LUISS

Department of Law

Master of Science in Law, Digital Innovation and Sustainability

Course: Management of Innovation and Entrepreneurship

A solution to tackle the variability of renewable energy generation: using the Matter IoT standard to enable implicit demand response for private consumers

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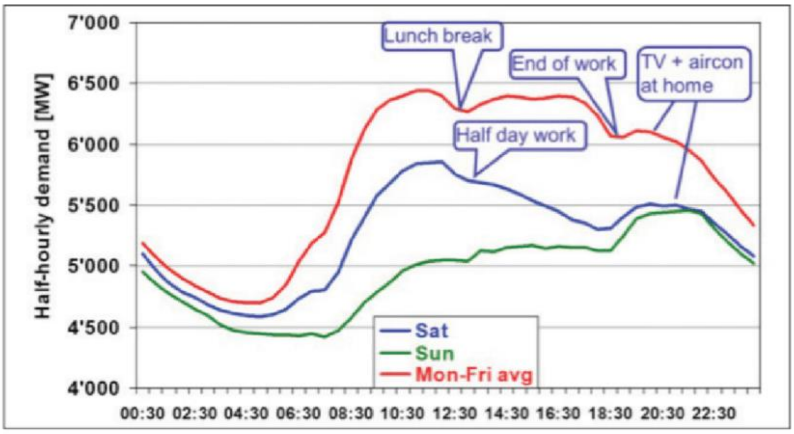
Introduction

Variability in electricity markets

Electricity is the backbone of economic development, progress, and decarbonization. It has some peculiar characteristics that make it incredibly easy to use, transport and produce in a wide variety of different ways. But it has one issue: it's difficult and costly to store. Electricity works with real-time production and consumption, this means that every kWh that is consumed in a certain moment has also been produced in the same moment. During the day the electricity demand varies significantly: during the night demand is typically low, then there typically is a morning ramp, a high consumption during the work hours, and continuous variation throughout the day, as shown in Graph 1[1].



Source: Image based on data from EMA—half-hourly demand from 23–29 Sep 2013.

Graph 1 - Electricity Demand variability. Source Researchgate

These variations are handled by modulating, ramping up, and ramping down, energy production plants, or even by activating "peaker" plants to fulfil the highest demand periods. This has a simple consequence: electricity prices vary depending on hourly demand and supply[2], as shown in Graph 2[3]

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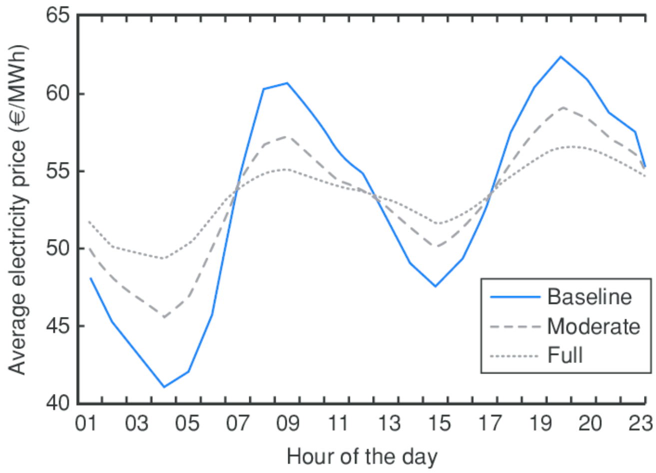
[1] 24hr daily energy demand pattern | Download Scientific Diagram (researchgate.net)

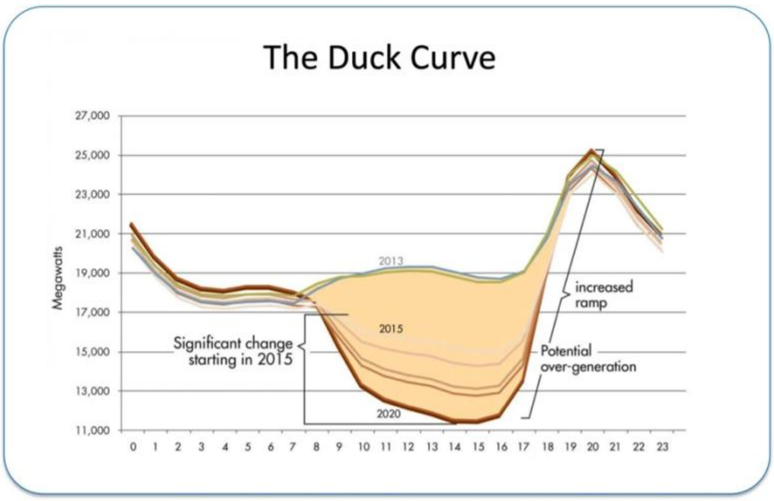
[2] https://www.researchgate.net/figure/Hourly-intra-day-variation-of-the-electricity-price-for-Germany-in-MWh-and-the_fig3_310021998

[3] 3: Hourly intra-day variation of the electricity price for Germany (in... | Download Scientific Diagram (researchgate.net)



Graph 2 - Electricity price variation throughout a day. Source:Researchgate

This trend is going to be even more accentuated by the ecological transition: renewables introduce non-controllable variability, in this case on the supply side. In California, where solar PV already has a substantial deployment[4], the demand curve is very different: during the daylight hours it drops significantly, then peaks in the evening hours when solar PV doesn't produce anymore, and the household demand is high due to the use of appliances. This phenomenon has been called "the Duck curve[5]" (Graph 3[6]) due to the shape of the demand curve, and it is predicted to worsen over time.



Graph 3 - The duck curve. Source: Greentech Media

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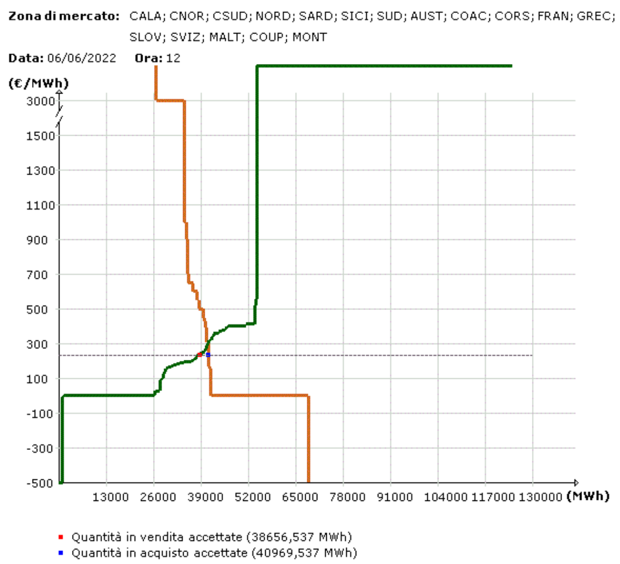
[4] https://www.iea.org/commentaries/california-s-power-resource-challenge-holds-lessons-for-clean-energy-transitions-worldwide

[5] https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

[6] https://www.greentechmedia.com/articles/read/the-grid-has-changed-how-energy-efficiency-can-help-manage-the-duck

This variability has several consequences: the system is overall inefficient, potentially not utilizing in full the cheap and zero-carbon renewable energy, and having to ramp up very inefficient, costly, and polluting peaker plants[7] in the hours of maximum demand. Furthermore, some types of energy plants cannot easily modulate their output (Nuclear) or in doing so they lose efficiency (Natural Gas plants)[8]. Variability also increases the risk for the actors involved in energy markets, especially energy retailing companies, that sell electricity at a fixed rate, and thus their price should include the risk linked with variability in wholesale prices.

When analyzing the static supply and demand curves for electricity, in relation to price, it can be noticed a very peculiar feature: demand is almost inelastic. This means that a variation in (wholesale) price does not trigger a variation in demand. Demand is not "responsive" to changes in wholesale price[9].



Graph 4 - Demand/Supply graph 06/06/2022 at 12:00, Italian market. Source: GME

The reason behind this is that the wholesale price is not transferred to end consumers, they instead have a contract with the retailer that has fixed and predetermined prices, and in any case with limited hourly granularity, so there is no incentive for the consumer to change his behaviour. Furthermore, the consumer doesn't have any information on real-time prices.

[7] https://en.wikipedia.org/wiki/Peaking_power_plant

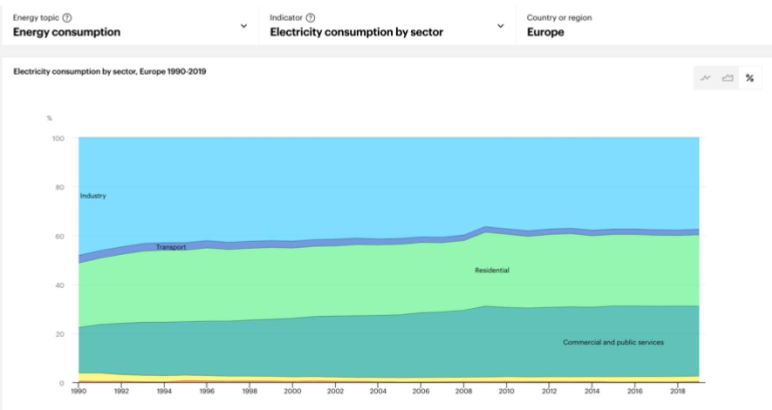
[8] https://www.raponline.org/knowledge-center/history-theory-wholesale-electricity-markets/

[9] https://www.mercatoelettrico.org/it/Esiti/MGP/EsitiMGP.aspx

The only solution energy companies have adopted to try to pass to the consumer's price information are bi-hourly rates, which provide slightly cheaper energy prices during night hours, based on the fact that during the night overall consumption is lower, thus there is unused capacity. While this is true, bi-hourly rates are a very poor proxy for the hourly variations in prices, and with energy production shifting quickly to renewables, the assumption of cheaper energy prices during the night might not even be true anymore, as the duck curve shows. Also, prices in the same time slot can vary significantly between days, due to different renewable energy generation. A shiny day in California will likely have lower prices than a rainy day. There is also another issue: adaptation of consumer behaviour is hard, and even with bi-hourly rates, the shift in consumer behaviour is partial, and the more complex the change, the harder adoption will be *Fowlie et al., (2021)*[10].

Another key trend to take into account is the electrification of energy consumption. Today, some of the most energy-intensive devices are not powered by electricity, but rather from some fossil energy source, like methane or LNG for heating systems, water heating, stoves, and ovens. Also, the transportation industry is getting electrified: petrol and diesel cars are being replaced by electric ones, at a rate that is quickly going to increase.

Today, in Europe, residential and transport constitute about one-third of the total electricity consumption (Graph 5)[11] This percentage is likely going to increase due to the electrification of energy consumption.



