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HOW TO MAKE ELECTRICITY DEMAND MORE RESPONSIVE TO VARIABLE RENEWABLE GENERATION

A Summary of 150 empirical estimations of demand flexibility

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FACULTEIT ECONOMIE EN BEDRIJFSKUNDE

KEY FINDINGS

- We conducted a meta-analysis of 150 empirical estimations of demand flexibility from 44 academic studies.
- We identified the effect of information-based stimuli, financial stimuli, and automation technology.
- In isolation, information-based stimuli, financial stimuli, and automation technology don't work very well at decreasing electricity demand at peak times.
- But when used in combination, demand response works much better. It's like combining different ingredients to make a tastier dish.
- Information-based stimuli help people notice the financial rewards of their actions, while automation technology makes these actions effortless.
- All types of financial stimuli for saving electricity work about equally well. In Flanders, households can easily estimate their savings from switching to a dynamic tariff on the VREG website https://vtest.vreg.be/.
- Comparing behaviour with others (social comparison) is more likely to improve demand flexibility than just being told what's right or wrong (moral appeal).
- Making demand more flexible requires that information-based stimuli, financial-based stimuli, and automation technology are all in place. In the context of Flanders, this means for instance having a dynamic contract, connecting to mijn.fluvius.be to monitor your usage, and automatically charging your electric vehicle and controlling heating with smart apps and smart devices like thermostats and plugs.

INTRODUCTION

This Gents Economisch Inzicht synthesizes the results of 44 academic studies analysing the most important factors to make electricity demand more responsive to variable renewable generation.

RESPONSIVE DEMAND HELPS RENEWABLE INTEGRATION AND SAVES MONEY

The transition to sustainable energy requires a significant increase in renewable electricity generation, like wind and solar. These sources generate electricity without emitting carbon, but their output depends on the presence of wind and sunlight.

Because the supply and demand for electricity must match second by second, the **variability of renewable energy generation means that electricity demand also needs to become more flexible**. On days with minimal wind and sun, it is important to reduce electricity consumption as much as possible to minimize the use of fossil fuels for power generation. Conversely, on days when there is abundant sunshine and strong winds, there is no need to conserve electricity, and we can freely consume the available power.

However, making households' electricity demand flexible is challenging, mainly during morning and evening peak consumption periods. In these times, the household's demand for power jumps quickly, driven by specific – and currently inflexible – needs like heating. The quick jumps in power demand are difficult to tackle by variable renewable generation, and often require gas plants. These plants are capable of supplying the additional power required for peak hours, but this comes at the cost of emitting greenhouse gases.

Demand flexibility not only benefits the environment but also makes economic sense. Since solar and wind produce at zero marginal cost, electricity prices are much lower when solar and wind generation are high. As shown in **Figure 1**, electricity prices vary significantly over time. In 2023, for instance, average prices in Belgium (represented by the black line) were 50-70 €/MWh cheaper during night-time and early afternoon hours compared to morning and evening peaks. For an average household consuming 3.5 MWh in a year, shifting electricity usage away from peak times can result in savings of up to €200 per year. The graph also reveals substantial day-to-day variations (grey area), with some days witnessing peak-to-off-peak price differences reaching as high as €200. Remarkably, there were 222 hours in 2023 with negative electricity prices, meaning that **consumers were paid to consume electricity during those periods**.

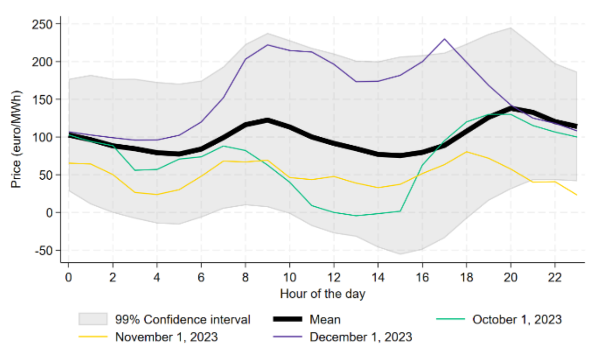

Figure 1*. The average 2023 electricity price in Belgium (black line) varies throughout the day. The 95% confidence interval (grey area) indicates that prices are sometimes negative, especially during night-time and early afternoon hours.*

