When the duck turns turtle: Prosumage and the challenge of distribution grid management

BY **JOACHIM GESKE, BORIS ORTEGA, LAURA ANDOLFI, and RAWAN AKKOUCH**

Abstract

We simulate realistic cross-sector prosumage flexibility[1] for 2040 in Luxembourg at the distribution grid level. We find that the increase in electricity demand requires extensions of the electricity infrastructure, but it is the timing of this demand that causes the main infrastructure overload: the duck curve evolves into a turtle-like one. Thus, operators need to consider this evolution of demand to avoid grid overload or unsustainable investment.

Introduction

Globally, the energy transition is being shaped by, among others, a rapid expansion of renewable energy generation and the electrification of the heating and mobility sectors (IRENA, 2024). The electrification of these two sectors is re-shaping and increasing electricity demand and generation. However, as intermittent renewable generation cannot shift to meet demand, demand must adjust accordingly. This call for demand-side flexibility, enabled by behavioural changes and storage, arises as a key alternative to support the ongoing electrification of different sectors. Additionally, demand-side flexibility or more generally, cross-sector prosumage flexibility, has the potential to make use of the existing grid infrastructure in a more efficient way to avoid expensive reinforcement to distribute electricity (IEA, 2023).

Currently, an increasing share of households are equipped with electrical and thermal storage solutions, highly insulated buildings (that will also serve as heat storage), electric vehicles (EVs), heat pumps, and photovoltaic (PV) systems. Additionally, automation, paired with the above technologies, will enable households to respond to market prices and signals. This response can take the form of shifting or reducing net demand, and using PV systems and storage solutions to profit from price differentials. Thus, a share of households will start supplying cross-sector prosumage flexibility, including reducing and shifting net demand.

But, how does this cross-sector prosumage flexibility look like in practice? To answer this question, in this paper, we model household load profiles in 2040 with different levels of flexibility and technologies for Luxembourg. Luxembourg serves as an interesting case study as there is close collaboration among energy stakeholders,[2] allowing for rich data availability. Additionally, Luxembourg has ambitious energy goals and, with over 95% of households already equipped with smart meters (ACER, 2022), aims to cut greenhouse gas emissions by 55%, limit final energy consumption to 35.6 TWh, and reach 37% renewables in gross final consumption by 2030 (Government of the Grand Duchy of Luxembourg, 2020).

While cross-sector prosumage flexibility plays a central role in the Luxembourgish strategy, helping to balance intermittent renewables and ensure supply security, does it really solve infrastructure overload? Or might it cause new issues? The answers to these questions concern grid operators beyond Luxembourg, and this paper provides insights based on an active building model of cross-sector prosumage flexibility.

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Active building model and scenarios

The analysis uses an active building model to simulate hourly household electricity demand and supply for a full year. Households are grouped into non-technological, technological non-flexible, and technological flexible. Non-technological households do not possess advanced energy technologies; rather, they may own an EV, operated without consideration of price signals or grid conditions. Technological non-flexible households own the full bundle of technologies (heat pumps, EVs, PV systems, heat storage and batteries) but do not optimise their energy usage according to electricity costs based on wholesale market prices. Technological flexible households are equipped with the same bundle of technologies as the previous group, but they use their technologies to minimise energy costs. We assume perfect foresight of prices based on 2040 Entso-e Ten Year Network Development Plan (TYNDP) scenarios, solar capacity factors, and outdoor temperature.

The model applies linear optimisation, considering technical limits (e.g., 11 kW EV charging and cycle lifetimes), thermal dynamics, and grid constraints. It evaluates low-voltage transformer loading for 166 representative households (scaled to Luxembourg's rural/semi-urban grid), comparing different flexibility shares, to identify its impact on the transformer load. We assume, in line with the national energy and climate plan and demographic statistics, that in 2040, around 60% of the households are technologically equipped. Therefore, we simulate flexibility shares of 0%, 30%, and 60% of all households.