Graph 5 - Electricity consumption by sector in Europe. Source: IEA

[10] Fowlie, M., Wolfram, C., Baylis, P., Spurlock, C. A., Todd-Blick, A., & Cappers, P. (2021). Default effects and follow-on behaviour: Evidence from an electricity pricing program. *The Review of Economic Studies*, *88*(6), 2886-2934.

[11] Europe – Countries & Regions - IEA

Energy storage

What could be done to solve these issues? One of the most talked-about solutions is energy storage. Batteries are becoming cheaper[12], and they might be used to shave off the peaks of demand and supply, by being charged when prices are low, and discharged when prices are high. The key issue with batteries is that, while decreasing, the price of the state-of-the-art technology, Lithium-ion, is still too high to make economic sense for most stationary storage applications. Also, global production of batteries is already fully booked[13] for the foreseeable future, due to the very high demand coming in particular from the transport sector, which is undergoing, as mentioned before, an extremely quick transition to electricity.

Also, while extremely advanced, lithium-ion might not be the right technology for stationary storage. Some of its key strengths are the high energy density and a good energy-to-weight ratio, these two characteristics are irrelevant for stationary energy storage. At the same time, their lifespan is still in the realm of 3000 full charge-discharge cycles, after which only about 40% of the original capacity remains usable. (Table 1)[14].

Depth of Discharge	Discharge cycles	
	NMC	$LiPO_4$
100% DoD	~300	~600
80% DoD	~400	~900
60% DoD	~600	~1,500
40% DoD	~1,000	~3,000
20% DoD	~2,000	~9,000
10% DoD	~6,000	~15,000

Table 1 - Battery lifespan. Source: Battery University

In conclusion, energy storage is going to be a key tool for electric grids, but it won't likely suffice, due to cost, demand from other sectors, and supply constraints.

[12] https://www.statista.com/statistics/883118/global-lithium-ion-battery-pack-costs/

[13] https://www.reuters.com/business/sustainable-business/how-battery-shortage-is-hampering-us-switch-wind-solar-power-2022-06-09/

[14] BU-808: How to Prolong Lithium-based Batteries - Battery University

An alternative solution

What if, instead of storing energy, we could directly use it when it's cheaper, and on the other side, reduce the consumption when it's more expensive? The concept is nothing new, shifting electricity consumption it's a very talked-about idea, broadly defined as "Demand Response" (DR) and some energy-intensive companies, that have direct access to the wholesale market, already do it. But the bulk of the demand is rigid, and not responsive to price variations, as explained before. One of the key challenges is to dynamically adapt the behaviour of household consumption. This thesis aims to outline a solution that could enable this consumption to shift in a very easy and effective manner for consumers.

IoT is a key enabling technology: connecting everyday objects to the network. Already today some new household appliances, like washing machines, HVAC systems, heating systems, lights, and others, have Wi-Fi or, more in general, network connectivity.

Today the usage has limited scope: a washing machine can notify your phone that it has finished, you can turn on the lights with a voice assistant like Siri, Google Assistant, or Amazon Alexa, and you can control HVAC temperature through an app instead of using the remote.

What if we could leverage the connectivity of energy-intensive appliances to automatically shift their activation when energy prices are low, and reduce their consumption when energy prices are high?

For example, washing machines could be loaded in the evening, and be programmed to automatically run in the hours of the night when electricity is cheaper. The same thing can be done for dishwashers and dryers. A water heater, instead, (be it an electric boiler or a heat pump) could heat the water not immediately after it is being used, but when, in the following 12 hours, electricity is cheaper. Conversely, HVAC systems could, for example, automatically increase/decrease the temperature by one or two degrees to reduce consumption if it's a moment of peak electricity demand, with very high prices. This concept can be brought even further, an electric car's wallbox charger could be dynamically scheduled in the hours with the lowest energy prices. Even robot vacuums could only start recharging their battery when rates are low. Almost all of the energy-consuming appliances in the home could automatically shift their consumption.

The key question then becomes: "why hasn't it already been done"?. The answer is that some key elements that could enable the aforementioned use cases are still missing: there isn't a way for energy retailers to communicate wholesale prices (and thus also provide variable rates) with customer appliances in real-time, and integration is extremely complex since the IoT devices sold until today mostly rely on closed, proprietary, single-purpose communication standards.

It would take a monumental effort for an energy retailer to undertake relations with every single appliance manufacturer to integrate a software stack that enables communication with real-time pricing, and dynamically triggers activation, or consumption modulation.

The IoT/Smart Home market is facing these issues also on another level: smart devices need to communicate with each other to really be "smart" and provide value to the customer.
For example, smart lights should be able to communicate with a voice assistant to be turned on by voice command, window opening sensor could communicate with air-conditioning to automatically turn it off when the window is open. Surveillance cameras could communicate with lights to automatically turn them on if a thief is detected. And so on…
At the moment, this is, for the most part, not possible: devices communicate with their proprietary app, and, at most, with some (not always all) voice assistants from Apple, Amazon, and Google.

This problem has led all the most important players in the smart home business to join forces in the Connectivity Standards Alliance (CSA), to develop a single, universal, and open protocol for smart home devices to communicate with each other. The new standard, called "Matter[15]", is mainly thought to control small IoT devices with voice assistants and, crucially, it doesn't require producers to develop separate integrations with Apple Home Kit (Siri), Amazon Alexa, and Google Home.
One of the most significant innovations brought by Matter is to allow a single smart home device to be controlled by multiple smart home ecosystems, at the same time, without requiring separate software-stack development. This kind of approach is exactly what could enable an energy company to easily develop integrations with connected appliances, thanks to a single, universal, software stack. The standard at the moment is not being developed with this objective in mind, but, being the CSA an open alliance, and being the standard only in the early phases of its development, energy retailing companies could enter the CSA and steer the standard towards what can be the ultimate use of IoT technology.
This thesis aims to answer the following research question: "**how households' electricity consumption can be reactive to supply changes to address the variability of renewable energy generation"**
In order to answer the question, the research is structured into seven chapters. The first chapter analyzes how energy markets are structured, with a particular focus on the Italian one. The chapter provides a basis to understand the issues and the proposed solutions. In chapter two I focus on the

[15] https://csa-iot.org/all-solutions/matter/

variability of demand and supply, and how it is reflected in electricity prices. I analyze causes and effects, with a parenthesis on the Italian regulatory framework of "time slots", originally meant to manage price variability. Chapter three analyzes the different energy storage solutions currently available, and their upsides and downsides. Chapter four introduces the concept of demand-response in all of its different variations.

Chapter five pushes forward the key concept of this thesis: implementing implicit demand response in households. In particular, it provides data and analysis regarding the relevance of such a solution. Chapter six provides a detailed explanation of how such a solution could be implemented, complete with technical analysis and use-cases simulations. In Chapter seven I performed calculations and estimations to quantify the savings such a solution can bring to the final customer, with granular detail per appliance. Chapter eight focuses on the underlying technology I deem crucial for the wide adoption and success of household demand-response: the Matter standard. Chapter nine performs a stakeholder interest map to demonstrate the convergence of interests that can be the lever for wide adoption and standardization of the enabling components of this solution.

Research Methodology

Analysis and sources

To perform a complete and insightful analysis of the matter, I utilized a wide range of different data sources. First, I conducted six interviews with industry experts from Enel X to grasp the most relevant industry trends and understand what are considered the most relevant limitations and difficulties in implementing a demand-response solution in households. Second, I collected data through observation and informal conversation with informants during IFA 2022[16], the most relevant consumer electronics show in Europe, to understand and ask industry leaders and appliance manufacturers about their vision and product solutions for smart-home and energy management. Third, I collected and analyzed both relevant academic papers and open-access data from the key industry players (such as reports, companies' documents and white papers). To better understand the context, industrial, legal and technical documents were collected. Legal documentation from competent authorities was also analyzed to verify legal and administrative restrictions on the deployment of such a solution. Technical documentation for IoT standards (Matter) was also taken into account to understand technicalities and implementation solutions for the proposed solution

Furthermore, to demonstrates the validity and perform a savings estimation, price data from the GME (Italian energy market operator) were re-elaborated with Microsoft Excel to produce savings estimates. Also, consumpions of different appliances and their modulabiliy were evaluated, both for savings estimates and calculation of the share of shiftable load. Results and calculation methodology are explained in the dedicated section.

Although the thesis focuses on and analyzes data and regulations from the Italian market, the proposed solution has a global relevance and implementation opportunity, in various regions potentially even more effectively than in the simulated Italian scenario. While Italian data represent a good proxy for other western and developed countries, further analysis and research should be done to get more accurate estimations and evaluate foreign legal framework enablement possibilities.

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[16] https://b2b.ifa-berlin.com/en/

Literature review

A key step in the analysis process for the thesis was the literature review. While, as mentioned before, most research elements reported in this thesis are retrieved directly from regulatory sources, on the variability generated by renewables, and on energy markets, a more In-depth analysis had to be conducted. Energy-markets related studies were considered to compare the "pay-as-bid" auctioning system versus the currently adopted "marginal price remuneration". In particular *Guerci & Rastegar, (2012)*[17] analyzes and simulates two different scenarios in the day-ahead session of the Italian wholesale electricity market (MGP), by comparing the two different bidding mechanisms. The conclusions are that with pay-as-bid mechanisms the seller's endeavours to adopt "guessing" mechanisms to identify competitor's biddings, aimed at maximising profits, were more costly than a simple marginal-price bidding, and thus reflected in a higher final price. The paper was considered relevant to corroborate the thesis of efficiency for marginal-price auctions for energy markets. For the development of the proposed solution, I referred to *O'Connell et al., (2021)*[18]. This paper evaluates a demand response solution deployed by using source consumption variability, thus modulating consumptions from appliances, in the specific case HVAC systems. While the implementation I propose is partially different from the one analysed in the paper, it provides some relevant data and positive judgement on the feasibility of such a solution. On end-consumer pricing mechanisms *Eid et al., (2016)*[19] provides a framework for managing volatile renewable energy sources with demand-response in households through price signals. It also provides some evaluations on the challenges on implementation. The presence of costly enabling technologies is seen as a crucial one, and it's one for which this thesis provides an effective solution. Further academic sources have been used to grasp more specific data or consideraitons, in particular to understand how price signals actually impacted end-user behaviour, *Fowlie et al., (2021)*[20] provided insightful analysis on the fact that, with bi-hourly rates and manual actuation a partial behavioural shift is present. While this data point can't be directly transferred to the solution proposed in the thesis, the automation system conceptualised would eliminate, or drastically reduce, the "noncompliance", and it is especially needed considering

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[17] Guerci, E., & Rastegar, M. A. (2012). Comparing system-marginal-price versus pay-as-bid auctions in a realistic electricity market scenario. In *Managing Market Complexity* (pp. 141-153). Springer, Berlin, Heidelberg.

[18] O'Connell, S., Reynders, G., & Keane, M. M. (2021). Impact of source variability on flexibility for demand response. *Energy*, *237*, 121612.