Today, many large industrial energy consumers are adapting their processes to earn money by shifting their demand to times when renewable energy is abundant and prices are low. At the household level, this demand responsiveness is still very much in its infancy, but the **growing number of electric vehicles (EVs) and heat pumps (HPs) provides opportunities**. Heating your home or charging your electric vehicle is much less time-sensitive and can easily be shifted a few hours (heating) to a few days (EV charging), without significantly impacting the user's comfort. This not only reduces the usage cost but also helps integrate large amounts of energy produced by solar and wind.[1]

[1] A recent study by Elia revealed that by 2034, making 80% of HPs and EVs highly flexible can reduce the need for backup production capacity (which is typically fossil-fuelled) by 2700 MW, compared to a scenario in which these assets are not flexible at all (Source: Elia, Adequacy & Flexibility Study for Belgium 2024-2034, p. 220). For reference, a new large-scale gas powerplant (CCGT) has a production capacity of ± 800 MW. Roughly speaking, this means that exploiting the flexibility of EVs and HPs can avoid the need to build three large new gas powerplants in Belgium by the year 2034.

Smart heating and smart charging benefit both your wallet and the environment

A BOOMING FIELD OF RESEARCH

In the field of energy economics, there has been a significant increase in research on how people can change their electricity usage. This worldwide effort by scientists aims to understand how much households can adapt their electricity consumption and which methods work best.

Nowadays, experiments are being implemented all around the world to try out various strategies and approaches to **shift from a static, supply-driven electricity system with passive and inflexible demand to one where electricity demand of households responds actively to the availability of renewable energy generation.**

META-ANALYSIS OF ACADEMIC LITERATURE

The research literature identifies three types of approaches that can help households to use electricity more flexibly:

1. **Financial stimuli** imply households can get paid or save money by using electricity at certain times. For example, they might pay less when using electricity during non-peak or at time of high renewable energy production.
2. **Information-based stimuli** empower households to adapt their electricity use through practical information on their electricity contracts and usage or through normative messages. For instance, they might get a SMS text reminding them of the cost of electricity during peak time hours; messages on the importance to conserve energy for society and the environment; or practical tips on how to save energy.
3. **Smart automation** helps households save money and energy without having to think about it, by using smart devices, like a thermostat that automatically adjusts the temperature based on electricity prices; or a smart charging app.

For example, households that have a thermostat that changes the heating automatically (smart automation) when electricity prices go up and down (financial stimulus) will save money. Or, if they get a message telling them when prices are very high, one can consider this a friendly nudge to save more (information-based stimulus).

It is key to find out how these three approaches compare in terms of their effectiveness. To understand this, our review dives into the energy economics literature and focuses specifically on papers published since 2007 that present the results of experiments that aim at making households reduce their electricity consumption during specific time periods – typically during specific hours of the day (peaks) – using one or more of the above three approaches. In doing so, we extracted 150 average treatment effects, which represent the percentage decrease in electricity consumption during these specific time periods.

Five key results

1 DEMAND RESPONSE IS HIGHEST WHEN INFORMATION-BASED STIMULI, DYNAMIC PRICES, AND AUTOMATION TECHNOLOGY ARE COMBINED

Figure 2 presents a summary of the identified 150 average treatment effects for all combinations of the financial or information-based stimuli and automation technology. For each type of approach – or each combination thereof – the figure shows a black dot representing the median decrease in electricity use during the targeted period. Along the black dot, black and grey lines show the level of variation around the median (from the 5^{th} to the 95^{th} percentile).

The figure shows that when we use only information-based or financial stimuli by themselves, the reduction in electricity demand is small, with a median reduction of 4% each (bottom two rows). This means that e.g. simply reminding people to save electricity during peak times or the mere existence of time-varying prices do not decrease electricity demand significantly.

However, when we combine two approaches, we observe a more substantial reduction in electricity demand, especially when experiments paired financial stimuli with automation technology. But the most substantial decrease occurs when we use all three strategies together: information-based stimuli, financial stimuli, and automation technology, reaching a median reduction in the electricity consumed of 19%. These three strategies are mutually reinforcing because certain types of information stimuli can help people understand the financial benefits of their actions, while automation technology makes shifting their demand relatively effortless.

To make electricity demand more flexible, it is therefore important to implement all three strategies. In the context of Belgium, this means for instance having a dynamic contract, having access to clear information on personal electricity usage[2], and using smart apps and devices like thermostats and electric plugs to automate tasks like charging electric vehicles and controlling heating.