Results

In the baseline scenario without flexible households (Figure 1, dotted red line), the average weekday load of the 166 households follows the well-known duck

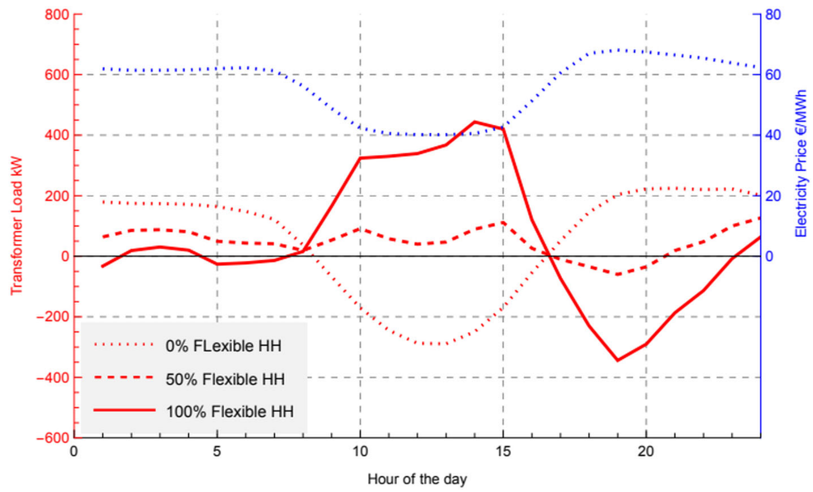

Figure 1: **Household Net Electricity Imports.** *It displays households' net electricity imports on the transformer level for an average weekday in 2040 with varying shares of flexible households. The x-axis represents the hour of the day, while the y-axis denotes power imports (kW). The blue line depicts scaled TYNDP electricity prices of 2040. The red lines represent scenarios of household consumption patterns - dotted curves 0% dashed 30% and solid curves 60% of flexible households.*

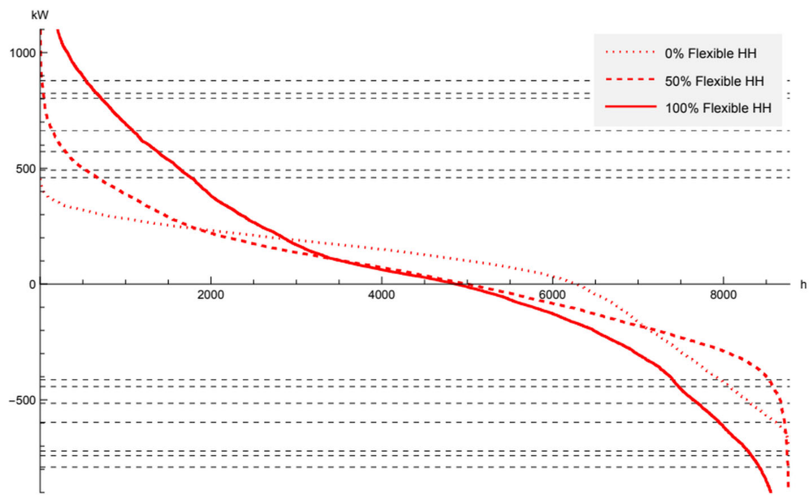

Figure 2: **Load Duration at the Transformer Level.** *It shows the load duration at the transformer level for all the hours of the year. The positive values represent the electricity imported from the grid to the households, while the negative values show the exports from the household to the grid. The horizontal dashed lines represent the upper and lower bounds of the representative transformer capacities.*

curve driven by midday PV systems exports and evening EV charging peaks (CAISO, 2013). In the second scenario, with 30% flexible households (dashed red line), households start to arbitrage wholesale prices: charging in low-price midday hours (blue dotted curve) and discharging/avoiding imports in high-price evenings. This behaviour flattens the aggregate load curve, arguably a desirable state. However, as flexibility provision increases to 60%, arbitrage increases until the duck curve inverts: substantial midday imports and evening exports from the household perspective, leading to the new turtle-like curve (solid red curve).