[19] Eid, C., Koliou, E., Valles, M., Reneses, J., & Hakvoort, R. (2016). Time-based pricing and electricity demand response: Existing barriers and next steps. *Utilities Policy*, *40*, 15-25.

[20] Fowlie, M., Wolfram, C., Baylis, P., Spurlock, C. A., Todd-Blick, A., & Cappers, P. (2021). Default effects and follow-on behaviour: Evidence from an electricity pricing program. *The Review of Economic Studies*, *88*(6), 2886-2934.

the higher complexity of managing the multi-hourly rates proposed in the thesis. Finally, to draw some data on households with the possibility to charge an electric vehicle at home, I analysed *Pasaoglu et al., (2012)*[21].

[21] Pasaoglu, G., Fiorello, D., Martino, A., Zani, L., Zubaryeva, A., & Thiel, C. (2014). Travel patterns and the potential use of electric cars–Results from a direct survey in six European countries. *Technological Forecasting and Social Change*, *87*, 51-59.

Chapter 1 – Electricity Markets

In the overall electricity system, we can identify five main actors: the energy generators (production), the resellers/retailers, the transmitter, the distributors, and the final customers[22]. In Figure 1 all the "physical" actors are represented, the retailer, instead, is a juridical entity that buys electricity from generators and resells it to customers following a contractual agreement, as illustrated in Figure 2.

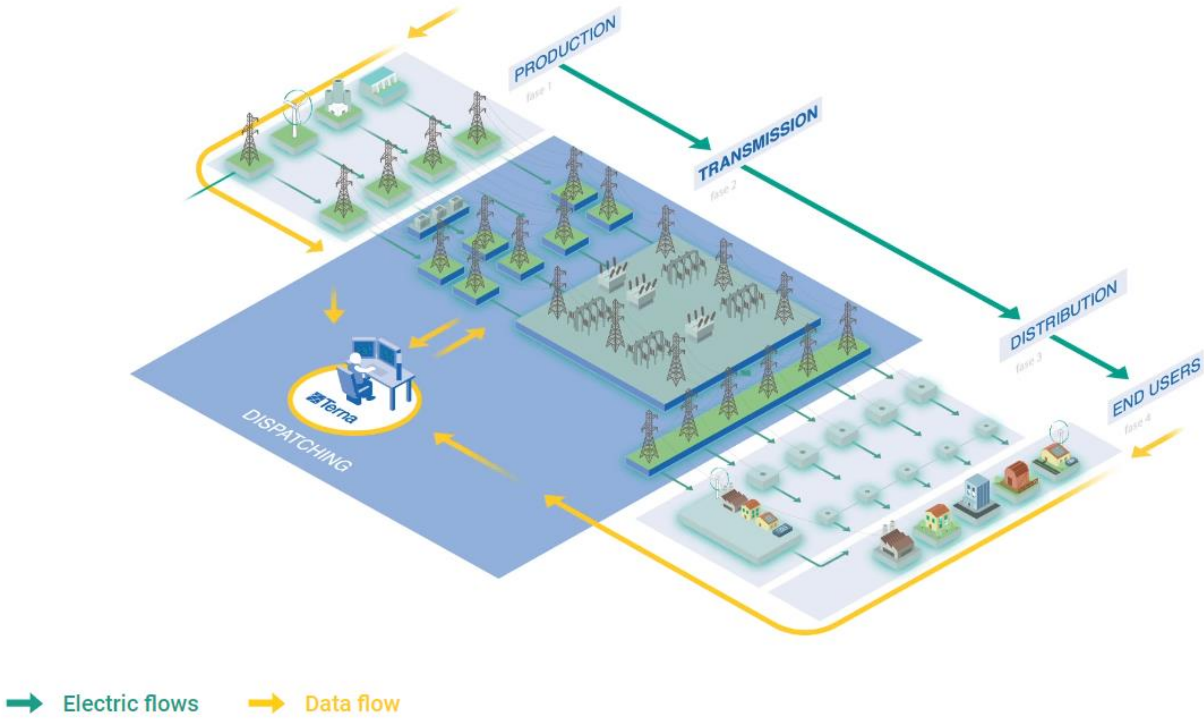

Figure 1 - The key actors. Source: Terna

The final customer signs a contract with a retailer for the supply of electricity, which generally sets a price for each energy unit consumed (kWh). Energy retailers then buy energy from the generators, to appropriately serve their customers. This operation can be done through long-term power purchase agreements or via energy markets, as it is more common in developed countries. Transmission constitutes the long-distance interconnection between generators and electrical substations, done by high-voltage transmission lines. Distribution refers to the last-mile delivery of energy, with lower voltage lines that connect the substations to the end user[23].

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[22] https://www.terna.it/it/sistema-elettrico/ruolo-terna/come-funziona-sistema-elettrico

[23] https://learn.pjm.com/?sc_site=learn

Electricity markets serve the purpose of efficiently allocating resources for energy production and providing the correct information to all the actors involved. The base model for the electricity market, which is used in most of the world is a day-ahead energy market[24].

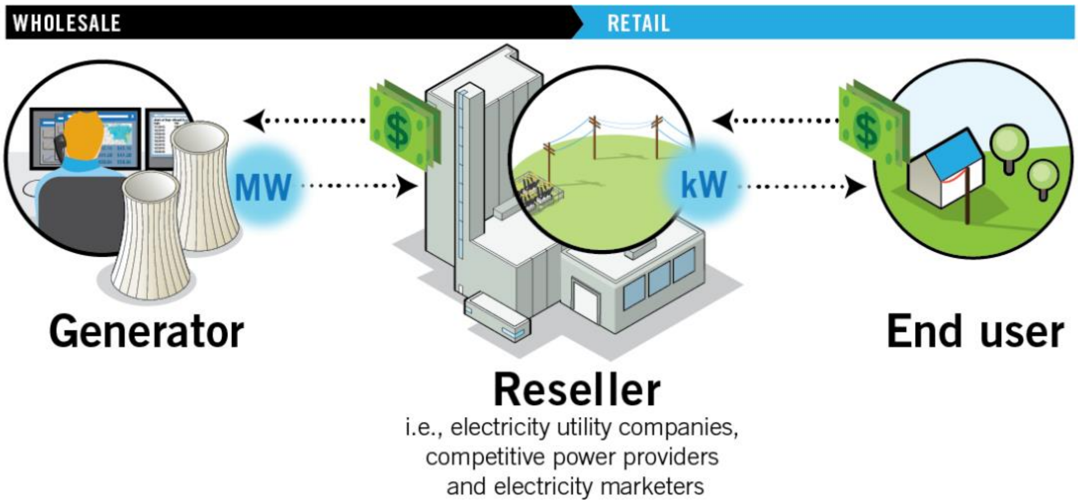
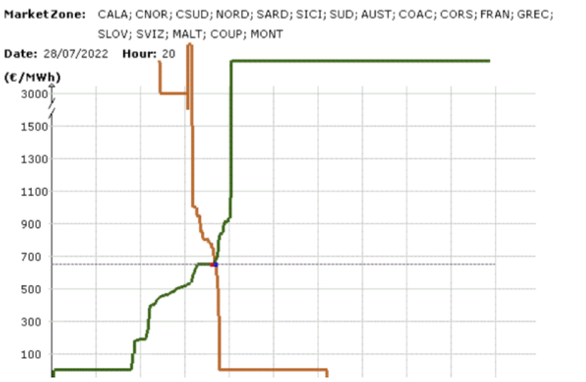


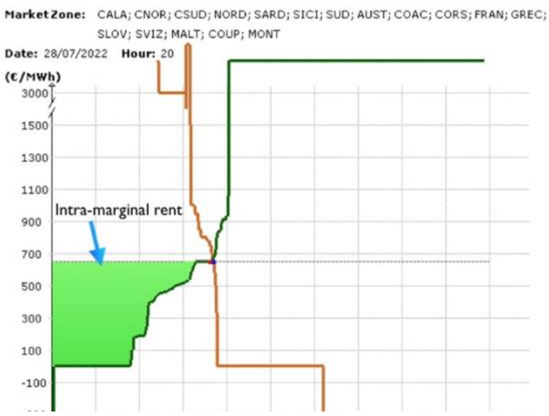
Figure 2 - Electricity Markets, credits: PJM Learning Center

The day-ahead market

In the day-ahead market, energy producers offer their generation capacity for the following day, and buyers, mainly energy retailers, buy it to supply their customers, based on demand estimations. The electricity market has a “marginal-price” functioning scheme, also known as a single-price auction: all the producers bid their capacity at their marginal price, which corresponds to the variable costs of generation (typically fuel cost) and then they get remunerated with the price of the highest bid accepted: the marginal offer. So, every producer gets remunerated not with the amount they bided (pay-as-you-bid), but rather with the price paid to the marginal powerplant (single-price auction). This allows for all the intra-marginal plants, those that have lower marginal costs than the marginal



Graph 7 - Supply/Demand graph Italian day-ahead market. Source: GME



Graph 6 - Intra-marginal rent

[24] https://www.raponline.org/knowledge-center/economics-for-wholesale-electricity-markets/

plant, to earn a rent that is used to pay off the "overnight cost" (the fixed costs of building the plant) plus the related capital cost, and to remunerate investors. This mechanism enables everyone to bid at their variable cost, and still cover their fixed cost.

The day-ahead market is divided into hourly blocks, producers and retailers bid for the energy price for every hour[25]. After the closure of the market, bids are accepted following the merit order[26] principle, from the lowest (marginal) price to the highest, until the demand is met. This mechanism allows for "Economic dispatch"[27]: the generating plants with the lower marginal cost are used first.

This allows for efficient allocation of resources, and it provides information to investors in power generation, through price signals. A company interested in building a new power plant could, based on the publicly available prices of electricity, market outcomes, and the cost structure of the new plant, carefully evaluate the economic convenience of building it.

How does a plant get remunerated?

The costs of a power plant can be divided into fixed and variable costs. Fixed costs are those linked to the construction of the plant (the so-called "overnight costs"), plus the cost of capital for financing. Fixed costs are amortized during the life of the plant, and can then be reported as a monthly (sunk) cost. Of course, fixed costs should be paid independently from the actual usage of the plant.

The variable costs of running a plant account for the costs linked to the operation of the plant: the lion's share, in thermal power plants, is constituted by the fuel cost. Other variable costs are linked to Operations and Maintenance, in particular, those that are linked with the use of the plant, such as moving components wear and tear, for example turbine maintenance, anti-pollution filters substitution etc…

Earn-as-you-bid vs uniform price auction

The Levelised Cost of Energy (LCOE) is a measure of the average cost per MWh (MegaWatt-hour, the unit of measure of energy, equivalent to 1MegaWatt of power delivered for one hour) of building and operating a plant over its whole assumed lifespan. It takes into account capital costs, fuel costs, operations and maintenance costs, financing, and the assumed capacity factor over the plant's lifetime. In essence, it includes all the costs of a plant and divides it by its assumed generation. It can be viewed as a long-term average cost of generating electricity.