Information stimuli help people notice the financial benefits of their actions, while automation technology makes these actions effortless

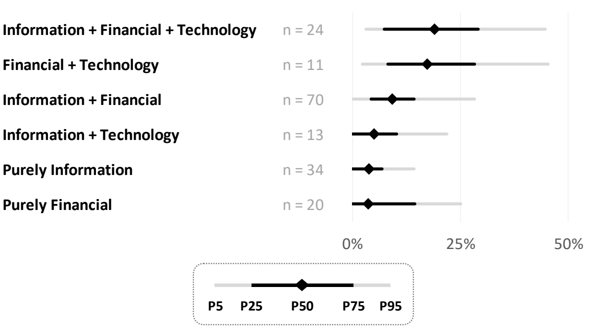

***Figure 2**. Reduction in electricity use by (combinations of) financial stimuli, information-based stimuli and technology treatments.*

Finally, it is worth noting that among the purely financial stimuli – without information stimuli or automation technology – the median effect is fairly low, but that some papers did report very large effects, indicated by the high values at the 75th and 95th percentiles. The reason for this variation is that the figure summarizes a wide range of research papers. Some of the papers investigated settings with relatively weak financial stimuli, where there was only a small difference between the prices during peak and off-peak hours. Other papers study settings where the financial stimuli were very strong, with peak prices being significantly higher than off-peak prices, which led to larger reductions in electricity consumption. Additionally, in certain situations, people may not even have been aware of the financial stimulus in place, which can further explain the observed effects. The next figures will dive deeper into these details.

2 ALL TYPES OF FINANCIAL STIMULI FOR SAVING ELECTRICITY DURING SPECIFIC HOURS WORK ABOUT EQUALLY WELL

One way to get households to use electricity when it is at its cheapest and greenest is to have time-varying prices that reflect the status of electricity production. Different financial stimuli exist and they differ mainly in how granularly they partition time. We categorize the ones most often encountered in experimental research as:

- **CPR/CPP/VPP** ("Critical Peak Rebate," "Critical Peak Pricing", and "Variable Peak Pricing") set different prices for rare peak events. For example, on days forecasted to have very little sun or wind and/or exceptionally high electricity demand, the utility may declare a "critical peak event". If this happens, households under these financial stimulus schemes face much higher prices during that day's peak time (in the case of CPP and VPP) or receive rebates for using less electricity than normal during these peak periods (for CPR).
- **RTP** ("Real-time pricing") closely follows the intra-day variation of electricity prices on electricity markets. Customers in this scheme experience prices which vary hourly or every quarter-hourly during the day and across days.

[2] E.g. through https://mijn.fluvius.be.

- **TOU** ("Time of use") sets different prices at different times of the day. TOU is typically simpler than RTP, with the key difference being that the price schedule remains constant from day to day within a season or year.

In Belgium, while TOU already exists in certain contracts (e.g. those with a day/night tariff), RTP is only developing in Flanders with the so-called "dynamic contracts" and CPR/CPP/VPP are not yet present. In practice, the VREG website[3] offers a **user-friendly tool to help Flemish households estimate their savings from switching to a dynamic contract**.

Figure 3 shows how these financial stimuli compare. Specifically, it presents the median electricity consumption reduction in targeted periods, averaged over all treatment effects where the treatment includes, among other approaches, a financial stimulus[4].

From **Figure 3**, there seems to be no clear indication of one type of financial stimulus being much more effective than another. All three types of financial stimuli result in a median decrease in electricity consumption ranging from 8 to 12%. While the results are inconclusive about what type of new tariff leads to the greatest changes in household electricity consumption, **Figure 3 in light of Figure 2** shows that **what matters is not the presence of a specific type of financial stimulus per se**. Instead, literature suggests that the **combination of financial stimuli to other strategies is what matters the most**. Specifically, households subject to one of these pricing schemes need to know about them (which information-based stimuli contribute to) and need to be able to react to them in an effortless manner (via technology and automation, see Section 5).

