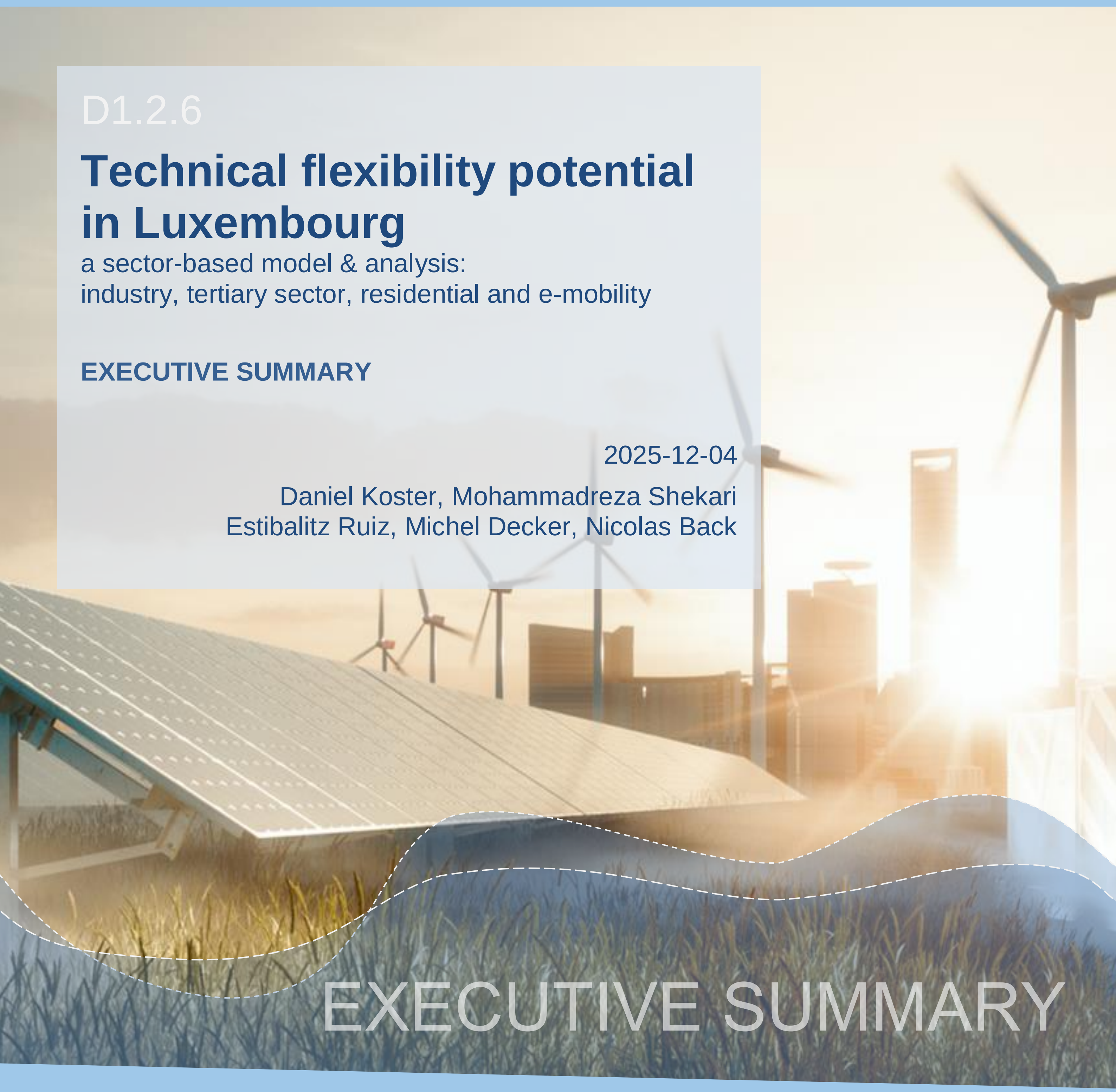
FLEXBEAN

Flexibility for Energy Transition PROJECT



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Technical flexibility potential in Luxembourg

a sector-based model & analysis:
industry, tertiary sector, residential and e-mobility

EXECUTIVE SUMMARY

2025-12-04

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EXECUTIVE SUMMARY

creos

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

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Executive summary

Introduction

In our future, renewable-based energy system, flexibility on the demand side is necessary to react on fluctuating energy production from volatile renewable energy sources, such as wind and solar, but also to manage changing energy consumption patterns, e.g. due to electric vehicle charging or electrification of the heating sector via heat pumps. Flexibility use cases reach from classical "balancing" flexibility (or system flexibility) to network / grid flexibility to help transport and distribution grid operators to avoid grid congestions. Further, the growing volatility on the spot markets for energy becomes an important driver for flexibility to economically use the price spread on the energy markets (market arbitrage). Internal usage of flexibility in households, private companies or energy communities is another rising demand, e.g. to optimize grid tariffs (peak shaving), to increase the share of self-consumption from own electricity production, or to use periods of low spot market prices to reduce the energy bill.

Nevertheless, the results presented in the following executive summary are focusing on grid flexibility and originate from the FlexBeAn Project, a joint project of CREOS, the Luxembourg Institute of Science and Technology (LIST) and the "Security and Trust" Institute (SnT), belonging to the University of Luxembourg.

Flexibility, in the understanding of this project, focused on demand side flexibility and can be defined as:

"Flexibility is the ability of consumers to adjust their electricity consumption, following an external signal, comprising an increase and/or decrease of power consumption. "

Such "external signals" can be manifold, reaching from dynamic electricity tariffs or grid fees, non-monetary incentives or direct load-control signals, to name the most important ones. The flexibility potentials that are reported in this executive summary are mainly the technical potentials, taking into account also some practical aspects.

Within the FlexBeAn Project, the partners are evaluating the flexibility potentials for the sectors industry, tertiary sector, households and e-mobility. In this ***executive summary of the final report on flexibility potentials***, the methodology for the estimation of those potentials is only very briefly addressed. Also, the results are documented in a very condensed form, requiring simplifications of the real complexity. The full report is publicly available on the projects website and the internet presence of the involved partners.

The project comprises potentials for today, 2030 and 2040 via a model that allows for spatial and temporally resolved results. The spatial resolution of the final model gives insights down to the level of communes, and hence, enables the allocation of flexibility in low voltage level and could be aggregated up to the distinctive high-voltage areas. The temporal resolution of one hour over a full year, allows findings regarding fluctuation of flexibility potentials over the seasons, across week-day and week-ends, as well as representing the diurnal cycle, if relevant.

The output of the FlexBeAn model is the technical flexibility potential, defined as the deviation from a baseline load profile under the technical and operational constraints of the considered technology. Its quantity is mainly characterized by power and duration. Flexibility is expressed consistently with the methodology to assess flexibility needs (defined by ENTSO-E and DSO Entity), from a generation perspective:

- **Upward flexibility,** corresponds to the possibility of increasing net generation or reducing consumption, as in our context for demand side flexibility.
- **Downward flexibility,** corresponds to the possibility of decreasing net generation or increasing consumption.

Industry sector

Industrial demand-side flexibility varies significantly across sectors, as differences in manufacturing processes, operating schedules, and technical constraints determine the potential for adjusting electricity demand. To capture these sectoral differences, we conducted a systematic literature review to collect data on flexible industrial processes. The reviewed studies provided information on the share of load that can be shifted or curtailed. This sector-specific flexibility data was then translated to the Luxembourgish industrial context. We assumed that facilities within the same sector and employing similar manufacturing principles could exhibit comparable flexibility characteristics. To account for uncertainty and variability in the reported data, we developed three scenarios: an optimistic scenario, using the highest flexibility values reported in the literature; a pessimistic scenario, using the lowest values; and an average scenario, based on the mean of the reported ranges.

Table 1: Spatial distribution of Luxembourgish industrial upward flexibility (load reduction) potential.