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[25] https://www.mercatoelettrico.org/en/mercati/mercatoelettrico/mpe.aspx

[26] https://en.wikipedia.org/wiki/Merit_order

[27] Economic dispatch explainations https://www.youtube.com/watch?v=JtleNB6br-0

An alternative scheme to the single-price auction currently in place, is considered by some a market system where every producer bids at its LCOE, in a pay-as-you-bid auction, where every actor gets paid for the sum that they offered to the market. This scheme would allow for the reduction of rents in the energy market but poses other issues. The actors in the market who bid at a price near to what it's likely going to be the marginal one, might not actually bid at their LCOE, but rather at a lower price, closer to the marginal cost. This is because, if their bid is over the closing price, they won't earn anything, so they prefer to bid at a price that only covers the fixed costs, to diminish their loss. When this mechanism is used by some actors in the market, it sparks a chain reaction where all producers, to avoid being out of the market, will lower prices to their marginal cost, creating a "fall to marginal cost" situation that would be unsustainable in a pay-as-you-bid market, where there are no intra-marginal rents to cover fixed costs. With this mechanism, there is also a strong incentive to make guesses on the closing auction price *Guerci & Rastegar (2012)*[28], and modulate the offer accordingly, thus not providing effective price discovery to other actors in the market, like potential new investors who are interested in building new capacity.[29] Furthermore, reducing the rents given to intermittent sellers with low or zero marginal cost plants can reduce the incentive to invest in renewables.

The intra-day market

Actual demand may vary with respect to the demand estimates of the day-ahead market, to adjust generation in a real-time way, intra-day markets are usually put in place, where participants can submit supply offers or demand bids to satisfy real market conditions. This market works in a real-time way, and the volumes traded are only those related to the deviation from the day-ahead forecast.

When to build a new plant - Annual revenue requirement

The decision on the construction of a new power plant can be done by analysing its annual revenue requirement (ARR) and checking it against the past market outcomes, and expected future market outcomes based on planned installed capacity.

The Annual Revenue Requirement represents the amount of revenue per MWh (unit of capacity) that a power plant needs to earn in order to break even by assuming a certain capacity factor of the plant and an average fuel cost.

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[28] Guerci, E., & Rastegar, M. A. (2012). Comparing system-marginal-price versus pay-as-bid auctions in a realistic electricity market scenario. In *Managing Market Complexity* (pp. 141-153). Springer, Berlin, Heidelberg.

[29] https://www.raponline.org/knowledge-center/economics-for-wholesale-electricity-markets/

$$ARR = \frac{Annual\ Fixed\ Cost}{Annual\ Capacity} + Variable\ costs * Annual\ Capacity$$

Thanks to the access to information that a single-price auction market offers, investors and new entrants can evaluate if a new generation plant would make economic sense.

Capacity Markets

Capacity markets are meant to provide more certainty about future capacity availability. They do so by providing capital to bidders in exchange for the commitment to making their plants' capacity available to the energy market in the future[30]. This ensures long-term grid reliability and facilitates investments in capital-intensive plants. The matching of power supply with future demand also creates price signals to attract long-term capital investments in a new plant that guarantees supply. Capacity Markets entail severe penalties if the committed capacity is not available when needed.

Ancillary Services

Ancillary services are additional services that are needed for the correct functioning of the grid. Typical ancillary services are frequency control or voltage control. Since these services can be provided by different actors, a market for ancillary services is generally put in place to allow for the most efficient allocation of resources.

In practice: The Italian Market, The different actors.

To ground this in reality, in this paragraph I'll analyze the different actors mentioned above in the Italian market.

Energy generation is performed by a plethora of actors, like Enel Produzione[31], Eni, Edison, A2A, EPH, Iren, Engie, Tirreno Power and others. Graph 3 shows the competitive landscape of generation in the Italian market.

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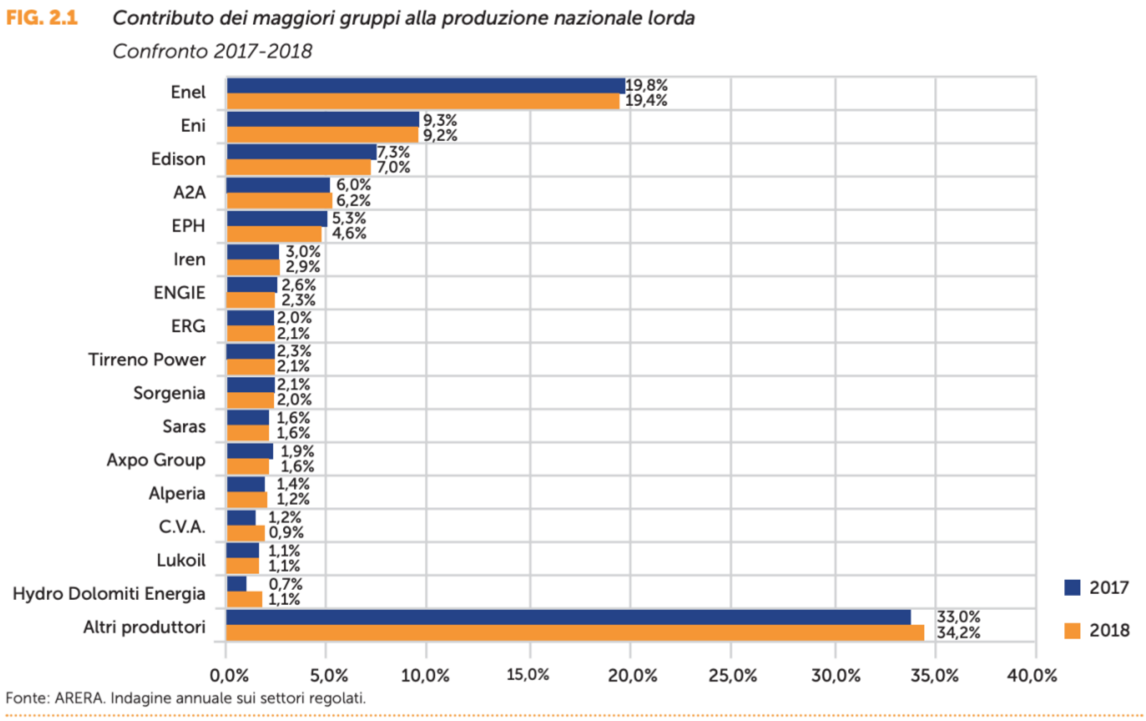
[30] https://learn.pjm.com/three-priorities/buying-and-selling-energy/capacity-markets.aspx

[31] https://it.wikipedia.org/wiki/Enel_Produzione



Graph 8 - Marketshare of generators in Italy, source: ARERA[32]

The electricity grid in Italy is managed by Terna[33] for long-distance high voltage electricity transport, while the local distribution is assigned with a concession contract to be managed by a single operator for every zone. This is because distribution infrastructure is a "Natural Monopoly", where it wouldn't make any economic sense to duplicate the physical infrastructure due to the very high sunk costs and the homogeneous nature of the good, which doesn't allow for differentiation. Table 1 shows the list of the most important distributors in the Italian market.

[32] https://www.arera.it/allegati/relaz_ann/19/RA19_volume1.pdf

[33] https://www.terna.it/it

TAV. 2.15 *Distribuzione di energia elettrica per società di distribuzione nel 2018*
Volumi distribuiti in GWh; punti di prelievo in migliaia

OPERATORE	UTENTI DOMESTICI		UTENTI NON DOMESTICI		TOTALE UTENTI	
	ENERGIA DISTRIBUITA	PUNTI DI PRELIEVO	ENERGIA DISTRIBUITA	PUNTI DI PRELIEVO	ENERGIA DISTRIBUITA	PUNTI DI PRELIEVO
e-distribuzione	49.773	25.172	178.146	6.231	227.919	31.403
Unareti	1.720	933	9.643	206	11.363	1.139
Areti	2.670	1.319	6.909	311	9.579	1.630
Ireti	821	555	2.517	137	3.338	693
Edyna	347	171	2.234	61	2.581	232
Set Distribuzione	395	263	1.839	66	2.234	330
Inrete Distribuzione Energia	387	200	1.832	61	2.219	261
Megareti	262	131	1.548	37	1.811	169
Servizi a Rete	113	54	1.034	18	1.146	72
Deval	136	103	781	26	917	129
AcegasApsAmga	229	130	600	33	829	164
ASM Terni	70	36	367	10	437	46
Altri operatori	826	455	2.742	129	3.568	584
TOTALE	57.750	29.524	210.191	7.328	267.941	36.852

Fonte: ARERA. Indagine annuale sui settori regolati.

Table 2 – Energy distributors in Italy by number of users. Source: ARERA 2019 Annual Report[34]

The Italian Wholesale energy market is managed by "Gestore dei Mercati Energetici" GME[35]. It manages both a platform for bilateral deals between operators (a Futures Market), and a spot market with a day-ahead-market (MGP) that uses the above-described "single price auction" mechanism, an intra-day market (MI) with continuous trading sessions, plus a market for the dispatching services, with a "pay-as-bid" formula, that is used by Terna to get the ancillary services needed for the correct operation of the grid.

Energy retailing in Italy is a bit peculiar: consumers can choose from a plethora of retailing companies each with different prices and offers ("Libero Mercato") or, instead can choose to buy energy from a regulated service called the "Servizio Elettrico Nazionale - Servizio di maggior tutela" (Translation: National Electricity Service - Higher protection service) whose energy prices are defined by ARERA (the independent authority responsible for Energy) based on projections of the wholesale energy prices. In turn, the "Servizio Elettrico Nazionale" buys energy through the "Acquirente Unico S.p.a." (translation: "Single buyer") which buys electricity on the market to supply the "Maggior Tutela" customers. Table 2 is shown a list of the top 20 Italian energy retailers on the free market, thus excluding "Servizio di maggior tutela".

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[34] https://www.arera.it/allegati/relaz_ann/19/RA19_volume1.pdf

[35] https://www.mercatoelettrico.org/it/

TAV. 2.48 *Primi venti gruppi di vendita al mercato libero nel 2018*
Volumi in GWh; quota percentuale

GRUPPO	ENERGIA	QUOTA	POSIZIONE NEL 2017
Enel	55.355	26,9%	1°
Edison	12.440	6,1%	3°
Eni	11.055	5,4%	2°
Axpo Group	9.437	4,6%	6°
Hera	8.393	4,1%	5°
A2A	7.591	3,7%	10°
Green Network	7.447	3,6%	11°
Duferco	6.560	3,2%	9°
Iren	6.465	3,1%	7°
E.On	5.553	2,7%	8°
CVA	4.860	2,4%	12°
Metaenergia	4.087	2,0%	4°
Repower	3.908	1,9%	17°
Egea	3.759	1,8%	19°
Alperia	3.554	1,7%	20°
Eviva	3.511	1,7%	13°
Dolomiti Energia	3.301	1,6%	16°
Sorgenia	3.268	1,6%	15°
Acea	2.698	1,3%	18°
Telecom Italia	2.059	1,0%	22°
Altri operatori	40.281	19,6%	-
TOTALE VENDITORI AL MERCATO LIBERO	205.583	100%	-

Fonte: ARERA. Indagine annuale sui settori regolati.