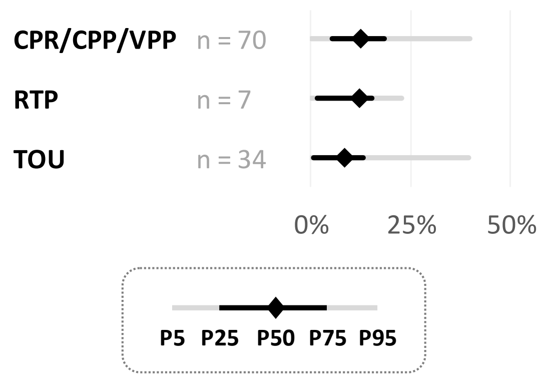

Figure 3. Reduction in electricity use by financial stimulus type. [5]

3 SOCIAL COMPARISONS WORK BETTER THAN MORAL APPEALS

An alternative method to induce more flexible uses of electricity is through information-based stimuli. Rather than offering economic incentives, this approach appeals to people's intrinsic motivation — i.e. by either issuing moral appeals or by comparing people's behaviour with one another — or it provides households with practical information that empowers them to actively adjust their electricity use — i.e. in the form of personalised messages on their electricity consumption, day-ahead peak notifications, tips on how to reduce electricity consumption and estimations of the potential savings from doing so. While the provision of practical information on electricity is often administered together with financial stimuli, moral appeals and social comparisons have been widely tested on their own, as purely normative programs. This enables us to review the empirical evidence on the effect of simply leveraging intrinsic motivation to save energy during peak times in the absence of financial rewards. More specifically:

[3] The tool is accessible on https://vtest.vreg.be/ - "Ik wil mijn verbruiksgegevens opladen".

[4] In the 150 average treatment effects we identified, financial stimuli are most often combined with information-based incentives such as alerts (e.g. for announcing critical peak days) and real-time feedback (to inform households on their consumption during peak periods). In many experiments, they are also paired with technology, which (as Fig. 2 shows) leads to substantial electricity consumption reductions.

[5] The diamond shapes correspond to median values; the black lines include 50% of observations in the middle; the grey lines include 90% of all observations, excluding the 10% most extreme.

- **Moral appeals** are requests to reduce electricity use during times of energy crises, typically issued by public authorities, and addressed to the general public. Governments have raised moral appeals to reduce residential demand of energy and water for decades; mostly during prolonged shortages — such as droughts or lately, the energy crisis provoked by the Russian invasion of Ukraine. More recent applications of moral appeals have been carried out in collaboration with energy utilities that disseminated private messages (via email, phone calls or SMS texts) asking people to conserve electricity for the sake of society and the environment over shorter time spans — e.g. for a few hours in case of a peak event projected for the following day.

- **Social comparisons** are the most widely tested information-based stimulus. Under this kind of program, households receive information on their average electricity consumption during peak times compared to that of their neighbours' or other comparable households. They typically also get a list of practical tips on how to reduce their electricity consumption. Households that consume less than their peers receive a symbolic positive reinforcement in the form of a smiley face or of an upward thumb, encouraging them to keep up the good job. This type of messages works because it impacts people's expectations regarding what others would consider appropriate or how others behave in certain situations. People's desire to conform and feel socially accepted is what ultimately induces such shifts in their consumption behaviour. While this behavioural lever has been tested to induce overall electricity reduction, regardless of time of use, more recent experiments have used social comparisons to reduce electricity use during peak times.

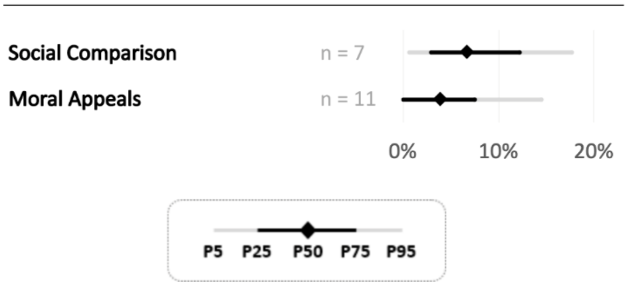

Figure 4. *Reduction in electricity use achieved by social comparisons and moral appeals.* [6]

Our review indicates that **both types of stimuli work, with social comparisons being slightly more effective compared to moral appeals.** As shown in Figure 4, they can achieve a median reduction of electricity use of 7% and 4% respectively. However, these results point out that **the overall reduction in electricity use that can be achieved by raising intrinsic motivation alone is still relatively small and on its own insufficient to meet the demand adjustments required to match the intermittent availability of renewable energy.**

4 INFORMATION MAKES FINANCIAL STIMULI MORE EFFECTIVE

While raising intrinsic motivation to conserve energy during supply shortages may not suffice on its own, these and other information-based stimuli can be used to complement financial stimuli. **Our review shows that information-based stimuli can significantly boost the effectiveness of financial ones.**[7] As Figure 5 shows, the median reduction in electricity use that the three types of financial stimuli can achieve when matched with information-based stimuli, increases **by 5 to 9 percentage points** compared to when the financial stimulus is administered on its own. The information-based stimuli that are most frequently matched with financial ones include saving tips, day-ahead peak time alerts and real-time information on one's own electricity consumption — typically provided through in-home

[6] The diamond shapes correspond to median values; the black lines include 50% of observations in the middle; the grey lines include 90% of all observations, excluding the 10% most extreme.