Region	Average (MW)	Pessimistic (MW)	Optimistic (MW)
Centre	2,6	1,4	4,5
North	2,7	1,5	3,8
West	3,8	1,9	9,0
East	4,2	2,0	8,9
South-East	4,0	2,8	7,0
South-West	3,0	1,7	5,8
Total	**20,2**	**11,3**	**38,8**

By combining these assumptions with actual electricity consumption profiles of major industrial consumers in Luxembourg, Creos estimated the theoretical demand response potential of key industrial facilities. The complete methodology and detailed findings are provided in the full report. Through this methodology, we identified that Luxembourgish industries can provide an average of 20,2 MW in upward demand response actions (load reduction). Table 1 outlines the distribution of this potential across Luxembourg's high-voltage transmission network.

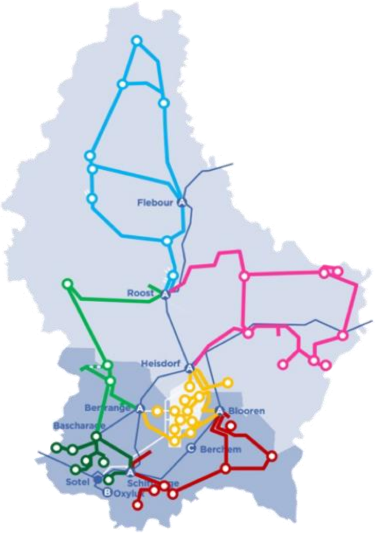


Figure 1: High voltage transmission grid from Luxembourg.

Moreover, the duration of such flexibility varies significantly across industrial sectors. Some processes can only sustain short interruptions, such as electric arc furnaces in steel production or mechanical refining in the paper industry, which allow 20 – 30 minutes of flexibility. Data centres are more variable: shifting or queuing IT jobs typically offers short windows of around 15 minutes, whereas load migration or temperature adjustments can extend flexibility to several hours. Conversely, less time-sensitive processes, like grinding mills in cement production, can remain flexible for one to two hours. Based on the collected data, Figure 2 illustrates the estimated total industrial demand response potential in Luxembourg, categorized according to the available flexibility durations.

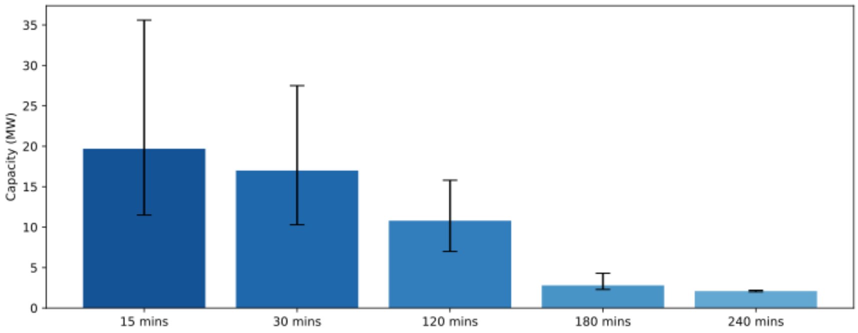


Figure 2: Industrial demand response potential in MW by flexibility duration.

Regarding the plastic industrial sector, discussions and data exchanges with two major Luxembourgish manufacturers confirmed that they currently have no demand-side flexibility, as they are unwilling to alter existing consumption profiles. However, this is expected to change with the electrification of steam production, driven by European carbon-neutrality regulations that will lead to the gradually replacement of gas-fired boilers with electric ones. During this transition period, when both boiler types operate in parallel, a temporary window of cross-sectoral flexibility will emerge. The actual flexibility potential will depend on the pace of technology adoption, the installed capacity of electric boilers, and the synchronisation of investments across companies. In this assessment, we assumed a gradual transition, with electric boilers covering 25% of peak steam demand by 2030, increasing to 75% by 2040, and gas boilers being fully phased out by 2050. The aggregated symmetrical flexibility potential (upward and downward) for the main Luxembourgish plastic manufacturers is presented in Table 2.

Table 2: Projected flexibility potential of the plastic industry (in MW).

Year	Gas	Elec.	Optimistic	Mean	Pessimistic
2024	100%	0%		0	
2030	100%	25%	27.4	20.8	15.2
2035	75%	50%	54.8	41.5	30.5
2040	50%	75%	54.8	41.5	30.5
2045	25%	100%	27.4	20.8	15.2
2050	0%	100%		0	

Gas: Capacity of gas boilers, Elec.: Capacity of electric boilers.

Tertiary sector

The tertiary sector is very diverse, and its electricity demand is heterogeneously distributed over versatile processes and demands. The assessment focused on building related demands linked to three processes: air-conditioning (AC), cooling processes and ventilation. Since individual data on the sector and these processes is scarce, the model has been mainly building on three data sources: the yearly electricity demand and standard load profile of the sector, literature data on the share of those processes on the total demand as well as temperature data of past years to model the demand and flexibility potential over time.

The demand and availability of flexibility from cooling and air-conditioning is dependent on the ambient temperature. The model considered air-conditioning demand depending fully on the ambient temperature using “Cooling Degree Hours” (CDH), which describe a temperature difference above a certain threshold. The cooling demand (e.g. for supermarket cooling) also rises with ambient temperatures, but to a smaller degree. Hence, the demand and flexibility potential for both processes are unevenly distributed over the season and shows large peaks during the summer period, opposed to a rather stable energy demand for ventilation. The standard load profile of the sector moreover reflects the daily variations in demand and flexibility potential.

Finally, the model results in an estimation of upward and downward flexibility from tertiary sector, based on the previously described assumptions and simplifications, using temperature data and tertiary sector electricity demand, as given in Table 3. The yearly average downward flexibility potential from ventilation, cooling, and AC in Luxembourg's tertiary sector, is approximately 48 MW, with a maximum of 189 MW, depending on demand peaks and system constraints. Similarly, the average upward flexibility potential from the same processes, is approximately -29 MW, with a yearly maximum of about -262 MW during peaks in summer.

Table 3 - Demand response potential from air-conditioning, cooling processes, and ventilation in the tertiary sector

	Yearly average	*Yearly maximum*	*Yearly minimum*
Downward flexibility	**48 MW**	**189 MW**	**0 MW**
Upward flexibility	**- 29 MW**	**- 262 MW**	**- 9.6 MW**

Specifically, due to the nature of the temperature sensitive demands of air-conditioning and cooling processes, the maximum available flexibility in the tertiary sector appears only in summer periods and is rather volatile. Further, daily variations regarding ventilation needs depend on opening hours and presence in office space. Hence, a reliable and plannable utilisation of flexibility should either be oriented along the average available flexibility (compare Table 4 and Figure 3) or needs to be well aligned with the fluctuating demand of the relevant processes.

Table 4 - Monthly averages of demand response potential from air-conditioning, cooling processes, and ventilation in the tertiary sector

Monthly averages	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Downward flex. [MW]	**16**	**16**	**17**	**25**	**83**	**88**	**109**	**112**	**57**	**17**	**16**	**17**
Upward flex. [MW]	**-25**	**-25**	**-24**	**-23**	**-34**	**-37**	**-47**	**-36**	**-25**	**-24**	**-25**	**-24**

