9.73	4.84
EV3Prf	0.	2.84		0.75	0.	0.	3.	0.42	0.		0.07	0.02
EVSto	28.11	30.23		28.67	28.11	23.33	36.52	28.67	28.11		30.23	28.67
PV	0.	10.		2.65	0.	10.	10.	2.65	0.		10.	2.65
BSto	0.	10.		2.65	0.	10.	10.	2.65	0.		10.	2.65
HSto	0.	9.		2.39	0.	9.	9.	2.39	0.		9.	2.39
WSto	0.	5.		1.33	0.	5.	5.	1.33	0.		5.	1.33
Load	3223.61	3270.91		3236.15	3249.05	2908.1	3703.7	3268.91	3230.85		3293.86	3247.55
Tmin	20.	20.		20.	20.	20.	20.	20.	20.		20.	20.
Tmax	30.	30.		30.	30.	30.	30.	30.	30.		30.	30.
U	0.37	0.16		0.31	0.37	0.16	0.16	0.31	0.37		0.16	0.31
HP	0.	3.82		1.01	0.	3.83	3.8	1.01	0.		3.82	1.01
Cost	-241.73	-399.99		-283.68	-244.37	-365.36	165.78	-202.85	-241.35		149.23	-137.82
eHeat	0.	6141.06		1627.75	0.	6167.39	7271.52	1787.71	0.		7301.74	1935.4
eWater	0.	260.79		69.12	0.	231.86	326.1	74.51	0.		292.55	77.54
	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
EVCons	323.85	404.56		345.24	339.	281.81	255.78	320.23	315.61		388.86	335.03
avTemp	19.87	20.03		19.91	21.18	20.03	22.07	21.16	22.08		22.08	22.08
SOCev1	28.01	30.11		28.56	28.	23.24	17.97	26.01	28.01		14.82	24.51
SOCbat	0.	0.44		0.12	0.	0.29	5.01	0.73	0.		4.96	1.32
SOCheat	0.	0.		0.	0.	0.	0.01	0.	0.		0.01	0.
SOCwater	0.	0.		0.	0.	0.	0.88	0.12	0.		0.85	0.23
SOCev2	28.1	30.21		28.66	28.1	23.32	3.06	24.03	28.1		3.22	21.51
SOCev3	28.11	30.22		28.67	28.11	23.33	1.34	23.8	28.11		0.74	20.86
CycEV1	21.31	31.92		24.13	25.18	31.4	104.35	36.93	27.98		86.36	43.46
CycBAT	0.	77.99		20.67	0.	54.44	200.	34.6	0.		200.	53.01
CycHEAT	0.	0.		0.	0.	0.	4.83	0.67	0.		4.89	1.3
CycWATER	0.	0.		0.	0.	0.	101.77	14.1	0.		92.59	24.54
CycEV2	4.57	18.18		8.18	3.92	19.05	17.39	7.7	4.96		18.18	8.47
CycEV3	0.	3.99		1.06	0.	0.	8.7	1.2	0.		4.55	1.2
GT-k	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
MAETemp	0.06	0.06		0.06	1.33	0.06	2.05	1.27	2.21		2.05	2.17
CourtH+	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
CourtH-	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
MeanP	0.06	0.06		0.06	0.06	0.06	0.06	0.06	0.06		0.06	0.06
Cost+GT	-194.06	-345.12		-234.1	-196.8	-321.08	121.48	-168.43	-191.85		115.91	-110.28
NetI	3536.58	-1489.54		2204.35	3577.08	-1976.48	-11.23	2377.34	3535.56		-289.92	2521.58