[7] Based on our review, we hypothesize that the increased impact of these incentives when administered in combination is due to two concurring reasons. On the one hand, information-based stimuli provide households with crucial and timely information on existing financial incentives, allowing them to adjust their consumption accordingly. On the other hand, these categories of stimuli appeal to distinct groups. Specifically, the literature shows that households with high energy consumption are more influenced by social comparisons, while those with lower consumption tend to be more sensitive to financial incentives.

displays or access to online portals like https://mijn.fluvius.be.

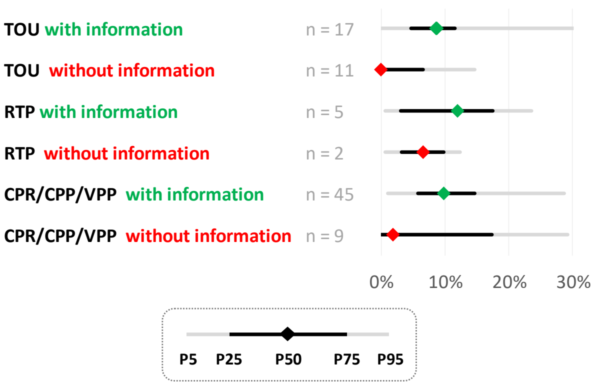

Figure 5. *Reduction in electricity use achieved by financial stimuli, in the presence (green) and absence (red) of information-based incentives.*[8]

5 AUTOMATION TECHNOLOGY GIVES A BIG BOOST TO THE RESPONSIVENESS OF ELECTRICITY DEMAND

The last piece of the puzzle in making household electricity demand flexible is to render it low effort or — better — fully effortless. **This can be accomplished through technologies that enable households to turn financial or information-based stimuli into more sizeable energy savings**. For example, technologies may be used to shift the functioning of certain appliances away from periods when it is both environmentally unfriendly and economically non-sensical to use them.

In our review, we identify two central roles by which technology may contribute to a flexible electricity demand.

First, in order to make the most out of the renewable electricity generation, we need to electrify as many end-uses as possible. That is, for example, replacing fossil fuel cars by electric vehicles (EVs) or gas heating with heat pumps (HPs). Of course, these appliances are highly electricity-intensive and may hence increase the pressure on the electricity grid. **But that also means that they offer a great potential for flexibility**. There is indeed the possibility to shift the moment an EV starts charging (or discharges on the grid) or the moment a HP heats a home. **These types of appliances are what we call "large shiftable loads".** Of course, already widely spread white goods such as electric ovens or washing machines fall in that category as well: they consume large amounts of electricity and it is beneficial for both the environment and our wallet (in presence of economic incentives) to shift their use away from peak times.

Second, while on paper these appliances may offer large potentials for flexibility, it may remain difficult to turn that potential into practice in the absence of what we call "enabling technologies". **Enabling technologies are devices that make the process of shifting electricity away from peak times easy.** That can be, for example, programmable thermostats, which help households set up schedules for heating; or smart charging stations for EVs. Controllable electricity plugs (for example with an app) may also help making some appliances flexible.

Figure 6 shows the median electricity consumption reduction averaged out over treatment effects which include technology, among other stimuli. As shown by the median value of 9%, **having large shiftable loads lead to reductions in electricity consumption during peak periods**. More remarkably, there is a clear signal that **households that own enabling technologies reduce their electricity consumption during peak periods substantially more**, as is shown by the median effect of 17% and the 75th percentile nearing 30%.