Table 3 - Top 20 Italian energy retailers in the "free market". Source ARERA 2019 Annual Report

Another relevant entity in the Italian market is ARERA[36] (Autorità di Regolazione per Energia Reti e Ambiente), which is an administrative independent authority, that is in charge of regulating, among other things, the energy market.

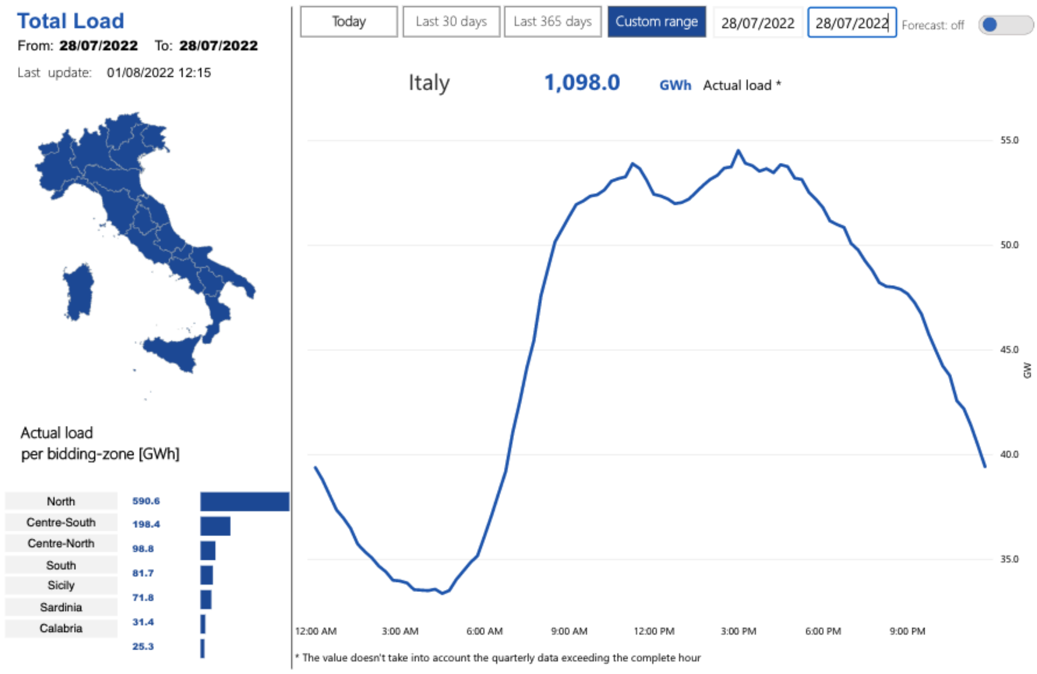
Chapter 2: variability in energy markets

Intra-day price variability

The electricity demand varies throughout the day, during the night it is typically low, companies are closed and individuals aren't actively using energy, while during the day it follows a curve like the

[36] https://www.arera.it/it/index.htm

one shown in graph 4: a quick ramp in the morning, followed by a peak load period during the central hours of the day and then a gradual decline after 5 PM.



Graph 9 - Electricity demand in Italy. Source: TERNA

Until recently, energy supply followed demand, by ramping up or down coal and gas plants, or by activating "peaker" plants during the periods of highest demand. Peaker plants are less efficient than "baseload" ones, and use more expensive fuel, this is why, back in the day, the daily price of electricity followed a predictable and quite constant path: during the night electricity was cheaper, since the marginal price-maker plant was a baseload plant, while during the central hours of the day, prices were higher due to the demand and the need to use costly peaker plants.

With the advent of renewables, Solar photovoltaics and Wind, variability emerges also on the supply side. It changes both inter-day, and intra-day, market dynamics. Solar PV is a perfect example: energy is only produced during sunlight hours, plus during cloudy or rainy days, power output is significantly reduced.

What is important to consider is that renewables are an almost-zero-variable-cost energy source. For this reason, their marginal price bids will always be close to zero. In this way, renewables have dispatchment priority on the grid.[37]

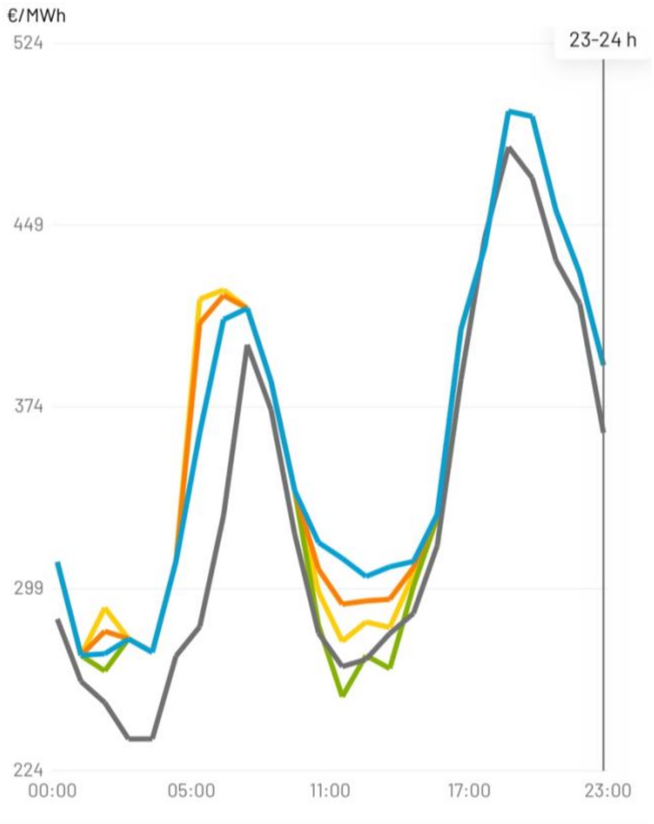
[37] https://www.energy.gov/eere/wind/articles/winds-near-zero-cost-generation-impacting-wholesale-electricity-markets

The “Duck Curve”

The emergence of supply-side variability has brought changes in the daily price dynamics of electricity. In markets with a high share of solar PV, daily prices follow what is called the “Duck Curve”[38]. This peculiar demand and price pattern has a significant dip in the central hours of the day, those with more solar generation. In the evening, instead, when energy consumption is still high, but the generation from solar PV is not present anymore, the price has its highest peak.

The “Duck Curve” pattern is already present in several US markets, like California, and also in Europe, it is starting to get more accentuated, especially during the summer.

Graph 10[39] shows the price dynamics on the 8th of August 2022 in various European markets. The trend is clear: in the central hours of the day, solar PV has a double effect: behind-the-meter solar, like panels installed on rooftops, that directly power household and business auto-consumption, partially reduce the load on the grid, plus, solar farms that sell electricity in the wholesale market at



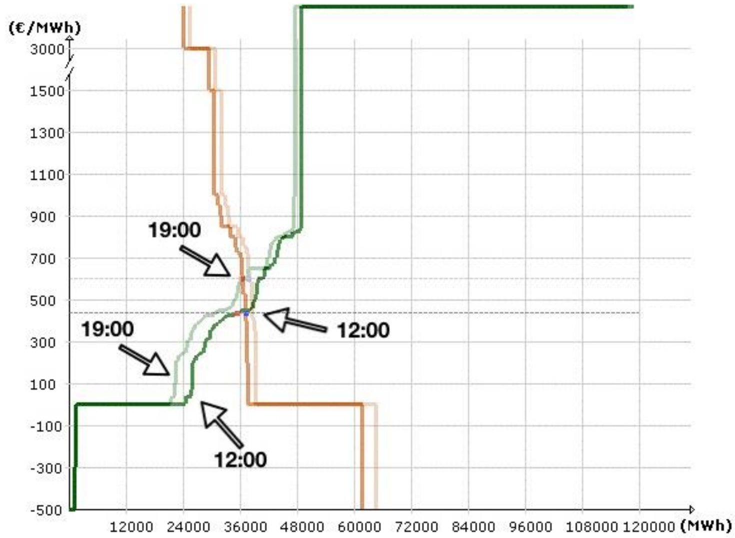
Graph 10 - Energy prices of the 8th of August 2022 in France (blue), UK (grey), Germany (orange), Belgium (green), Netherlands (yellow). Source: Red Electrica de España App

[38] https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

[39] Red Electrica de España App https://apps.apple.com/it/app/redos/id781388455

zero marginal price significantly push down the closure price of electricity by not rendering necessary higher-cost peaker plants, and thus making a lower marginal cost baseload plant the price-maker.

By taking the demand/supply graph of two different hours of the same day -Graph 11- (in this case from the Italian market) it can be seen that the supply curve at noon (strong green) has a zero-marginal cost supply (the flat part of the line) which is higher (the line is longer) than at 19:00 (light green). This shifts the whole curve to the right, rendering a higher marginal cost to the price-maker plant. [40]



Graph 11 - S/D compared in two different time slots. Italian market 08/08/2022. Source: GME

Also, the demand curve at noon (strong orange) is slightly shifted to the left, possibly due to the contribution of behind-the-meter solar. The combination of these two factors rises significantly the closing price. From 437€/MWh at noon to 599€/MWh at 19:00.

For context, Graph 13 shows the price fluctuations on the 8th of august in the Italian market. It displays a less accentuated duck curve, that, compared to other European countries seen before in Graph 10, lacks a “dip” in the central parts of the day. This is because, in Italy, the increased production from solar PV was just enough to compensate for the increased in demand in the central hours of the day compared to the early morning ones.[41]

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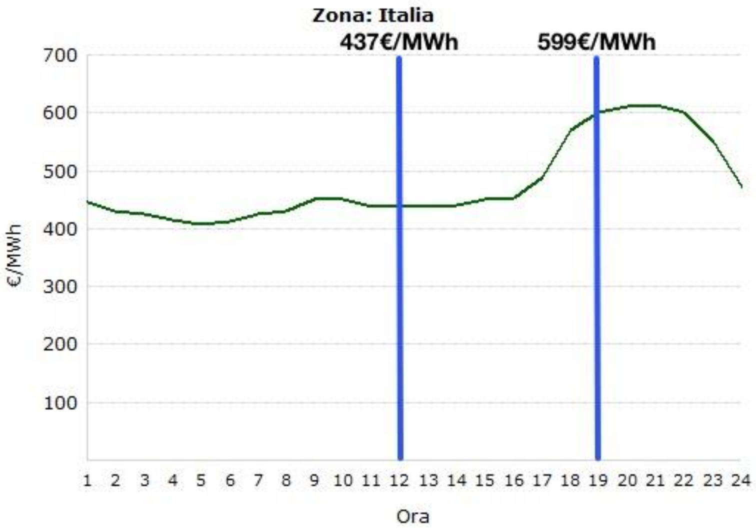
[40] https://www.mercatoelettrico.org/It/Esiti/MGP/EsitiMGP.aspx

[41] Ibid.