Scenario 2040 Base

	2040 0				2040 50				2040 100			
	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All
HH	2.3	2.13		2.2	2.3	1.96	2.29	2.2	2.3		2.13	2.2
EV	1.35	1.27		1.3	1.35	1.27	1.27	1.3	1.35		1.27	1.3
o/m/n	0.	0.52		0.31	0.	0.5	0.53	0.31	0.		0.52	0.31
tech	0.	1.		0.6	0.	1.	1.	0.6	0.		1.	0.6
flex	0.	0.		0.	0.	0.	1.	0.31	0.		1.	0.6
ID	86.55	81.49		83.5	86.55	77.92	84.92	83.5	86.55		81.49	83.5
EV1Prf	66.68	62.51		64.17	63.59	65.51	60.49	63.2	64.42		71.49	68.68
EV2Prf	34.64	30.97		32.43	35.21	30.2	33.94	33.34	37.68		29.73	32.89
EV3Prf	4.29	8.56		6.86	5.29	10.	3.94	6.27	8.15		9.36	8.88
EVSto	58.33	56.		56.93	58.33	57.14	54.9	56.93	58.33		56.	56.93
PV	0.	10.		6.02	0.	10.	10.	6.02	0.		10.	6.02
BSto	0.	10.		6.02	0.	10.	10.	6.02	0.		10.	6.02
HSto	0.	9.		5.42	0.	9.	9.	5.42	0.		9.	5.42
WSto	0.	5.		3.01	0.	5.	5.	3.01	0.		5.	3.01
Load	3357.7	3180.68		3251.06	3282.44	3012.76	3390.29	3235.97	3343.8		3196.6	3255.13
Tmin	20.	20.		20.	20.	20.	20.	20.	20.		20.	20.
Tmax	30.	30.		30.	30.	30.	30.	30.	30.		30.	30.
U	0.4	0.22		0.29	0.4	0.22	0.22	0.29	0.4		0.22	0.29
HP	0.	4.83		2.91	0.	4.87	4.79	2.91	0.		4.83	2.91
Cost	-283.23	-606.34		-477.88	-274.56	-596.68	184.25	-228.68	-281.59		177.19	-5.21
eHeat	0.	8432.28		5079.69	0.	8466.22	9703.75	5480.34	0.		9740.15	5867.56
eWater	0.	253.6		152.77	0.	240.21	303.37	164.11	0.		283.85	170.99
	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
EVCons	1014.28	928.4		962.54	944.26	921.55	312.87	743.57	1013.12		698.02	823.3
avTemp	20.04	20.04		20.04	21.24	20.04	21.76	21.04	21.77		21.76	21.76
SOCev1	58.1	55.78		56.7	58.13	56.91	27.5	48.36	58.08		27.65	39.75
SOCbat	0.	0.62		0.37	0.	0.39	4.93	1.63	0.		4.59	2.77
SOCheat	0.	0.		0.	0.	0.	0.76	0.23	0.		0.48	0.29
SOCwater	0.	0.		0.	0.	0.	0.94	0.29	0.		0.83	0.5
SOCev2	58.22	55.9		56.82	58.2	57.05	14.32	44.38	58.21		12.31	30.56
SOCev3	58.32	55.97		56.9	58.32	57.12	2.67	40.87	58.31		3.28	25.16
CycEV1	70.63	95.58		85.66	104.31	107.65	156.86	121.44	121.78		160.	144.81
CycBAT	0.	137.35		82.74	0.	149.12	200.	105.46	0.		200.	120.48
CycHEAT	0.	0.		0.	0.	0.	168.85	51.88	0.		155.26	93.53
CycWATER	0.	0.		0.	0.	0.	101.46	31.17	0.		93.36	56.24
CycEV2	48.71	68.4		60.57	58.19	62.49	82.35	66.88	73.14		74.	73.66
CycEV3	3.79	17.44		12.01	8.16	24.39	15.69	15.26	8.25		20.	15.33
GT-k	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
MAETemp	0.06	0.07		0.07	1.22	0.07	1.73	1.04	1.74		1.73	1.73
CourtH+	0.	0.		0.	17.	17.	17.	17.	413.		413.	413.
CourtH-	0.	0.		0.	24.	24.	24.	24.	885.		885.	885.
MeanP	0.06	0.06		0.06	0.06	0.06	0.06	0.06	0.06		0.06	0.06
Cost+GT	-143.94	-468.11		-339.23	-129.87	-452.09	117.43	-149.01	-131.85		112.77	15.51
NetI	4360.64	1228.39		2473.74	4215.62	1074.74	2143.02	2651.73	4345.63		2352.	3144.65