However, as aggregate loads do not exceed 500 kW, we are still within current transformer capacities ranging from 500 to 900 kW (according to data from the distribution grid operator). However, recall that Figure 1 represents average loads, meaning that intermittent supply (intermittent renewable generation) and demand (via temperature) cause high price peaks that motivate extreme trading activities of the flexible households (load duration in Figure 2). Therefore, in 2040 even without flexibility exporting households exceed capacities of four out of seven representative transformers (right-hand side) while the import capacities are sufficient (left-hand side). At 30% flexibility, all transformers overload at least once for both, import and exporting activities (dashed red curve). Finally, at 60% flexibility, overloads occur thousands of hours, with up to three additional transformers required per site (solid red curve).[3]

Discussion

While the turtle-shaped curve may support PV integration (i.e., by increasing midday consumption during high PV generation), it also introduces new stress points for grid infrastructure, particularly at the distribution transformer level. This potential grid overload calls for an urgent evolution of the market towards a design that harnesses the potential system-wide benefits of flexibility while ensuring a reliable and sustainable grid.

Unregulated or unaccounted cross-sector prosumage flexibility can overwhelm local infrastructure, offsetting its potential benefits, which highlights the need for careful policy design. Policymakers must ensure that flexibility is enabled responsibly, through supportive market mechanisms that (1) avoid allocating the system costs of flexibility to non-flexible households, (2) apply dynamic pricing to provide the right local signals to households, and (3) encourage investment in digital grid management that allows real-time management of the system. More than a challenge, the evolution from duck to turtle should be seen as an opportunity to, for example, integrate renewable generation and optimise the use of the grid infrastructure; however, to fully capture the potential system-wide benefits of this new paradigm, we must start now understanding the nuances of this new reality and properly prepare our energy system.

The results shed light on the importance of considering the effects of cross-sector prosumage flexibility at the transformer level. However, it must be noted that there are other infrastructure aspects (i.e., voltage levels, line congestion, etc.) that policymakers and system operators must take into consideration for the system-wide adaptation. Our analysis is a step to integrate grid and other system aspects in addition to wholesale markets and transmission capacity.

Conclusions and Future Research

Driven by increasing household flexibility and prosumer engagement, the shape of electricity demand is evolving. In this paper, we estimate cross-sector prosumage behaviour and flexibility configurations for 2040 and its grid implications at the low-voltage transformer level.

We show that a high share of prosumage flexibility in 2040 leads to the evolution of the duck curve towards a turtle-like one. While this transformation may support renewable integration, the price-responsiveness of households may also introduce new grid challenges if markets do not adapt and provide the right signals. These effects suggest that flexibility is not inherently beneficial or harmful, but its value depends on how, when, and where it is activated. To fully harness its potential, we must develop strategies that coordinate and localise flexibility activation, avoid grid congestion, and support consumer empowerment without unfairly shifting risks onto households.

Our results assume that electricity prices do not respond to the cross-sector prosumage flexibility. This limitation most likely leads to overestimation of the hours exceeding the transformer capacities, as flexible prices would adapt to the flexibility supply. While the TYDNP scenario prices already incorporate some degree of flexibility, as evidenced by the high night average prices (recall the blue curves of Figure 1), fully dynamic prices have the potential to mitigate some of the challenges of flexibility supply described in Figure 2. Nevertheless, our results provide valuable insights into the potential problems of unregulated cross-sector prosumage flexibility.

While the insights presented here are informative, they also highlight the need for further research to fully understand the evolving shape of electricity demand. This modelling framework offers opportunities to explore several interesting venues, such as the role of individual technologies in shaping the profitability of arbitrage, as well as the potential unintended consequences of flexibility, like increased electricity use for heating to leverage buildings as storage units. It also draws attention to the significance of out-of-home EV charging, particularly at workplaces, and the varying effects of market and non-market mitigation mechanisms like grid tariffs, curtailment, or local capacity markets. Altogether, the future shape of electricity demand is far from settled, and holds fascinating questions that are only beginning to be explored.

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Notes

[1] We define cross-sector prosumage flexibility as the electricity production and consumption behavior of the households across different sectors like transportation (EV), heating (heat pumps), electricity storage, etc.

[2] The analysis was conducted within the FlexBeAn (Flexibility Potentials and User Behaviour Analysis) project together with CREOS (grid operator) and Luxembourg Institute of Science and Technology (LIST). FlexBeAn examines how households, SMEs and industry can provide flexibility to support the energy transition. The project combines behavioural, technical, economic, and market perspectives to inform policy and grid operations (Luxembourg Institute of Science and Technology et al., 2025).

[3] Estimations of additional transformer needs available upon request.