Graph 12 - Hourly energy price Italy 08/08/2022. Source: GME

Inter-day price variability

A key difference between the price dynamics in the past and the future resides also in the inter-day irregularities. In the past, when non-programmable renewables didn't occupy a relevant share, variability resided only on the demand side, which has the characteristic of almost always following the same pattern: low demand during the night, a sharp increase in the morning, high demand throughout the day, and a more gentle decline during the evening. Outliers from this trend were also quite predictable: during Sundays and holidays, the demand was generally lower.

For this reason, energy regulators like ARERA in Italy (Autorità Regolazione per Energia Reti e Ambiente), created time slots[42] (fasce orarie) following energy demand, so that energy retailers could create bi-hourly or tri-hourly fees with different prices on each of the pre-defined ARERA time slots (Table 3). F1 represents the hours of peak demand and, in theory, peak prices. It's valid during workdays from 8 AM to 7 PM. F2 represents the "mid load" hours, so in the early morning and the evening, plus the central hours on Saturday. F3 represents the "off-peak" hours: during the night and holidays.

Time Slot	Monday to Friday	Saturday	Sunday and Holidays
07:00 – 08:00	F2	F2	F3
08:00 – 19:00	F1	F2	F3
19:00 – 23:00	F2	F2	F3
23:00 – 07:00	F3	F3	F3

[42] https://www.arera.it/it/schede/C/faq-fascenondom.htm

Table 3 – ARERA Time Slots. Source: ARERA

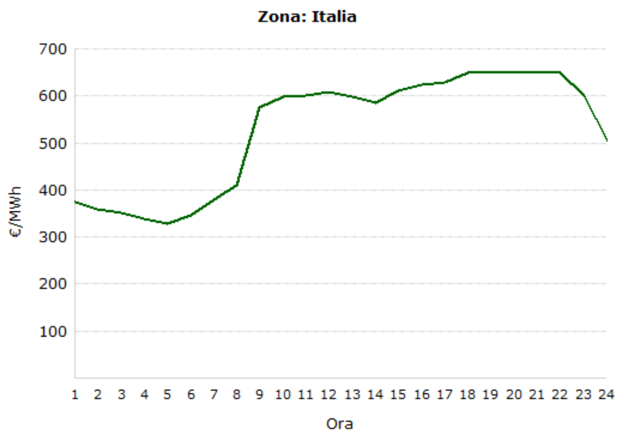
Pre-defined time slots don't make sense anymore

Non-programmable renewables do not only change the graph of the daily energy prices (form a "bell curve" to a "duck curve"), but make it significantly different between similar days in an irregular fashion: certain days might be cloudy or rainy and reduce solar generation, some days the wind could blow less, and so on.

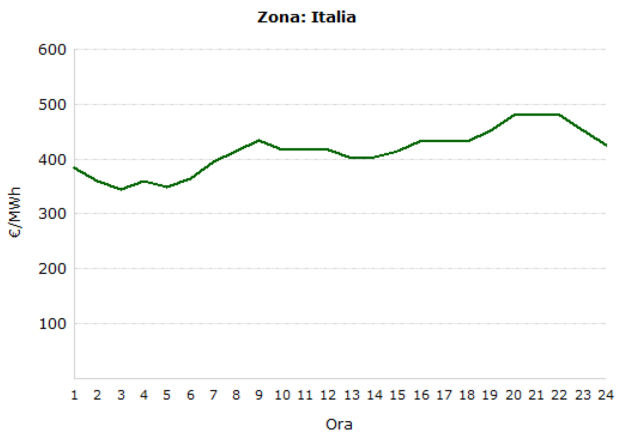
This variability, which is going to increase even more in the future due to a predictably larger share of renewables, cannot be easily managed by trying to shift load in predetermined hours of the day, as with bi- or tri-hourly rates.

The following graphs from the Italian energy market show different prices and different patterns not only between different weekdays (Graph 8) but also on the same weekdays of the same month (Graphs 5,6,7).

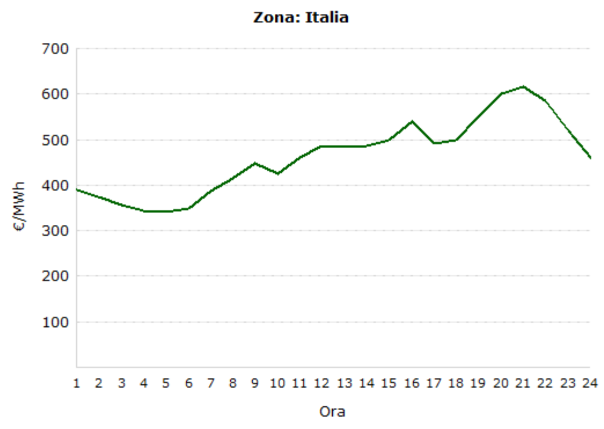
What should be noted is in particular the difference in the pattern, more than the price difference, since the latter might be influenced by fluctuating gas prices due to the current energy crisis.



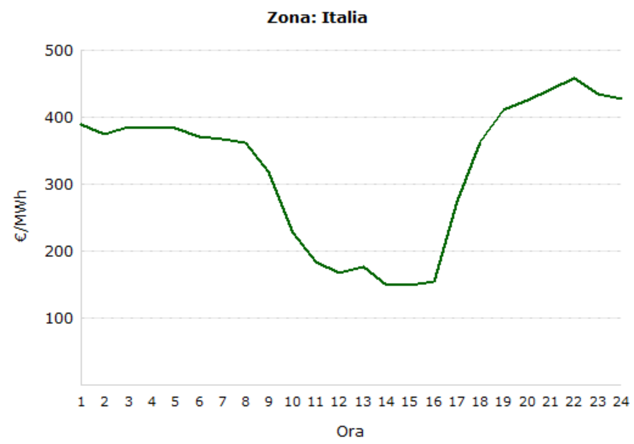
Graph 5 – prices 25/07/2022 (Monday)



Graph 6 – prices 11/07/2022 (Monday)



Graph 7 – prices 18/07/2022 (Monday)



Graph 8 – prices 10/07/2022 (Sunday)

With a growing share of renewables, the predetermined ARERA time slots aren't fitting anymore the price curve. In particular, F2, which should be a "mid load" time slot, is, instead, often the one with the highest prices. At the same time, the central hours of the day, from about 10 AM to 5 PM often present the lowest prices of the day, while being part of the F1 "peak" time slot. In the same way, during the night (F3 time slot) prices might not be lower than during the day, for the aforementioned reasons.

The issue here is not only the fact that these time slots are not fitting the new price curves, but that the concept itself of fixed time slots likely won't work anymore. As I have just shown, due to the nature of renewables, the price and its pattern could be wildly different each day. Creating, for example, an "F4" time slot that covers the central hours of the day, from 10 AM to 5 PM, when prices are lower due to solar PV, wouldn't necessarily make sense, since this trend does not repeat in a similar fashion each and every day, and it would be significantly less accentuated in the winter.

In Table 4 are shown the average prices of energy in the different time slots in different months. As I mentioned, prices in F2 are in some instances higher than in F1.[43]

[43] https://www.a2aenergia.eu/assistenza/tutela-cliente/indici/indice-pun

MESE	MONORARIO (€/kWh)	F1 (€/kWh)	F2 (€/kWh)	F3 (€/kWh)	F23 (€/kWh)
lug 22	0,441650	0,495240	0,473260	0,386070	0,426180
giu 22	0,271310	0,297170	0,293310	0,241030	0,265079
mag 22	0,230060	0,237210	0,253520	0,212330	0,231277
apr 22	0,245970	0,256230	0,266580	0,228860	0,246211
mar 22	0,308070	0,320080	0,329120	0,286190	0,305938
feb 22	0,211690	0,224880	0,225680	0,193650	0,208384
gen 22	0,224500	0,257190	0,242350	0,196390	0,217532

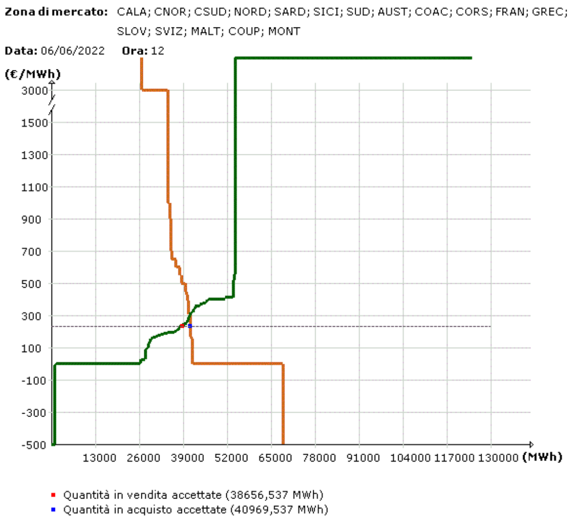
Table 4 – Average energy price (PUN) by time slot, per month.

Demand elasticity

Price elasticity of demand is the measure of how sensitive the demand is to a variation in price. It is a coefficient based on the slope of the demand curve (first derivative).

Fixed time slots, that don't reflect the true price pattern of wholesale markets, have a direct consequence: reduced price elasticity. This means that demand is not responsive to price increases in the wholesale energy market. Consuming electricity at noon on a summer sunny day, when electricity prices are low, or consuming it on the same day but at 7 PM, when prices are high, for a consumer is indifferent, since the price paid to the retailer is exactly the same.

This creates an inefficient situation where the different actors in the market are acting against market efficiency. The higher cost of using electricity during the evening is not correctly transferred to those consumers who actually consume it in the evening, but it's rather spread between all users. Less-efficient, more costly and more polluting peaker plants need to be used more often, rather than efficiently using baseload plants or renewables. As it is shown in Graph 8, the demand curve is almost vertical. This means that buyers would accept to purchase the bulk of their demand, at almost any price.



Graph 13 - Demand/Supply graph 06/06/2022 at 12:00, Italian market. Source: GME

How does this variability affect retailers

Energy retailers usually have commercial offers that provide a fixed price for energy. This fixed price includes a "risk premium" since the retailer buys electricity at prices that vary continuously, which might unexpectedly rise due to a combination of external factors.