Scenario 2040 Grid Tariff

	2040G 0				2040G 50				2040G 100			
	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All
HH	2.3	2.13		2.2	2.3	1.96	2.29	2.2	2.3		2.13	2.2
EV	1.35	1.27		1.3	1.35	1.27	1.27	1.3	1.35		1.27	1.3
o/m/n	0.	0.52		0.31	0.	0.5	0.53	0.31	0.		0.52	0.31
tech	0.	1.		0.6	0.	1.	1.	0.6	0.		1.	0.6
flex	0.	0.		0.	0.	0.	1.	0.31	0.		1.	0.6
ID	86.55	81.49		83.5	86.55	77.92	84.92	83.5	86.55		81.49	83.5
EV1Prf	66.68	62.51		64.17	63.59	65.51	60.49	63.2	64.42		71.49	68.68
EV2Prf	34.64	30.97		32.43	35.21	30.2	33.94	33.34	37.68		29.73	32.89
EV3Prf	4.29	8.56		6.86	5.29	10.	3.94	6.27	8.15		9.36	8.88
EVSto	58.33	56.		56.93	58.33	57.14	54.9	56.93	58.33		56.	56.93
PV	0.	10.		6.02	0.	10.	10.	6.02	0.		10.	6.02
BSto	0.	10.		6.02	0.	10.	10.	6.02	0.		10.	6.02
HSto	0.	9.		5.42	0.	9.	9.	5.42	0.		9.	5.42
WSto	0.	5.		3.01	0.	5.	5.	3.01	0.		5.	3.01
Load	3357.7	3180.68		3251.06	3282.44	3012.76	3390.29	3235.97	3343.8		3196.6	3255.13
Tmin	20.	20.		20.	20.	20.	20.	20.	20.		20.	20.
Tmax	30.	30.		30.	30.	30.	30.	30.	30.		30.	30.
U	0.4	0.22		0.29	0.4	0.22	0.22	0.29	0.4		0.22	0.29
HP	0.	4.83		2.91	0.	4.87	4.79	2.91	0.		4.83	2.91
Cost	-283.23	-606.34		-477.88	-274.56	-596.8	146.51	-240.32	-281.59		142.16	-26.32
eHeat	0.	8432.28		5079.69	0.	8466.22	9682.71	5473.87	0.		9713.42	5851.46
eWater	0.	253.6		152.77	0.	240.21	300.78	163.31	0.		281.7	169.7
	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
EVCons	1014.28	928.4		962.54	944.26	921.51	32.88	657.54	1013.12		366.72	623.72
avTemp	20.04	20.04		20.04	21.32	20.04	21.86	21.11	21.87		21.83	21.84
SOCev1	58.1	55.78		56.7	58.13	56.91	28.59	48.69	58.08		29.23	40.7
SOCbat	0.	0.62		0.37	0.	0.43	4.7	1.57	0.		4.65	2.8
SOCheat	0.	0.		0.	0.	0.	0.74	0.23	0.		0.34	0.2
SOCwater	0.	0.		0.	0.	0.	0.87	0.27	0.		0.77	0.46
SOCev2	58.22	55.9		56.82	58.2	57.05	13.67	44.18	58.21		12.28	30.54
SOCev3	58.32	55.97		56.9	58.32	57.12	2.52	40.82	58.31		3.21	25.12
CycEV1	70.63	95.58		85.66	104.52	109.59	156.86	122.1	120.45		160.	144.28
CycBAT	0.	137.35		82.74	0.	150.72	200.	105.94	0.		200.	120.48
CycHEAT	0.	0.		0.	0.	0.	159.87	49.12	0.		145.	87.35
CycWATER	0.	0.		0.	0.	0.	94.11	28.91	0.		86.23	51.95
CycEV2	48.71	68.4		60.57	48.	63.03	82.35	62.99	47.58		74.	63.49
CycEV3	3.79	17.44		12.01	4.22	24.49	15.69	13.73	5.88		20.	14.39
GT-k	0.	0.		0.	6.57	6.24	6.92	6.58	6.8		6.86	6.84
MAETemp	0.06	0.07		0.07	1.31	0.07	1.84	1.11	1.84		1.8	1.82
CourtH+	0.	0.		0.	17.	17.	17.	17.	413.		413.	413.
CourtH-	0.	0.		0.	24.	24.	24.	24.	885.		885.	885.
MeanP	0.06	0.06		0.06	0.06	0.06	0.06	0.06	0.06		0.06	0.06
Cost+GT	-143.94	-468.11		-339.23	-292.22	-605.01	-74.84	-317.76	-302.46		-71.86	-163.55
NetI	4360.64	1228.39		2473.74	4215.62	1074.7	1839.4	2558.43	4345.63		1991.83	2927.68