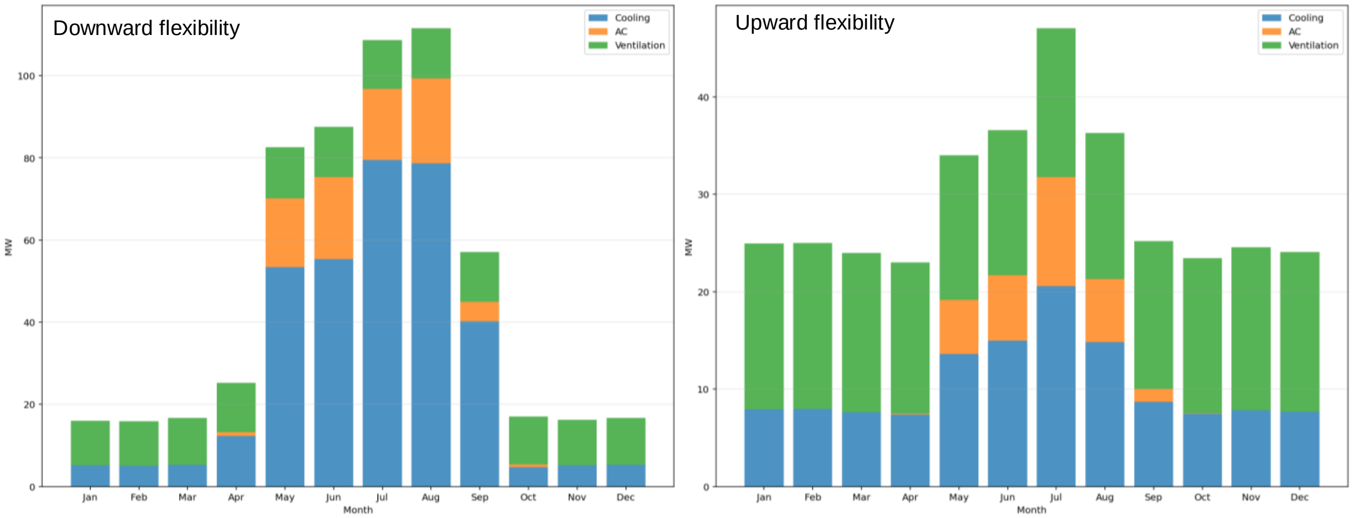


Figure 3 - Flexibility potentials by cooling, air-conditioning and ventilation in tertiary sector – monthly averages

Above figure demonstrates, that the largest potential for downward flexibility arises from cooling processes, followed by air-conditioning (e.g. by pre-cooling a building or buffer storage) but is drastically depending on the seasons. The right panel depicts the upward flexibility, indicating the potential to temporarily reduce electricity use during peak periods, being much less temperature depended.

Overall, these results highlight the dominant role of cooling loads in shaping seasonal flexibility, especially for downward adjustments, while ventilation systems provide a reliable source of upward flexibility throughout the year.

Residential sector

Within the residential sector, there are versatile electricity consuming devices that could provide flexibility. The challenge lies in the automation and control as well as to avoid or minimize the impacts on user comfort. Nominal power and energy demand of single devices may appear small, but the large number of households makes up for a huge potential, although this depends strongly on the assumption of the percentage of households participating in demand response schemes.

Residential heat pumps

Heat pumps are an essential component of the decarbonisation strategy in the residential sector and represent a rapidly growing technology. Hence, to assess the importance of their flexibility potential, future scenarios on the technology penetration are important. The main assumptions on the technology penetration for heat pumps in 2040 are based on national strategy papers (updated NECP & CREOS Scenario report from 2040), considering that by then, 56% of all residential buildings (existing and new constructions) would be heated by heat pump systems, as well as that all these heat pumps are participating in demand side management programmes. The different options to activate flexibility from heat pumps reach from blocking the operation (e.g. for up to 2 hours, as common in some EU countries) or using smart grid ready functions (SGR), to adapt set points and even use the back-up heater. This results in upward or downward flexibility of different scales and durations, which are result of a time series simulation of a set of representative heat pump systems and buildings, over one year. All following results are assuming the heat pump penetration scenario for 2040:

Downward flexibility (increasing or preponing the consumption) could only be reasonably used during the heating period (Sept/ Oct – April/May) and reaches from about 225 – 345 MW, with the higher values during warmer periods (Figure 4 - SGR-On). If the back-up heater is activated in addition this could even be further increased by 50-60 % but would drastically reduce the efficiency (SGR-On-SH-BH). The average duration of this flexibility provision strongly depends on the activation signal and is very short (e.g., 10 minutes on average for SGR-On) if the temperature set points for the buffer storage are not increased, which could prolong this duration to about 1 – 1,5 hours (SGR-On-SH).

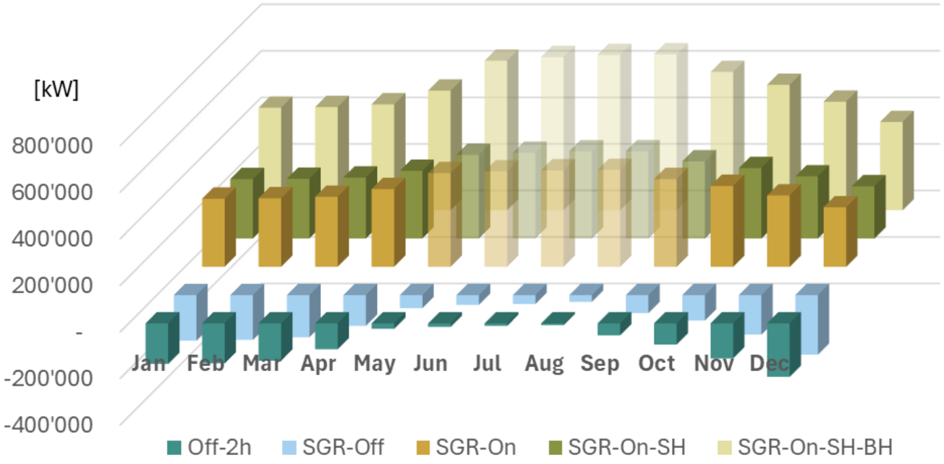
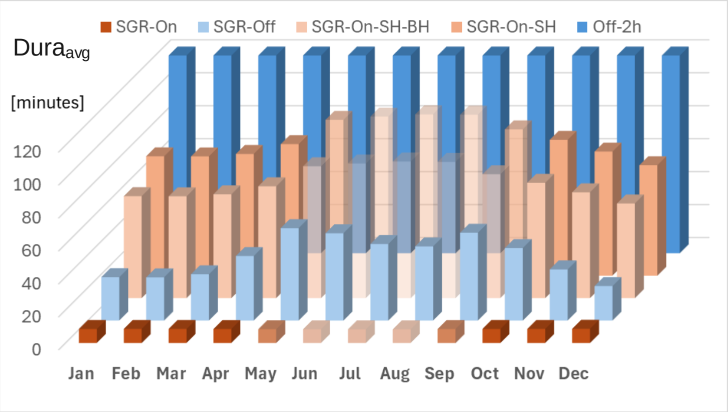


Figure 4 - Flexibility potential of heat pumps by activation signal (scenario 2040)

Upward flexibility (reducing or postponing consumption) is conventionally done by a blocking signal and could be held for up to 2 hours, if the heat pump systems are designed for this. During the heating period, a potential of -91 MW to -256 MW has been estimated, growing with falling temperatures. It should be noted, that a high rebound effect could be expected, resulting in an increased power consumption after the signal is lifted. Practically, this should be accounted for by an adequate, cascaded activation strategy. If upward flexibility is activated via smarter options (SGR-Off), the power flexibility remains similar, but the duration strongly varies with outdoor temperatures reaching from 50 minutes in the autumn / spring period and dropping to 20 minutes during cold winter days.



This does not imply that the buildings would fall uncomfortably cold, in case of a deactivation of the heat pump (downward flex.). But the effect of the thermal inertia of the building on the potential prolongation of flexibility provision via the SGR-Off function is limited and difficult to assess (due to the control function setup by system return temperature). The average durations for which a heat pump could sustain the flexibility provision under the different activation options, are depicted in Figure 5.

Figure 5 - Average duration of flexibility activation

As described earlier, the figures above represent a technology penetration scenario for 2040, considering that 56% of the residential buildings are operated by heat pumps, resulting in 98.000 heat pumps systems on national scale. The 2020 technology penetration scenario accounts for about 3.000 heat pumps in Luxemburg, representing about 2% of the residential heating systems, while the 2030 scenario foresees 48.000 heat pumps for 2030 (30% share of the future building stock). As the amount of heat pumps in those scenarios only affect the magnitude of power flexibility and energy flexibility within our model, while the other parameter stay constant, the duration remains unchanged. Figure 6 outlines the power flexibility for 2020, 2030 and 2040 in comparison.