Some retailers, instead, have contracts with electricity unit prices indexed to the PUN (Prezzo Unico Nazionale / Single National Price): the wholesale price of energy. These offers are advantageous since there is a reduction of the risk premium charged by the retailer, but, of course, the transfer of related risk.

While these offers are indexed, the indexing is not done at a granular level. It's generally indexed to the average monthly PUN, divided by the ARERA time slot (Table 4). Since, as explained in the previous paragraph, the ARERA time slots don't fit anymore the dynamic of market prices, a retailer could also be bearing a risk related to the distribution of consumption from his customers, that, inside a single time slot could be skewed towards the more expensive hours, and then the retailer costs are higher than the average cost indicated by the PUN. This creates a rather small, but still existent, additional risk-premium that the final customer will bear.

Issues and opportunities

Focusing on Italy, for this thesis, changing the "time slots" mechanism is not easy. The first problem resides in the meters that are currently used to monitor energy consumption. The "First generation Smart Meter"[44] only provides energy consumption data aggregated in the pre-defined ARERA time slots[45], and is not able to provide more detailed and granular information on consumption, in particular with hourly consumption data. Changing the time slots on the 1st generation Smart Meter requires a significant reconfiguration.[46]

On the bright side, distribution companies have started from 2017, a substitution program that aims to install in every household a second-generation meter[47] (2G), that, among other upgrades, can provide granular details, with segmentation of consumed energy every 15 minutes, that creates a daily consumption curve made up of 96 data points.

About 22 million[48] of 2G meters have already been installed, which is about 69% of the total, which accounts for 32 million meters[49] currently active in the country. The share should also grow quickly in the upcoming years since all the distributors have plans to conclude the majority of 2G meter installations in a time range from 2024[50] [51] to 2026[52]. This is a key enabling technology for creating dynamic rates that better respond to the price dynamic.

Regulatory framework

On the technical side, a solution is already available and is going to be sufficiently pervasive in the near future, but since ARERA provides the time slots, it's also relevant to understand if they are binding on a legal level, and are not only put in place to cope with the limitations of the 1G meter.

For retailers, the regulatory scheme is contained in the "Code of business conduct for the sale of electricity and natural gas to end customers"[53] which, does not provide any specific obligations to

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[44] https://www.e-distribuzione.it/a-chi-ci-rivolgiamo/casa-e-piccole-imprese/guida-al-contatore-1-generazione.html

[45] https://www.arera.it/allegati/elettricita/170111smartmet.pdf

[46] Ibid.

[47] https://www.arera.it/it/docs/16/087-16.htm

[48] https://www.e-distribuzione.it/open-meter.html

[49] https://www.e-distribuzione.it/content/dam/e-distribuzione/documenti/open-meter/pms/PMS2-2dicembre2016.pdf

[50] https://www.e-distribuzione.it/content/dam/e-distribuzione/documenti/open-meter/pms/PMS2-2dicembre2016.pdf

[51] https://www.unareti.it/unr/unareti/downloads/pdf-ele/UNARETI-SM2-Opusclo-informativo-A4-17-web.pdf

[52] https://www.ireti.it/contatori-2g#:~:text=LE%20TEMPISTICHE,entro%20la%20fine%20del%202026.

[53] https://www.arera.it/allegati/docs/21/CCC21.pdf

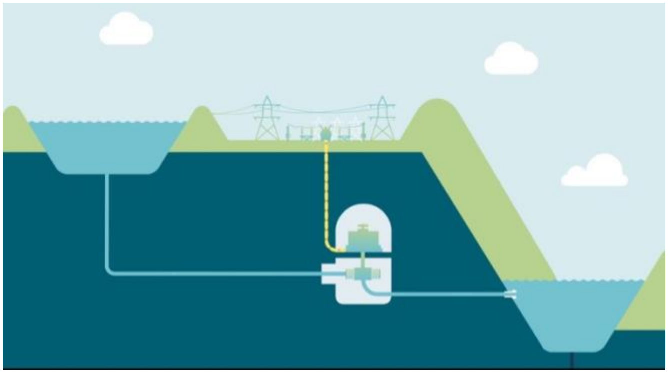
follow the pre-defined time slots. Instead, in article 6.2, which provides detailed requirements for the calculation of annual predicted costs, it’s clearly considered the option of hourly calculation: “In the presence of fees articulated on an hourly basis or which provide for…” (page 8).
Confirmation of the absence of restrictions on retailers' fee hourly composition is the availability of a commercial offer provided by Enel Energia, called “Ore Free”[54] (“Free Hours”), which allows the customer to select from an app three hours of the day in which the customer doesn’t pay for the electricity consumed. The customer can choose freely these hours, and change them day by day. This offer requires a 2G energy meter, that can provide the needed granularity of energy consumption information to the retailer.

Chapter 3: Storage-based solutions

The potential solution for the above-mentioned problem that is currently most talked about and used to cope with variations in demand and supply of electricity is storage. The basic concept is rather simple: buy and store energy when it’s cheaper, then resell it when it’s more expensive.
There are two main solutions for energy storage: pumped hydro and batteries.

Pumped Hydro

Pumped Hydro works by using the difference in gravitational potential energy of water between two basins situated at different elevations. When energy prices are low, the plant buys electricity from the grid and pumps water from the lower basin to the one at a higher elevation. When wholesale prices are higher, the water flows in the opposite direction and spins a turbine generator that feeds electricity into the grid.



Pumped Hydro is currently the most used form of energy storage by far, according to the 2021 US Hydropower Market Report from the US Department of Energy[55], it accounts for 93% of all energy storage at the utility-scale in the United States.
The main obstacles to further development of pumped hydro are linked to the initial capital cost, the need for appropriate locations with the possibility of two natural basins close by at different elevations

[54] https://www.enel.it/it/luce-e-gas/luce/offerte/ore-free

[55] https://www.energy.gov/sites/prod/files/2021/01/f82/us-hydropower-market-report-full-2021.pdf

and the time required for the construction. Another relevant aspect is the energy losses that pumped hydro entails. According to the Environmental and Energy Study Institute, the full-cycle efficiency[56] of a pumped-hydro plant ranges between 70% and 85%, so on average about 20% of electricity gets lost (consumed) during the process. Directly using the electricity when it's cheaper is clearly a better option.

Batteries

Batteries are a solution of growing relevance for grid-scale applications. Thanks to the massive demand from other sectors, especially in automotive, lithium-ion battery technology is being deployed for energy storage at the grid scale, or for behind-the-meter solar to increase self-consumption and reduce reliance on the grid. With the growing share of renewables, batteries are considered the key solution to cope with variability. While they are for sure a promising solution, they still present several issues: first and foremost, their price is still very high, and not economically convenient for all but the countries with the highest grid reliability issues or variability.

Also, global production of batteries is already fully booked[57] for the foreseeable future, due to the very high demand coming in particular from the transport sector[58], which is undergoing, as mentioned before, an extremely quick transition to electricity.

While extremely advanced, lithium-ion might not be the right technology for stationary storage. Some of its key strengths are the high energy density and a good energy-to-weight ratio, these two characteristics are irrelevant for stationary energy storage. At the same time, their lifespan[59] is still in the realm of 3000 full charge-discharge cycles, after which only about 40% of the original capacity remains usable. The lifespan could potentially be prolonged to 9000 cycles, but with a further drop of usable capacity to about 20%.

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[56] https://www.eesi.org/papers/view/energy-storage-2019#:~:text=Pumped%2Dstorage%20hydropower%20is%20more,hours%20for%20lithium%2Dion%20batteries.

[57] https://www.reuters.com/business/sustainable-business/how-battery-shortage-is-hampering-us-switch-wind-solar-power-2022-06-09/

[58] https://www.theguardian.com/business/2022/may/10/electric-car-battery-shortage-looms-in-2025-warns-stellantis-boss

[59] https://batteryuniversity.com/article/bu-808-how-to-prolong-lithium-based-batteries

For this reason, some companies are focussing on other technologies like “flow batteries”[60], which trade energy density for lower cost and longer lifespan. Still, this technology is in the early stages, in pilot projects[61], and there isn’t anyone that is manufacturing them at scale, an indispensable requirement considering the number of batteries that will be needed to stabilize the world’s energy grids.

Depth of Discharge	Discharge cycles	
	NMC	$LiPO_4$
100% DoD	~300	~600
80% DoD	~400	~900
60% DoD	~600	~1,500
40% DoD	~1,000	~3,000
20% DoD	~2,000	~9,000
10% DoD	~6,000	~15,000

Table 4 - Battery lifespan table. Source: Battery University

Chapter 4: Demand Response

Demand response is the adaptation of energy consumption to the supply offered. It can be declined in various forms, and the main distinction is between implicit and explicit demand response.

Explicit Demand Response

Explicit demand response is the adaptation of consumptions (typically, the reduction of load), based on explicit needs from the transmission service operator (TSO), forwarded through purpose-designed demand response programs which aim to offer to a number of high-energy consuming actors an economic reward in exchange for the commitment, through a legally binding contract with penalties, to reduce their load when needed. In this way, the grid operator has a reliable flexibility option to use when there is an unbalance between demand and supply, or in the case of emergencies in which new demand can’t be met. Explicit DR programs are usually set up as ancillary services, needed to ensure

[60] https://www.enelgreenpower.com/learning-hub/renewable-energies/storage/flow-battery

[61] MSNBC report on energy storage https://youtu.be/EoTVtB-cSps

the correct functioning of the grid. A good share of TSOs worldwide deployed explicit demand response programs, each with different scope, characteristics and implementation.

Implicit Demand Response

Implicit demand response is the modulation of energy consumption based on price mechanisms. If consumers have retailing contracts that match the hourly price of energy, they can adapt their behaviour to shift their loads when electricity is cheaper, and adopt energy-saving measures when prices peak. It is a price-signal-driven incentivisation mechanism.[62] The key difference with explicit demand response is the lack of any commitment (and related direct remuneration). Implicit demand response has the potential to significantly increase demand price elasticity in the electricity market *Eid et al., (2016)*[63].

A parallel with Uber's success

Removing informational asymmetries by providing demand and supply information through price signals is the basis of the thunderous success of the very well-known ride-hailing platform Uber. One of the key success factors of Uber is its dynamic-pricing model[64]. When demand is low, prices automatically decrease, this mechanism allows for consumers who wouldn’t otherwise use the service, to consider it and potentially utilize it. When demand is high, instead, the rise in price increases offer, with more drivers that are willing to offer the service with higher remuneration. A higher price also reduces demand, with customers that aren’t willing to pay the increased price not taking a ride, or delaying to a later moment. Conversely, the traditional cab services with fixed pricing schemes don’t take into account any information on demand and supply: when demand is low the high price offered will result in unused capacity (drivers searching for passengers with empty cars), and in peak ride request periods, demand won’t get satisfied, typically producing long waiting times or queues at airports/train stations. Uber’s dynamic pricing allows it to keep a lower base rate and provide an efficient service even in peak demand situations. The same principle could be applied to energy prices.