Scenario 2040 Curtailment 1

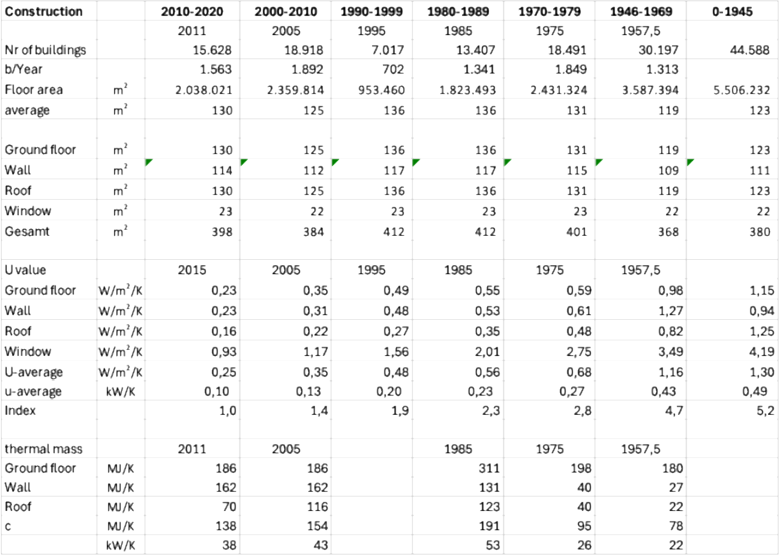
	2040C1 0				2040C1 50				2040C1 100			
	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All	Nontech	TNonflex	Flex	All
HH	2.3	2.13		2.2	2.3	1.96	2.29	2.2	2.3		2.13	2.2
EV	1.35	1.27		1.3	1.35	1.27	1.27	1.3	1.35		1.27	1.3
o/m/n	0.	0.52		0.31	0.	0.5	0.53	0.31	0.		0.52	0.31
tech	0.	1.		0.6	0.	1.	1.	0.6	0.		1.	0.6
flex	0.	0.		0.	0.	0.	1.	0.31	0.		1.	0.6
ID	86.55	81.49		83.5	86.55	77.92	84.92	83.5	86.55		81.49	83.5
EV1Prf	66.68	62.51		64.17	63.59	65.51	60.49	63.2	64.42		71.49	68.68
EV2Prf	34.64	30.97		32.43	35.21	30.2	33.94	33.34	37.68		29.73	32.89
EV3Prf	4.29	8.56		6.86	5.29	10.	3.94	6.27	8.15		9.36	8.88
EVSto	58.33	56.		56.93	58.33	57.14	54.9	56.93	58.33		56.	56.93
PV	0.	10.		6.02	0.	10.	10.	6.02	0.		10.	6.02
BSto	0.	10.		6.02	0.	10.	10.	6.02	0.		10.	6.02
HSto	0.	9.		5.42	0.	9.	9.	5.42	0.		9.	5.42
WSto	0.	5.		3.01	0.	5.	5.	3.01	0.		5.	3.01
Load	3357.7	3180.68		3251.06	3282.44	3012.76	3390.29	3235.97	3343.8		3196.6	3255.13
Tmin	20.	20.		20.	20.	20.	20.	20.	20.		20.	20.
Tmax	30.	30.		30.	30.	30.	30.	30.	30.		30.	30.
U	0.4	0.22		0.29	0.4	0.22	0.22	0.29	0.4		0.22	0.29
HP	0.	4.83		2.91	0.	4.87	4.79	2.91	0.		4.83	2.91
Cost	-283.23	-606.34		-477.88	-274.62	-597.35	182.77	-229.36	-281.85		146.74	-23.66
eHeat	0.	8432.28		5079.69	0.	8466.26	9712.76	5483.12	0.		9675.94	5828.88
eWater	0.	253.6		152.77	0.	240.21	303.86	164.26	0.		284.39	171.32