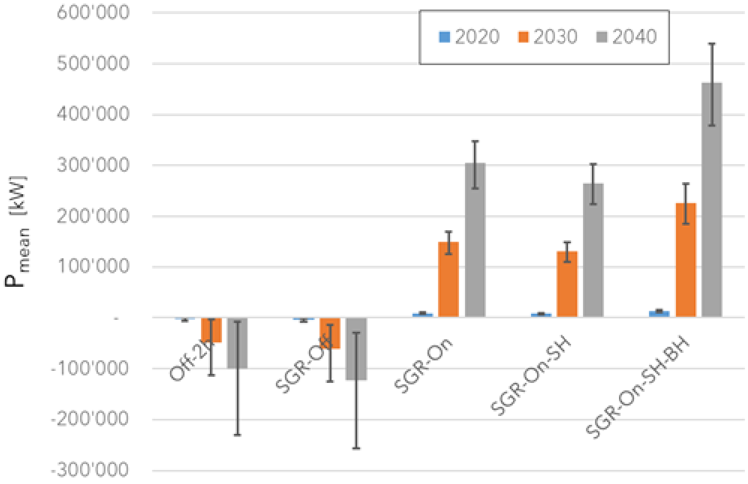


Figure 6 - Power flexibility (P_{mean}) for three technology penetration scenarios (2020, 2030, 2040)

The broad bars depict the average of the power flexibility that could be provided according to the respective scenario and given activation signal. The lines on top of each bar mark the range given by the minimum and maximum of the monthly averages across the seasons. For downward flexibility, activating heat pumps, only the heating period is considered (Oct.- April.).

Residential whiteware

Residential whiteware, in the context of demand response schemes, refers to household appliances traditionally used for washing, drying, and dishwashing. While continuously running appliances such as refrigerators and freezers are technically whiteware, those are not suitable for demand response, while washing machines, tumble dryers, and dishwashers are shiftable devices with inherent flexibility potential. These appliances can be scheduled to operate at alternative times of the day without negatively impacting user comfort or could be controlled by an energy management system.

The estimation of whiteware flexibility potentials follows a structured, multi-step approach to quantify the shiftable load flexibility from whiteware across Luxembourg. The model runs a yearly time series simulation in hourly resolution and considers for each appliance the probability of start times during weekdays and weekends, the average load profile of a complete operating cycle and simulates typical daily demand patterns. A simulation performs the shifting of appliance start times within acceptable time windows, enabling the estimation of hourly flexibility potential. Device ownership rates specific to Luxembourg (95%

for washing machines, 40% for tumble dryers, and 50% for dishwashers) were used to scale the calculated flexibility potential to the household level.

The model distinguishes between weekdays and weekends, reflecting known behavioural differences in appliance usage. The results of the model, show fluctuating flexibility potentials depending on time of day, for both weekdays and weekend days. The following table summarizes the mean and peak values of the upward (forward shift) flexibility potential for shifting by 1 hour on national level:

Table 5 - Demand response potential from residential whitewares

	Mean Flexibility Potential (MW)	***Maximum Flexibility Potential (MW)***	***Peak Hour***
Weekday	**11**	**22**	**Hour 21 to 22**
Weekend	**11,5**	**23**	**Hour 20 to 21**

It's worth to mention that washing machines dominate the flexibility share with 55%, followed by dishwashers (23%) and tumble dryers (22%). During weekdays, the flexibility potential is more concentrated in the evening hours, with the highest shiftable potential occurring at 21:00 (see Figure 7). On weekends, the flexibility potential is more evenly distributed rising from late morning until late evening, with some fluctuations, and comparably low values up from 22:00 o'clock.

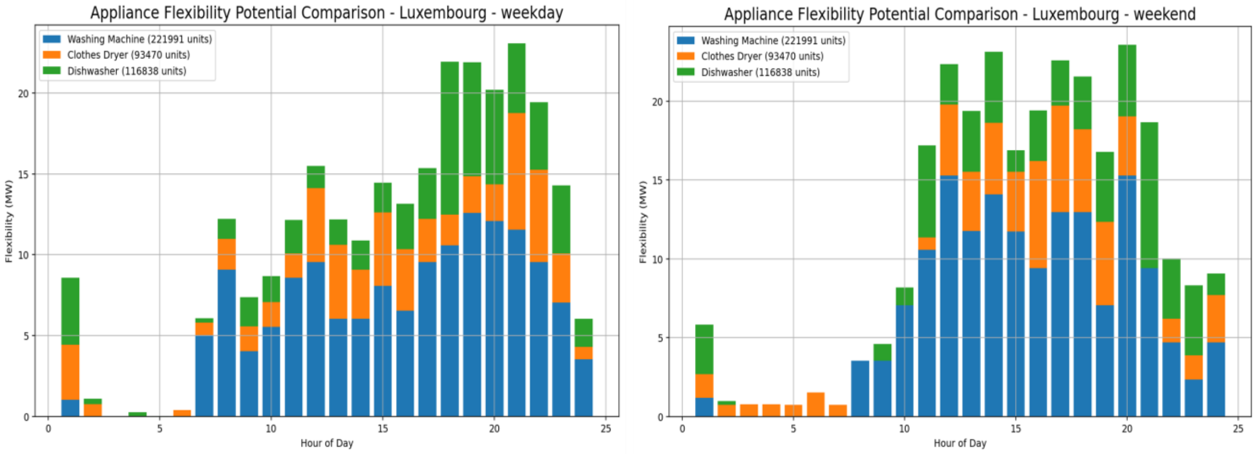


Figure 7 - Weekday and weekend aggregated flexibility potential from white ware

Residential electric water heaters

Electric water heaters (EWHs) with storage tanks are considered storable household devices, as they can temporarily decouple hot water consumption from electricity consumption. Unlike shiftable whiteware appliances, the flexibility of EWHs stems from their thermal storage capability, where electricity consumption can be rescheduled without immediately affecting user comfort, which allows for meaningful flexibility. Electric water heaters, as the ones considered within this analysis, mean larger scale water heaters providing centralized domestic hot water supply, starting from a storage volume of 50 Liters.

The analysis follows a structured modeling approach to quantify the flexibility potential of EWHs across Luxembourg, using 50 different hot water usage profiles, typical thermal characteristics of these devices, as well as boundary conditions for water temperatures. A thermodynamic and electrical model was used to simulate EWH operation under normal and flexible conditions. The flexibility simulation evaluated three distinct methods to provide flexibility via load increase or reduction:

- *On/Off Control*: switching on/off the EWH until they reach to boundary limits.
- *5°C Setpoint Change*: Temporarily increasing the upper or decreasing the lower temperature setpoint by 5°C.

- *10°C Setpoint Change*: Temporarily increasing the upper or decreasing the lower temperature setpoint by 10°C.

The resulting flexibility potential was scaled to the amount of all households in the country, reflecting a 15% device ownership rate for EWHs in Luxembourg (as taken from literature).

The following tables summarizes the average power increase/decrease and duration of flexibility for the mentioned methods, based on aggregated country-level simulations. For this estimation, it was assumed that electric water heaters in Luxembourg can be activated simultaneously and operate at their full nominal power from the beginning of the flexibility event.

Table 4 - Downward Flexibility Potential from Residential Electric Water Heaters

Flexibility Method	*Average flexibility potential (MW)*	*Average Duration (minutes)*
On/Off Control	**74.3**	**~3.6**
5°C Setpoint Increase	**90.0**	**~6.2**
10°C Setpoint Increase	**92.4**	**~7.7**

The results show that setpoint increase methods provide higher power flexibility compared to simple On/Off control. A 10°C increase offers the highest average flexibility potential, with nearly 92 MW of load increase, sustained for 8 minutes on average.