While this is great proof that enabling technologies may help shifting electricity and hence support an electricity system largely based on renewables, **there is room for much more.**

Indeed, across the 27 average treatment effects that we identified as linked to owning enabling technologies, the vast majority of these households only had programmable thermostats. While these thermostats help households shifting their heating, they are definitely not "smart", as is the case with most enabling technology devices currently available on the market. Instead, in the future, **smart enabling technologies will scale up and be used to automatically shift the**

[8] The diamond shapes correspond to median values; the black lines include 50% of observations in the middle; the grey lines include 90% of all observations, excluding the 10% most extreme. All treatment effects that have a tech. treatment are excluded.

functioning of the appliances that they control by receiving direct signals from the utilities, telling them when it is most financially and environmentally beneficial to operate, while respecting households' comfort boundaries. For instance, EV **smart chargers can optimize the charging time** of an electric vehicle **while ensuring that households' preferences in terms of guaranteed minimal range and other comfort needs (e.g. specified through an app) are met at all times.**

Smart, safe, simple and accessible enabling technologies are really the key to unlock the flexibility potential of large shiftable loads. That will not only help the integration of renewable energy but also save us money on the electricity bill through financial stimuli; achieving both effortlessly while respecting our comfort preferences.

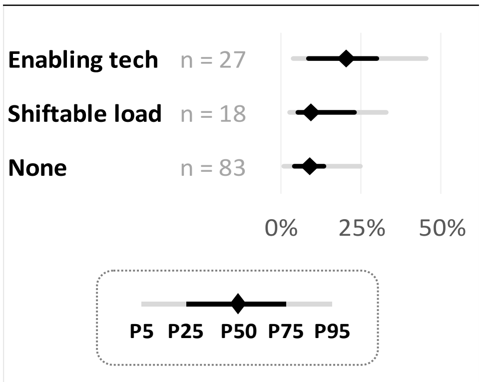

Figure 6. *Reduction in electricity use in the presence of enabling technologies and shiftable loads.* [9]

"Smart, safe, simple and accessible enabling technologies are the key to unlock the flexibility potential of large shiftable loads."

CONCLUSION

Our study on household electricity demand responsiveness in a renewable energy-dominated system reveals several key findings.

Our analysis indicates that information and financial stimuli alone may not be sufficiently effective to trigger the level of demand responsiveness needed to support an electricity system predominantly powered by wind and solar.

The results are more promising when information-based and financial stimuli are combined, especially since information messages can help making households more aware of and attentive to the financial stimuli that may benefit them. Additionally, the availability of technology that can automatically adapt electricity consumption profiles greatly enhances the effectiveness of these incentives. The presence of large, flexible loads, such as heat pumps (HPs) and electric vehicles (EVs), is also beneficial in achieving meaningful demand flexibility.

However, for this vision to become a reality, concerted action is needed from policymakers, manufacturers, and the scientific community. Policymakers must ensure the rapid proliferation of shiftable loads like HPs and EVs, in tandem with the expansion of wind and solar power. But equally important is ensuring that the loads from HPs and EVs are easily shiftable in a fully automated way.

To support the transition towards more demand flexibility, policymakers should support large-scale, on-the-ground experimentation with fully automated household flexibility. As scientists, our role in this evolving landscape is to partner with market players at the forefront of this transition, aiding in the acceleration of learning and scaling processes. Simultaneously, policymakers should strive to eliminate barriers hindering the development of an interoperable ecosystem of flexible household assets. This involves enforcing transparent and well-documented communication protocols and avoiding the creation of 'walled gardens' by manufacturers, thereby ensuring that different brands and types of appliances can seamlessly interact with each other and the energy market.

In summary, while the current state of household demand responsiveness may be modest, the potential for significant impact is undeniable. The journey to realizing this potential will require collaborative and proactive efforts across multiple sectors, ensuring that the future energy system is not only sustainable but also resilient and efficient.

[9] The diamond shapes correspond to median values; the black lines include 50% of observations in the middle; the grey lines include 90% of all observations, excluding the 10% most extreme.

Intermezzo: Is residential flexibility already possible in Belgium?

Scientific experiments have shown that financial stimuli, information-based stimuli and automation technology can help in making household electricity demand flexible. **So far, how widely are these approaches implemented in Belgium?**

A first key step for achieving significant flexibility is to install smart electricity meters in homes. They are essential for implementing the new dynamic contracts. However, in Belgium, their installation varies across regions, as shown in Table 1.