	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
EVCons	1014.28	928.4		962.54	944.45	921.9	293.04	737.66	1013.52		247.13	551.84
avTemp	20.04	20.04		20.04	21.25	20.04	21.77	21.05	21.73		21.71	21.72
SOCev1	58.1	55.78		56.7	58.13	56.91	27.53	48.37	58.08		27.97	39.94
SOCbat	0.	0.62		0.37	0.	0.38	4.84	1.6	0.		4.51	2.71
SOCheat	0.	0.		0.	0.	0.	0.83	0.26	0.		0.46	0.28
SOCwater	0.	0.		0.	0.	0.	0.96	0.29	0.		0.84	0.51
SOCev2	58.22	55.9		56.82	58.2	57.05	14.09	44.31	58.21		11.78	30.24
SOCev3	58.32	55.97		56.9	58.32	57.12	2.62	40.85	58.31		3.1	25.05
CycEV1	70.63	95.58		85.66	104.1	112.63	156.86	122.83	120.38		160.	144.25
CycBAT	0.	137.35		82.74	0.	142.39	200.	103.48	0.		200.	120.48
CycHEAT	0.	0.		0.	0.	0.36	170.11	52.37	0.		174.08	104.87
CycWATER	0.	0.		0.	0.	0.03	101.64	31.23	0.		93.52	56.34
CycEV2	48.71	68.4		60.57	58.55	61.71	82.35	66.79	70.91		74.	72.77
CycEV3	3.79	17.44		12.01	7.5	24.49	15.69	15.03	7.96		20.	15.21
GT-k	0.	0.		0.	0.	0.	0.	0.	0.		0.	0.
MAETemp	0.06	0.07		0.07	1.23	0.07	1.74	1.04	1.7		1.68	1.69
CourtH+	0.	0.		0.	110.	110.	110.	110.	1988.		1988.	1988.
CourtH-	0.	0.		0.	45.	45.	45.	45.	1305.		1305.	1305.
MeanP	0.06	0.06		0.06	0.06	0.06	0.06	0.06	0.06		0.06	0.06
Cost+GT	-422.52	-744.57		-616.53	-418.86	-741.64	247.	-309.57	-431.82		185.78	-59.77
NetI	4360.64	1228.39		2473.74	4215.81	1086.12	2143.68	2655.37	4346.03		2063.27	2970.88