Hourly and daily average comparisons show that the highest downward flexibility potential occurs during the nighttime and early morning hours (00:00–06:00). By raising the setpoint temperature during these periods, additional electrical energy can be stored in the water tanks, thereby increasing the load in a controlled manner. As the day progresses and hot water demand rises, the available flexibility decreases but remains consistently significant.

Overall, EWHs represent a highly reliable source of downward flexibility, especially during off-peak hours. The control strategy plays a crucial role in shaping the flexibility profile: setpoint increases (e.g., +10°C) result in higher load uptake but require careful thermal management to avoid unnecessary energy use or reduced efficiency.

Table 5 – Upward Flexibility Potential from Residential Electric Water Heaters

Flexibility Method	*Average Flexibility Potential (MW)*	*Average Duration (minutes)*
On/Off Control	**4.9**	**~5.6**
5°C Setpoint Decrease	**5.5**	**~8.4**
10°C Setpoint Decrease	**5.6**	**~9.3**

The results show that decreasing the setpoint temperature provides moderately higher load reduction potential than basic on/off control. A 10°C setpoint reduction resulted in the highest average load drop, offering up to 5.5 MW of flexibility for about 9 minutes, primarily by delaying heater activation. These reductions are most effective in the morning period (07:00–11:00), when consumption typically ramps up. Temporarily lowering the setpoint during this time helps flatten the morning peak and reduce grid stress.

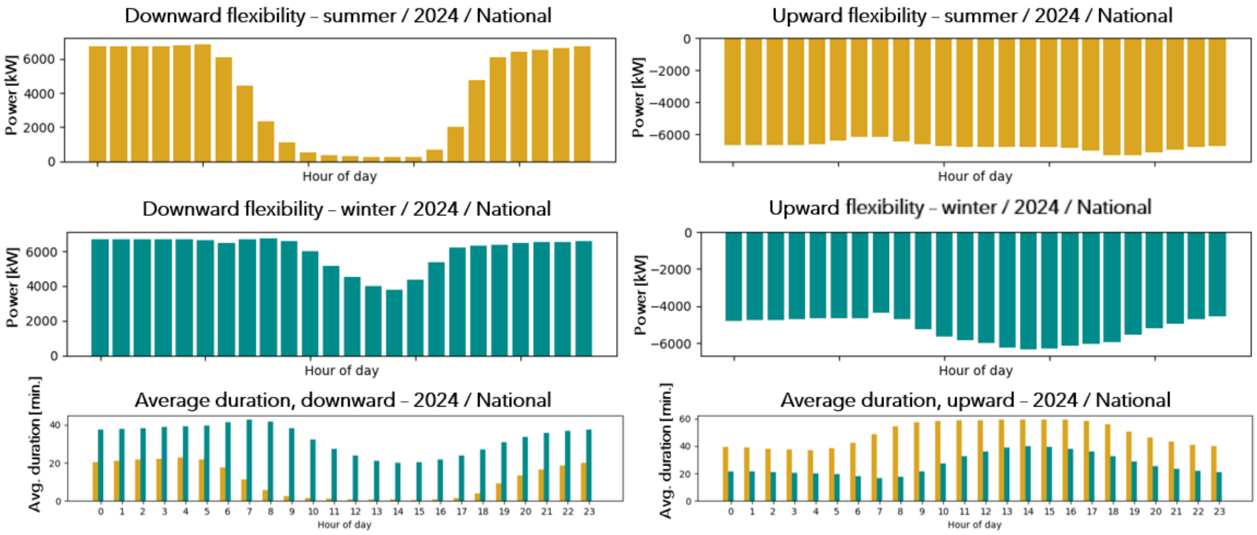
Overall, EWHs are a valuable source of upward flexibility, particularly during morning and early afternoon periods. While On/Off control provides quick responses, setpoint adjustments allow for smoother and longer-duration flexibility, making them more suitable for sustained demand shaping and grid support.

PV - Battery Energy Storage System

Battery energy storage systems for PV installations (PV BESS) are becoming increasingly popular, are in some countries already even the norm for residential PV systems and are meanwhile also being financially supported in Luxembourg. The objective of PV BESS is to increase the share of locally consumed electricity on the PV generated energy. Besides the optimisation of self-consumption for the battery owner, the battery capacity could technically be used to provide flexibility. Exact numbers of PV BESS in

Luxembourg are not known, and the amount is expected to be rather small. But since end of 2022, about 820 batteries have been financially supported.

The estimation of flexibility potentials of PV BESS is based on the simulation of 100 statistically representative battery storage systems and connected PV systems, using past meteorological data and artificial electricity consumption profiles. The calculated SoC (state of charge) allowed at any time to estimate the power and duration for which the system could either be charged to store energy from the grid (downward flexibility) or could feed-in previously stored energy to the grid (upward flexibility). Those results for 100 representative PV BESS were then upscaled to the amount of known system in Luxembourg today.


Downward flexibility – summer / 2024 / National

Upward flexibility – summer / 2024 / National

Downward flexibility – winter / 2024 / National

Upward flexibility – winter / 2024 / National

Average duration, downward – 2024 / National

Average duration, upward – 2024 / National

Figure 8 - Residential PV BESS flexibility potential – today (summer and winter)

The simulation results have been analysed to estimate the flexibility profile for a typical summer day, as well as a winter- and transition period profile: As depicted above (Figure 8) for winter and summer, with the amount of known PV BESS installations today, the ***flexible charging to store energy from the grid*** (downward flex., left graphs) has a clear diurnal profile: During summer (top, left), the batteries could take up energy from the grid with more than 6 MW charging power until the early morning hours, when they start being charged by the PV systems, while from noon until late afternoon, the potential is almost zero. Also the average duration for which the systems could charge this power during summer (bottom, left) is rather short – up to 20 minutes outside the sunny hours, falling to almost zero quite early. During the winter period, the capacity to charge energy from the grid (about 4-6 MW downward flexibility) is permanently given, although also here the capacity and duration (20-40 minutes) varies during the day.

The possibility to ***flexibly feed energy to the grid***, defined as upward flexibility, is rather stable during the diurnal cycle (6 MW): During summer, the batteries almost never run empty, while in winter, the power during the day-light hours is about 20-30% higher than outside the sunny period. The average duration a PV BESS could provide upward power flexibility varies between 40-60 minutes during summer and 15 – 40 minutes during winter.

The most interesting aspect about the PV BESS potential are the large growth rate that can currently be observed: 35% of the recent requests for financial support for residential PV systems included a battery energy storage system. To project the number of PV BESS in 2030 and 2040, several assumptions need to be made. Considering the past national and European developments of PV[1] and PV BESS installations, the PV growth scenario of the updated NECP for 2030, and the “target scenario” for 2040 in the initial NECP have been considered as a basis. Until 2030 we assume that 37% of the new PV installations are residential PV of which 50% would be built in combination with a battery system, resulting in 120 MW PV

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[1] The ILR reported a total of 590 MW photovoltaic installation at the end of the first quarter of 2025

BESS capacity. From 2030 to 2040, again 37% of the new installations are considered residential systems, with a share of 80% BESS, meaning additional 167 MW of PV BESS capacity. In addition, 10% of the currently installed 590 MW of PV systems are considered to be upgraded with a battery storage system, as well as additional 40% of existing systems, until 2040.