Table 1. *Smart meter rollout to date across the three regions in Belgium*

	Flanders	Wallonia	Brussels
Number of installed smart elec. meters	> 1 800 000	230 000	(Rollout started in Oct. 2023)
Target	80% by end 2024 (of all customers)	80%* by 2029 (*of priority customers)	≈ 100% by 2030 (of all customers)

Financial stimuli - Under EU regulation, large electricity providers must offer dynamic contracts. These contracts have tariffs that change every hour and they require a smart meter (to calculate the bill). This is why such contracts are currently only available in Flanders. **Table 2 shows an overview of the nine dynamic contracts currently available to Flemish customers**, as well as the way to calculate the price per kWh of electricity. **As the rollout of smart meters has now also started in Wallonia and Brussels, we expect that dynamic contracts will also be offered in these regions in the near future.**

Table 2. *The nine dynamic contracts available to Flemish households in January 2024 (Courtesy of Paul Van Cotthem).*
Note: SPOT is the hourly electricity price (in €/MWh) on the spot market, for Belgium.

Provider	Contract name	Formula purchasing price (€cent/kWh) VAT excl.	Formula injection price (€cent/kWh) no VAT	Subscription (€/year) VAT excl.
Bolt	Bolt Online	0,11225 * SPOT + 0,999	0,08840 * SPOT – 0,5000	90,45
EBEM	Groen Dyn@mic	0,10800 * SPOT + 1,750	0,08500 * SPOT – 0,5000	70,75
Ecopower	Dynamische burgerstroom	0,10200 * SPOT + 0,400	0,08500 * SPOT – 0,4000	60,00
Eneco	Zon en wind Dynamisch	0,10200 * SPOT + 1,000	0,10000 * SPOT – 1,1880	94,34
Energie.be	Dynamisch tarief particulieren	0,10580 * SPOT + 1,500	0,08000 * SPOT – 0,5000	33,02
Engie	Dynamic	0,10000 * SPOT + 0,204	0,10000 * SPOT + 0,0000	95,00
Frank Energie	Dynamisch	0,10680 * SPOT + 1,500	0,08505 * SPOT + 0,0000	23,21
Luminus	Dynamic	0,10440 * SPOT + 0,370	0,08525 * SPOT – 0,9550	70,75
Octa+	Dynamic	0,10380 * SPOT + 0,393	0,09880 * SPOT – 1,1683	70,75

Information-based stimuli - For these contracts to be beneficial to households, they need to be empowered to react through timely information on the hourly electricity prices. Every provider offers an overview of the day-ahead prices like the one in Fig. 1, usually on their website and/or on their smartphone app. **Based on that, households can optimally plan to e.g. run a washing machine, increase the heating, charge their electric vehicle,… when it is cheapest to do so.**

Technology - Technology facilitates all this. For example, controllable thermostats are offered by many brands like Nest, Netatmo, Honeywell, Tado,… Some of these thermostats are even designed to **automatically follow electricity hourly tariffs to optimize the heating, avoiding the need for households to set a schedule**. Additionally, there are apps that can manage the charging of electric vehicles, to align it with periods of low prices. Examples of such apps in Belgium are the "ENGIE Drive" app by Engie or the "Eneco Slimladen" app, developed by Eneco NV (see Figure 7). **These apps help households under dynamic contracts make the most savings by charging when electricity is cheap and green.**

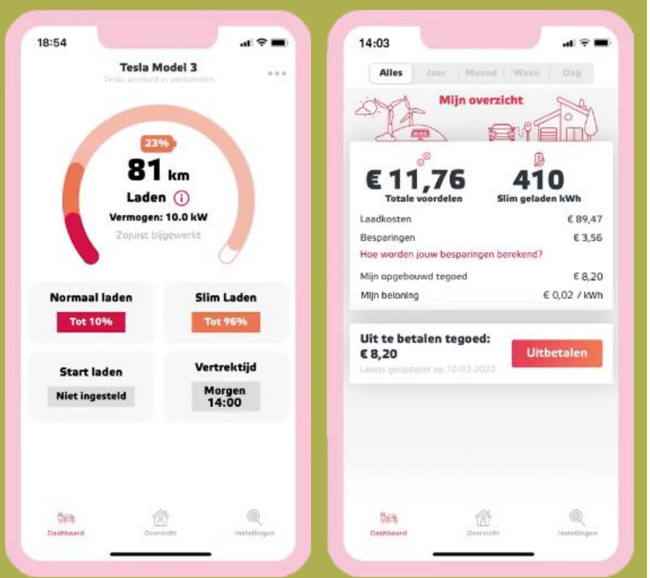

Figure 7. *Smart automatic charging of an electric vehicle via the 'Eneco Slimladen' app. (Courtesy of Eneco NV).*

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