Appendix B: Building parameters

Building parameters C and U:

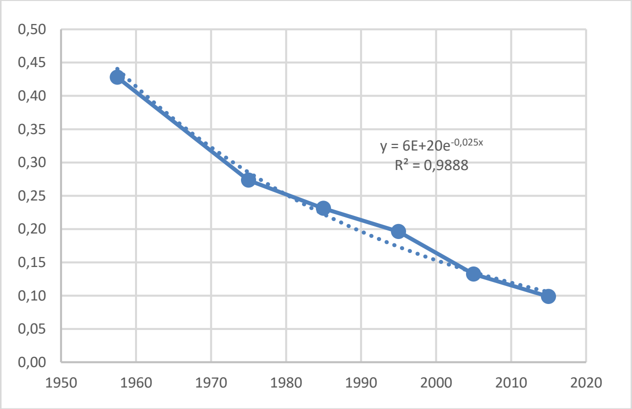
$$u\left[\frac{kW}{K}\right]=\mathrm{U}\left[\frac{W}{Km^2}\right]\frac{A[m^2]}{1000} \tag{23}$$

Residential: data source building stock Luxembourg, Data: 1. EU Building stock statistics 2. hh – electricity consumption + further: Link Destatis 3.; Lux statistic



Construction		2010-2020	2000-2010	1990-1999	1980-1989	1970-1979	1946-1969	0-1945
		2011	2005	1995	1985	1975	1957,5	
Nr of buildings		15.628	18.918	7.017	13.407	18.491	30.197	44.588
b/Year		1.563	1.892	702	1.341	1.849	1.313	
Floor area	m^2	2.038.021	2.359.814	953.460	1.823.493	2.431.324	3.587.394	5.506.232
average	m^2	130	125	136	136	131	119	123
Ground floor	m^2	130	125	136	136	131	119	123
Wall	m^2	114	112	117	117	115	109	111
Roof	m^2	130	125	136	136	131	119	123
Window	m^2	23	22	23	23	23	22	22
Gesamt	m^2	398	384	412	412	401	368	380
U value		2015	2005	1995	1985	1975	1957,5	
Ground floor	$W/m^2/K$	0,23	0,35	0,49	0,55	0,59	0,98	1,15
Wall	$W/m^2/K$	0,23	0,31	0,48	0,53	0,61	1,27	0,94
Roof	$W/m^2/K$	0,16	0,22	0,27	0,35	0,48	0,82	1,25
Window	$W/m^2/K$	0,93	1,17	1,56	2,01	2,75	3,49	4,19
U-average	$W/m^2/K$	0,25	0,35	0,48	0,56	0,68	1,16	1,30
u-average	kW/K	0,10	0,13	0,20	0,23	0,27	0,43	0,49
Index		1,0	1,4	1,9	2,3	2,8	4,7	5,2
thermal mass		2011	2005		1985	1975	1957,5	
Ground floor	MJ/K	186	186		311	198	180	
Wall	MJ/K	162	162		131	40	27	
Roof	MJ/K	70	116		123	40	22	
c	MJ/K	138	154		191	95	78	
	kW/K	38	43		53	26	22	

Table building data Luxembourg – single family house



Development of u-values

Appendix C: Distribution of household size and car ownership - Max Entropy Estimation

$P^*_{s,c}$ is the distribution that maximizes relative entropy $\sum_{s,c} -p_{s,c} \log \frac{p_{s,c}}{\tilde{p}_{s,c}}$ based on the boundary distributions P_c, P_s and the expected value of cars per person $\bar{c}$ and the prior distribution $\tilde{P}^*_{s,c}$:

$$P^*_{s,c}\left(P_c, P_s, \bar{c}, \tilde{P}^*_{s,c}\right) = \mathrm{argmax}_{p_{s,c}} \sum\nolimits_{s,c} -p_{s,c} \log \frac{p_{s,c}}{\tilde{p}_{s,c}} \tag{1}$$

$$\text{s.t.: } \sum\nolimits_{s,c} p_{s,c} = 1, p_{s,c} \geq 0 \tag{2}$$

$$\text{s.t.: } \sum\nolimits_{s} p_{s,c} = P_c, \sum\nolimits_{c} p_{s,c} = P_s \tag{3}$$

$$\text{s.t.: } \sum\nolimits_{s,c} \frac{c}{s} \cdot p_{s,c} = \bar{c} \tag{4}$$

Iterative procedure to estimate the common distribution of Cars and household size. The distribution of EVs per household can be determined by EV share in cars: Today - 15% EVs, NECP: 50% EV by 2030, IAE: 70% by 2040.

Scenario		**2018**						**2030**						**2040**					
$\bar{c}$ [cars/pers]		0.66						0.75*						1.00(1.5)*					
P_c Cars/household [%]		{0:14%,1:45%,2:30%,3:8%,4:3%}**						-											
P_s Pers/Household [%]		{1:33.3, 2:27.4 3:15.9, 4:15.0, 5: 5.9, 6: 2.5}***						{1:40%, 2:27.5% 3:13, 4:12.0, 5: 5, 6: 2%}****											
$P^x_{s,c}$		$P^*_{s,c}(P_c, P_s, 0.66, \emptyset)$						$P^*_{s,c}\left(\emptyset, P_s, 0.75, P^{2018}_{s,c}\right)$						$P^*_{s,c}\left(\emptyset, P_s, 1.0(1.5), P^{2030}_{s,c}\right)$					
Result		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
	0	11	2	1				10	2					4	1				
	1	19	14	6	5	2	1	24	13	4	4	1		21	9	3	3	1	
	2	3	10	7	7	3	1	6	10	6	5	2	1	13	12	6	5	2	1
	3		2	2	2	1	1		2	2	2	1		2	4	3	3	1	
	4			1	1	1			1	1	1	1			2	1	2	1	
EV share in cars [%]		15						50 (NECP)						70 (IEA)					

Table: *Scenario, ** Link, *** rp11-08-13-DE.pdf, **** calibrated to expected share of 1 person households of 40% (Economie et Statistiques Working Papers du STATEC N° 106 Avril 2019; Link), 50% - with some adjustments to become feasible.