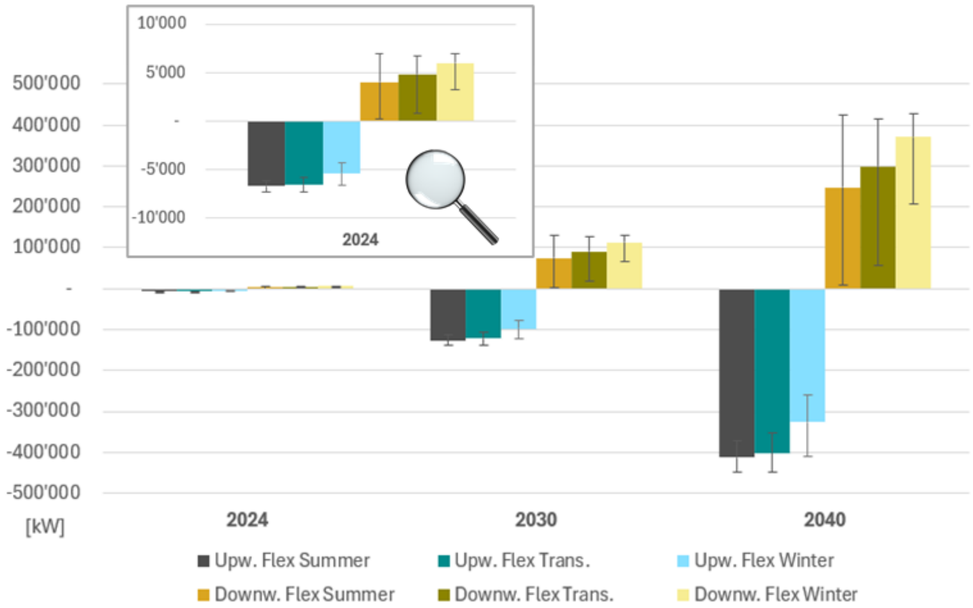

Figure 9 - Upscaled PV BESS power flexibility potential 2030 and 2040

Upscaling the simulation results with these numbers, the resulting average up- and downward flexibility for 2030 and 2040, as depicted in Figure 9, is hence dominated by these huge growth rates. The bars show the average flexibility for each season and scenario year, while the daily variation of this power flexibility is expressed by the interval bars (thin black lines) for each bar.

Table 6 – average power flexibility of PV BESS across seasons and scenarios

	Season	Today (2024)	2030	2040
Average Upward Flexibility (feed-in mode)	Summer	6.7 [MW]	125 [MW]	413 [MW]
	Transition	6.6 [MW]	122 [MW]	401 [MW]
	Winter	5.4 [MW]	98 [MW]	327 [MW]
Average Downward Flexibility (storage mode)	Summer	4.0 [MW]	75 [MW]	248 [MW]
	Transition	4.8 [MW]	92 [MW]	299 [MW]
	Winter	6.0 [MW]	113 [MW]	370 [MW]

Electro-Mobility

One important, if not the main, pillar of Europe’s as well as Luxemburg’s strategy for climate change mitigation in the mobility sector is the shift towards full electric mobility. Besides the arising challenges associated with the increasing electricity demand, this transition process comes also with opportunities via “smart charging”. Within this study we considered flexibility provision via “smart charging” (not yet the more advanced vehicle-to-grid concept) at three different charging locations: public charging stations, charging at home and at workplace. The “smart charging” model took rather conservative assumptions, as the modelling approach assumes,

a) to guarantee the EV user the maximum charge possible and only uses flexibility whenever the expected “time of leave” allows for a full charge, and
b) that the mobility- and charging-behaviour remains unchanged and EVs are only plugged-in when the state of charge (SoC) is below 50%.

The methodology for the simulation of public charging processes deviates from the simulation of charging processes at home or workplace: Data on the usage for the main public charging infrastructure (“chargy”) has been used as a basis to assess the flexibility potential from public charging. Flexibility from home charging and at workplace has been simulated with the help of artificial mobility profiles.

The model calculates the expected charging behaviour for all three charging locations as the baseline consumption. Flexibility can be provided by deviating from this baseline via smart charging, following three strategies – two continuous charging settings and one “on-demand” flexibility provision mode:

> **Maximum delay** (continuous) - delaying the charging process until the latest moment in time that still allows for a full charge (EV user defines foreseen departure time)
>
> **Modulated charging power** (continuous) – reducing charging power to a minimum that guarantees a full charge at departure (user defines departure time)
>
> **Instantaneous flexibility** (on demand) – the hourly instantaneous flexibility describes the amount of load reduction that could be acquired by activating flexibility *instantaneously* within a specific hour of the day. This results in delaying all EVs during that hour for which the foreseen departure time allows a maximum charge.

The graphs in Figure 10 indicate the baseline consumption profile for EV charging on a typical weekday (as solid lines) for home- and workplace-charging on the left side and public charging in the right graph. The dashed lines (indicated as “max delay”) represent the potentially shifted charging profile if each charging cycle is maximally delayed. The dotted lines (“modulated”) is the charging profile if the power is reduced to still reach a full charge at the time of leave. All profiles represent the current amount of electric vehicles in Luxembourg (2024).

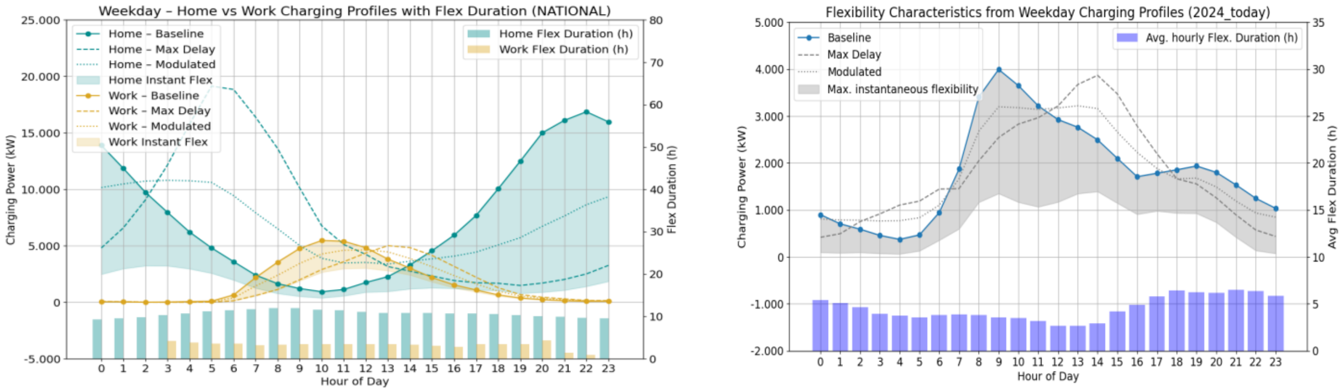

Figure 10 – baseline consumption, power flexibility and average duration from home- and work-charging (left graph) and public charging (right graph) – at today’s level of EV penetration

The potential hourly charging power reduction that could be activated instantly (**instantaneous flexibility**) is marked by the shaded area underneath the baseline curve. The **average duration** for which an EV could sustain the instantaneous flexibility provision is presented by the bars at the bottom of the graph, referring to the right side y-axis.

On a typical weekday, the ***baseline consumption*** (solid line, **cyan**) at ***home charging*** is relatively high during the night & early morning hours, but drops to a minimum in between 7:00 and 12:00, rises then steadily and reaches a peak between 19:00 and 00:00. The ***instantaneous flexibility*** that could be requested within a certain hour, visualized by the shaded area below the baseline graph, is at a high level during night with about 13.8 [MW], but drops to about 550 [kW] at 09:00, and rises again towards the evening to a peak of 15.4 [MW] at 22:00. On average, EVs could hold up flexibility provision for about 10 [h], under the assumption that they remain plugged once charging until next leave – although the aggregated instant flexibility would drop during that period.

The ***workplace*** charging ***baseline consumption*** (solid line, **beige**) is expectedly zero during night times and rises up from 6:00 to a peak between 10:00 – 11:00 and slowly drops again towards the evenings – the general consumption level is much lower than at home charging (peak at 5’470 kW at 10:00). ***Instant. flexibility*** remains relatively low, with a peak of about 2’870 [kW] at 10:00, while the average duration remains rather short, with 3 - 4 hours maximum.

The **baseline consumption** (solid line, blue, right figure) at **public charging** is low during night and rises up from 6:00 to reach a peak of comparably low 4’000 [kW] at 9:00. During the day, the consumption drops gradually and rises at late afternoon to a lower second peak around 19:00. The instantaneous flexibility remains between 2’550 [kW] and 740 [kW] in the time range from 8:00 until the late evening, at an average duration between 3-6 hours.

A continuous **max. delay strategy** can be found as an effective mean to reduce the evening peak (for home charging) by approximately 80%, but would shift large parts of this consumption towards the early morning hours and create an even higher peak then - obviously, this effect could be scaled down to the desired level by activating only a share of the flexibility. For public- and workplace charging, a similar effect can be observed during the day, but at much lower scales, reducing their peak during the morning (25-40%) and shifting towards the afternoon.

The continuous **modulated charging power** strategy has a smoothening effect on all three profiles, resulting in peak reductions (e.g. up to minus 50% of the evening peak for home charging) but does not create new peaks.

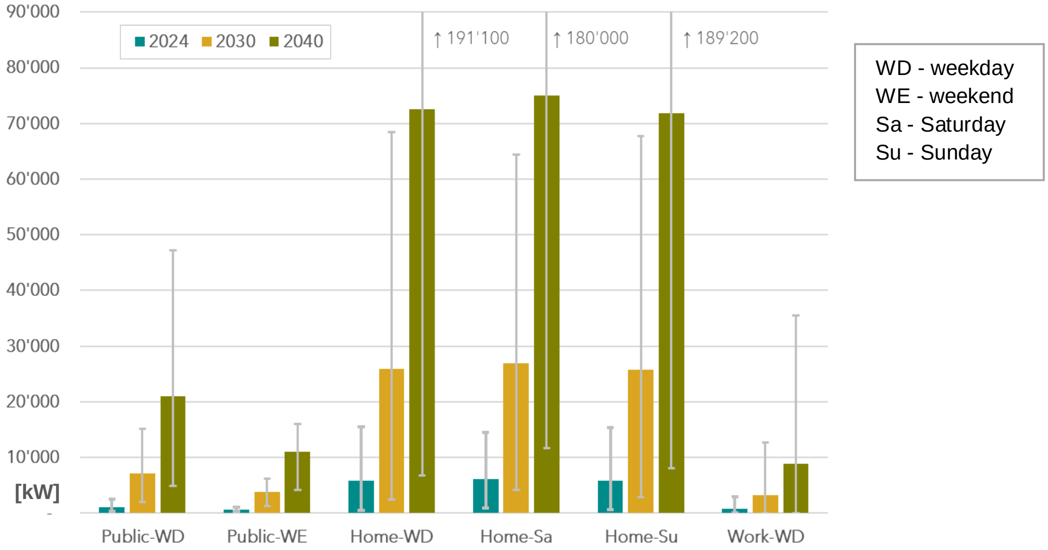

Figure 11 - daily average, instant flexibility for different charging options and scenario years - interval bars indicating the daily fluctuation (min/max)

While previous results represent the daily dynamics and the technical potential today (at 34’819 EVs registered nationally), the EV sector is dynamically growing. Our model considered EV penetration scenarios for 2030, with 154'000 EVs and 2040, with 430'500 EV in Luxembourg – taken from CREOS scenario report (2024 version). The upscaling of previous results to future scenarios is done proportional to the amount of EVs and does not consider the charging infrastructure as potentially limiting factor. Scaling up and averaging the fluctuating instantaneous flexibility over the day, Figure 11 depicts the average instantaneous flexibility by scenario and charging location, and distinguished weekdays and weekends – interval bars represent the daily minima and maxima.

In total, the daily average instant flexibility, summed up over the three charging locations, reaches about 36 MW in 2030, for a typical weekday. In 2040, the potential rises further to about 102 MW, on average. But the peak instant flexibility over three charging locations appearing around 22:00 is substantially higher and sums up to 75 MW in 2030 and 210 MW for the 2040 scenario.

Summary and qualitative evaluation of flexibility potentials

A superficial comparison of flexibility potentials across sectors may mislead conclusions, if based on simplifications of complex results. The previous chapters demonstrated that flexibility potentials for the different sectors vary over time – for some sectors with the daily cycle, weekly schedule, based on seasons or weather conditions. Nevertheless, a comprehensive overview is required to set priorities and draw conclusions towards the mobilisation of these potentials. Hence, the simplified numbers shown in Table 7 are mostly averages of a fluctuating availability of this flexible power, that could be provided over a limited, also fluctuating and individual duration.

As briefly laid out in the previous chapters, the data availability and modelling approaches for each sector are very different. Tertiary sector and industry sector flexibility are based on statistics, literature values and assumptions. While the models for heat pumps and electro mobility are based on more solid number for today's technology penetration and the dynamics are based on detailed model-based representations of reality. Results for whiteware, electric water heaters and PV-battery storage systems are also based on technical models, while the numbers for today´s technology penetration is more uncertain.

Table 7 - Summary of flexibility potentials and qualitative assessment indicators

		Industry sector	**Tertiary sector**	**Heat pumps**	**White ware / EWH**	**PV-Battery**	**EVs**
	Technical maturity	●	◑	◕	◑	◑	◕
	Ease of implementation	◑	◑	◑	◔	◔	◑
avg. flexibility potential [MW]							
2024	Upward Flex.	-20.2	-29	-3.6	-16	-6.6	-17
avg. Pot.	Downward Flex.		48	7.9	74	4.8	
2030	Upward Flex.	-41.0	-29	-60	-16	-122	-76
avg. Pot.	Downward Flex.	20.8	48	130	74	92	
2040	Upward Flex.	-61.7	-29	-123	-16	-401	-212
avg. Pot.	Downward Flex.	41.5	48	265	74	299	
avg. flexibility duration [min.]							
	Upw. Duration	*15-240*	*60**	*20-120*	*60* / 5.6*	*20-60*	*180-600*
	Downw. Duration		*60**	*9-80*	*- / 3.6*	*0-40*	

* the marked durations are no modelling results, but assumed model inputs

The technology penetration of heat pumps, EVs and PV-BESS is rapidly growing. This dynamic development of the related potential needed to be represented by scenarios, which inherently underly large uncertainties. All scenarios were evaluated against current developments and based on national, either political strategy or technical scenario papers.

Beside the plain numbers characterizing the flexibility potential in terms of power and duration, there are other factors that should be taken into account when considering the mobilisation of these potentials:

Technical readiness – using flexibility from different assets and sectors requires technical solutions and a level of standardisation that is quite different for each sector. The maturity of technical solutions (e.g. communication, automation and standardisation of control interfaces) plays a crucial role in assessing how quickly a flexibility potential could be mobilised. This qualitative assessment has been summarized in Table 7.

- Flexibility from (large scale) industries are already today used for balancing flexibility in other European countries.
- Also heat pumps are used for economic optimization purposes by energy suppliers and some manufacturers offer (almost) standardized control interfaces. Hence, the technical maturity for those assets can be considered moderately high, although it's usage for network needs is not established today. Further, the currently used approaches are often low-tech solutions, while more granular, nuanced control options and bi-directional communication is hardly established.
- "Smart EV charging" solutions exist, although these are mainly implemented for shared use of limited, local power capacities, and less common for network needs – but pilot projects and start-ups exist,

testing solutions in operational environments. A technical standard is available and is being pushed, but it is not very stringently defined, leaving a lot of room for interpretations.

- Some aggregators and energy service companies offer furthermore flexibility from tertiary sector facilities, often linked to other services (e.g. energy saving contracts) or electric water heaters. Latter mainly in markets where those devices are widespread (e.g. France) – although these solutions are much less common.
- For white ware, the larger scale activation of those potentials would require a local automation and control instance, such as an energy management system, and compatible devices.
- Flexibility from PV battery storage is today only used by some of the battery manufacturers themselves, offering business models e.g. on balancing markets, but many products offer functionalities (e.g. production peak shaving or forecast based injection modes), that are basic functions for a smart, flexible operation. Also regarding this technology, a lack of standardisation and transparency hinders the large-scale usage of this potential, complicating the control and incentivisation of smarter solutions.

Ease of implementation – besides the technical aspects other factors influence the complexity and challenges of mobilising the flexibility potentials:

- Within the industry sector, a small number of stakeholders hold a large part of the potential, which is a huge advantage as compared to the potentials from the residential sector, that is very scattered in large amounts of small units. On the other hand, the tight economic pressure in the industry and focus on their core business, requires tailored solutions to minimize the impact on their production processes.
- Similarly, the tertiary sector is driven by economic pressure and a focus on their core business, hence their resources are rather constrained by daily routines. Opportunities might arise when building- and energy management is outsourced to specialized companies.
- The impact on user comfort is another factor, specifically regarding flexible use of whiteware devices, where consumer interaction is required. This is a clear advantage of heat pumps and storage-based water heaters, that could provide flexibility with minimum impact on the user’s comfort, if well implemented. Mobilisation of the comparably low potentials from white ware and electric water heaters is further hampered by the scattered nature of these assets. Additionally, the lack of a heat pump tariff, which would imply the option of a flexible switch-off and would lead to a more flexible system design (eventually including larger storage volumes), as well as the lack of experience of the installers with such smart solutions, hinders the mobilisation of this potential.
- Concerning PV BESS, the strong economic interest of the PV system owner for self-consumption optimisation and resentments regarding battery degradation, might stand against this use-case (although studies seem to proof that win-win scenarios are possible). While technical solutions for a smarter operation exist, though not highly standardized, the economic incentive is lacking. This might change with more attractive dynamic electricity tariffs, adapted injection time-of-use grid tariffs or even dynamic grid fees.
- Further, smart EV charging at workplace or public charging stations could be implemented with less effort, considering the ownership of charging stations and contractual situation. But flexibility from home charging has been proven to be more interesting for network needs, although appears to be more complex to be mobilized. Hence, a real smart charging option for home charging is not straightforward due to technical challenges. But a user-driven grid-relieving charging behaviour, via a delayed charging or modulated charging power induced by the user, can be incentivised, via time-of-use tariffs for example.

Activation strategy

The technical flexibility potentials identified here can be considered as the upper bound and might only be available for short durations. Through carefully designed activation strategies, these short-term peaks can be spread over longer durations of lower power flexibility. Such sequencing requires managing rebound effects and device-specific constraints to ensure reliable and usable flexibility for system operation.

Matching the characteristics of flexibility potentials to needs and our main use cases

Some of the network needs for flexibility are characterised by specific properties regarding where and when these conditions occur. These characteristics need to be matched by the characteristics of the individual flexibility potential to effectively alleviate the stress on the network:

Distribution (LV) and MV-networks will be increasingly experiencing congestions and voltage-issues due to ***high PV-production during spring- and summer period***, which specifically concerns rural areas with long distribution lines and low demand. Downward flexibility from tertiary sector would be suitable during this period but is situated mainly in urban areas. Heat pumps are seasonally not well suited but could contribute to a limited extend via domestic hot water production, such as electric water heaters can deliver this downward flexibility. EV-based flexibility is limited during mid-day (mainly public- and workplace charging), but suitable. If PV BESS are purely operated for optimisation of self-supply (as done today), the grid-relieving effect is minimal. But they could contribute very targeted flexibility if operated smartly, by e.g. forecast-assisted charging over noon, as some of the manufacturers already include similar functionalities and could be a good fit to alleviate the PV peak induced grid stress.

Table 8 - Qualitative assessment of the suitability of flexibility to alleviate the grid during PV peak periods

Flexibility use case: high PV peak production mid day, spring/summer locations: LV and MV, (urban &) rural	Industry sector	Tertiary sector	Heat pumps	White ware / EWH	PV-Battery	EVs
Suitability rating		◑	◔	◑	○ (◑)	◑
seasonal suitablity		++	-	+	- - (+)	+
diurnal cycle		+	+	+	- - (+)	-
location (voltage level, urban/rural)		-	+	+	+	+

The already existing ***evening peak***, specifically ***during winter***, is expected to be fortified by the home-charging of EVs and intense operation of heat pumps in the cold period. To alleviate potential congestions, upward flexibility by reducing or postponing loads could be activated. Specifically, home-charging EVs have the potential to be very effective for this use case, being available at the suitable time and location, while the average durations to shift their charging is long enough. Heat pumps themselves, having long operation cycles during cold periods, are limited in the flexibility duration during that season. But if heat pump systems are designed with the option to be switched off for a limited, but long enough period (e.g. 2h), reducing impacts on user comforts, a smart activation strategy can help reducing grid stress. Whiteware and electrical water heaters could potentially shift loads into the night but are limited in potential. Also, PV battery systems are potentially available to feed energy back to the households, but their average state of charge during winter evenings is low, resulting in short durations. If the PV BESS would be charged from the grid during the day, the potential is obviously largely increased.

Table 9 - Qualitative assessment of the suitability of flexibility to alleviate the load peaks at winter evening

Flexibility use case: Heat pump and EV peak evenings, winter locations: LV, urban & rural	Industry sector	Tertiary sector	Heat pumps	White ware / EWH	PV-Battery	EVs
Suitability rating	○	◔	◑	◑	◔	◕
seasonal suitablity	+	-	-	+	-	+
diurnal cycle	+	-	-	+	+	+
location (voltage level, urban/rural)	- -	+	++	+	+	++

Prioritisation and recommendations

Based on identified potentials, technical characteristics, and constraints, the following priorities are recommended:

I. **Heat pumps** can provide flexibility via “smart grid ready” modes, but their duration in cold periods is limited, reducing their impact on the winter evening peaks. Policy should incentivise designs with thermal storage or other measures to enable longer blocking periods, supported by tariffs or programmes rewarding e.g. two-hour flexibility.

II. **PV-battery systems** currently provide little grid-relieving effect, as operation is not aligned with system needs. Existing support schemes could therefore be reviewed to incentivise operation modes that explicitly target grid support (e.g. midday charging) for congestion and peak reduction.

III. **Electric vehicles** could offer major flexibility, specifically valuable through smart charging at home. To harness this potential, ensuring that wall boxes meet future-proof standards and interoperability is essential.

IV. **Industry** provides large, site-specific flexibility and should be integrated into balancing and grid services. Electrification trends (e.g. electric steam generation) should be monitored, as they will shape future potentials, specifically for a transitional period.

V. **Tertiary sector** flexibility from cooling and HVAC can relieve summer grid stress and absorb PV surplus, even if limited in duration. Energy service companies could be an enabler, e.g. by integrating flexibility into efficiency contracting models.

VI. **Household appliances and electric water heaters** offer small but scalable flexibility if aggregated and automated through digitalisation: home energy management systems will play a crucial role to access that sector.

Finally, the results of the FlexBeAn project demonstrate that Luxembourg holds a significant technical demand response potential in terms of the potential power flexibility, although the durations that flexibility could be sustained are, for some assets, rather limited on average. If harnessed effectively by an adequate activation strategy, the available flexibility could, nevertheless, play a crucial role in addressing the challenges posed by the Luxembourgish power system decarbonization, i.e., alleviating grid congestion, better integration of RES, and contributing to price stability in electricity markets. As shown, especially household assets such as heat pumps, PV batteries and EV hold a significant flexibility potential in the future, suiting network flexibility needs, if implemented and operated in an adequate manner.

The practical activation of those potentials can be a demanding and requires concerted actions of all involved stakeholders to set the right framework conditions and incentivise grid relieving usage of the available flexibility potential. The necessary steps towards a targeted implementation of demand side flexibility are documented in our policy advice paper: *“The beating heart of the Luxembourgish energy transition - How flexible energy consumers contribute to a reliable and low-carbon energy system in Luxembourg”.*

If you are interested in further details on the availability and modelling of the flexibility potentials, please refer to the full report on “Technical flexibility potential in Luxembourg”. Both reports, alongside further interesting insights in the additional activities of the project, can be found on the project’s website, as well as the individual project partners websites, at CREOS, LIST and SnT.