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[62] https://www.smarten.eu/wp-content/uploads/2016/09/SEDC-Position-paper-Explicit-and-Implicit-DR-September-2016.pdf

[63] Eid, C., Koliou, E., Valles, M., Reneses, J., & Hakvoort, R. (2016). Time-based pricing and electricity demand response: Existing barriers and next steps. *Utilities Policy*, *40*, 15-25.

[64] https://www.uber.com/us/en/drive/driver-app/how-surge-works/

Explicit DR implementation

The kind of demand response that is already seeing good success and expansion is the explicit one. Grid operators that aim to increase their flexibility options and reliability are adopting purpose-designed Explicit DR programs. Their aims are multiple: providing Emergency DR, when production capacity can't meet demand, to keep the grid stable; reducing the load on the electricity transport network in peak load instances, with Network DR; or providing frequency control ancillary services through Ancillary services DR.[65] In all these instances, the grid operator TSO (transmission system operator) develops a program in which BSPs (balancing service providers) can participate in. A single BSP aggregates a plethora of end-customers, typically energy-intensive businesses who can shift or modulate their loads, which sign a contract with it. BSPs are private companies that, upon request from final customers, evaluate and quantify the balancing capacity, implement a technical solution to enable it (IoT sensors and actuators, protocols, digital platform), and offer a revenue-sharing contract that usually matches the conditions that, in turn, the TSO requires to the BSP itself, remunerating both the availability "per se" of DR capacity, plus single DR events. Stringent clauses and penalties upon failure to comply with the DR requests are also provided by the TSO to the BSP, which can mirror the conditions to its customers.

The Italian Ancillary Services Market (MSD)

In Italy, demand response is managed by Terna, the transmission system operator (TSO). The ancillary services market is called the MSD[66] (Mercato per il Servizio di Dispacciamento). The function of this market is to provide Terna with the resources (power reserves[67]) needed to manage grid stability, to cope with the real-time nature of electricity supply. Consumers, by absorbing a continuously variable load of energy, cause oscillations in the grid, that need to be counter-balanced. Energy reserves can assume different forms: hydroelectric, batteries or demand response.

There are two different types of power reserves: Frequency Containment Reserves (FCRs[68]) and Replacement Reserves (RR). The former enacts a real-time frequency control, the latter should be available in fifteen minutes from the TSO's request. These resources are negotiated in the MSD and on the "balancing market" MB (Mercato del bilanciamento) which is the equivalent of the MSD but with real-time operations.

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[65] https://www.enelx.com/au/en/resources/the-four-types-of-demand-response

[66] https://www.centrali-next.it/hub-della-conoscenza/mercato-dei-servizi-di-dispacciamento-msd

[67] https://www.centrali-next.it/hub-della-conoscenza/riserve-di-potenza

[68] https://www.next-kraftwerke.com/knowledge/frequency-containment-reserve-fcr

Demand response in the MSD

With ARERA's deliberation 300/2017/R/eel[69], the introduction of virtual demand response units was green-lighted; Terna then opened up, with a pilot project[70], the MSD to demand response. Terna's regulation[71] identifies the UVAM (Unità Viruutali Abilitate Miste) entity, which is the virtual aggregation unit able to provide a demand-response service. A UVAM can be constituted by at least one of the following elements: a consumption unit (any energy-consuming system), a non-relevant production unit (a behind-the-meter generator or solar PV), or a storage system (battery), and it should have a minimum power value of 1MW, and should be able to perform a modulation within fifteen minutes from Terna's request, and maintain it for up to two hours. Terna's regulation also identifies as the BSP (Balance Service Provider) the subjects that can request to create and qualify for a UVAM. A BSP aggregates multiple modulation points that are in the same aggregation perimeter, which are geographic perimeters[72] defined by Terna separating different grid areas.

Remuneration mechanism

The BSP gets remunerated by Terna both for available capacity "per se" offered and for single activation instances. Terna auctions[73] the total amount of DR capacity needed (1000MW in 2022) in multiple reverse auctions with different validity periods (yearly, quarterly, monthly). BSPs who participate offer their modulable capacity at a price from 1€/MW/year to a maximum of 30.000€/MW/year, also based on their opportunity-cost of having to suddenly reduce demand. Bids are accepted from the less costly until the total balancing capacity is met. Additional remuneration is provided for each time the DR service is actually requested by Terna, based on the modulated energy quantity (MWh)[74].

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[69] https://www.arera.it/it/docs/17/300-17.htm

[70] https://www.terna.it/it/sistema-elettrico/progetti-pilota-delibera-arera-300-2017-reel/progetto-pilota-uvam

[71] https://download.terna.it/terna/Regolamento%20MSD%20UVAM%20del.215-21_8d9276de4d1cbd3.pdf

[72] https://download.terna.it/terna/0000/1117/99.ZIP

[73] https://www.youtube.com/watch?v=NInQ9_eKz3I&t=428s

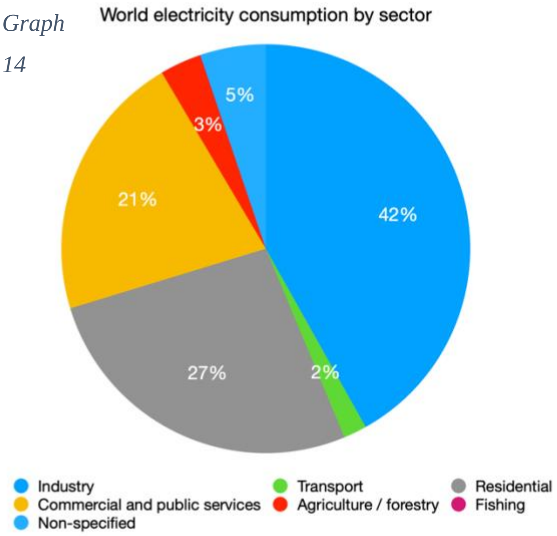
[74] https://download.terna.it/terna/20220503_Allegato_A.23_Domanda_elastica_TERRE_8da2d0034a9efd1.pdf

Chapter 5: Implementing implicit demand response in households

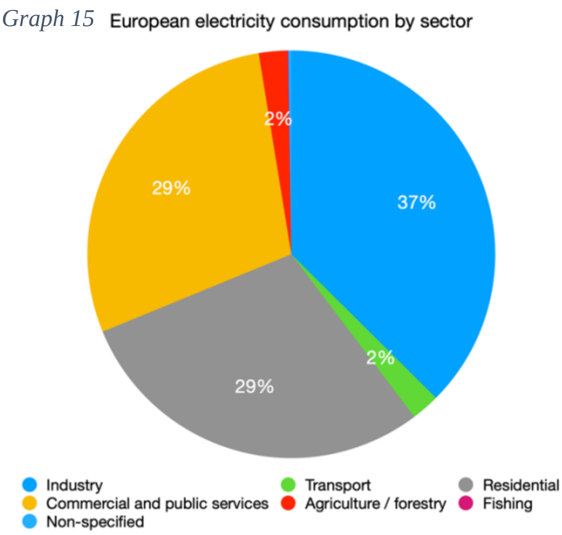
Opportunities

Households represent a significant share of electricity consumption. In 2019, data from IEA[75] indicate that 27% of worldwide consumption comes from the residential sector, with a more relevant share in developed countries. In Europe, the percentage rises to 29%.

Graph 14



Graph 15



Still, this data doesn't show the full picture: electricity is only one part of the overall energy consumption. Today, other fossil sources are massively utilised to power the global economy. Natural gas, in particular, is widely used in the residential sector for the most energy-intensive tasks: ambient heating, hot water, and cooking. 2020 data from Eurostat[76] indicate that space heating accounts for 62,8% of total energy consumption by EU households, water heating 15,1%, and cooking 6,1%. These three sources combined, which are currently mostly powered by natural gas, account for 84% of total residential energy consumption. By analyzing[77] data from IEA, electricity only accounts for 33% of the residential energy consumption in Europe, the majority, 52%, is constituted by natural gas, and also oil, typically used for ambient heating, represents a relevant share (12%).

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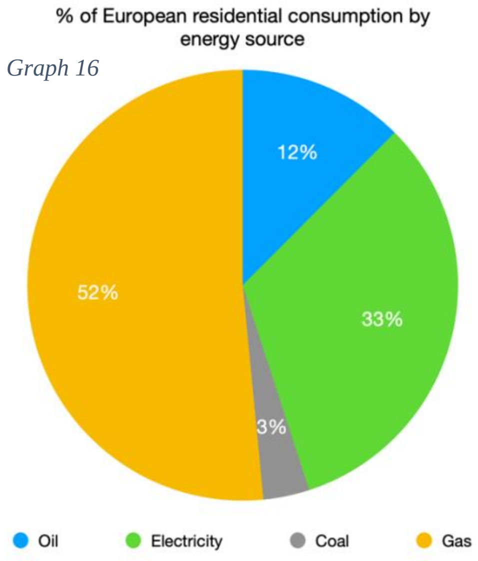
[75] https://www.iea.org/regions/europe

[76] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households&oldid=569853

[77] IEA data (link) re-elaborated on spreadsheat available here



Graph 16

Table 5

European residential consumption by energy source (TJ)

Source	Value (TJ)	% of total
Oil	1405536	12,5%
Coal	390603	3,5%
Electricity	3663643	32,5%
Gas	5806565	51,5%
Total	11266347	

Electrification of consumptions

The decarbonization objectives that are set on a global level[78], aim to drastically reduce carbon emissions in the next four decades, to minimise the effects of climate change, in particular, the EU Green Deal commits to net-zero CO2 emission by 2050, with a 55% reduction at the 2030 checkpoint. Electrification of consumption is the only way in which these objectives can be reached. This element was particularly stressed by industry players I interviewed, since the use of natural gas and oil in end consumption needs to be substituted with electricity, which is one of the few energy vectors that can be produced with zero-carbon technologies like solar photovoltaic, wind, geothermal, hydro, tidal and nuclear. While for some sectors and use-cases, those that are called in technical jargon "hard to abate", electrification is still considered an extremely difficult feat, for others, electrification technologies are already mature and growing, in some cases even more economically convenient than their carbon-emitting counterparts. Residential energy consumption is a key example: every fossil-fuel-powered appliance has an efficient electric counterpart already available. Ambient heating and water heating can be electrified by using heat pumps, and gas stoves can be substituted by induction stoves. Hard-to-abate sectors are, for example, aviation, maritime freight transport, steel production, cement production and a plethora of industry-related production processes. For these uses electrification will certainly not be deployed in the short run, and even in the future, other solutions, such as carbon capture, or CO2 compensation might be used. The bottom line of this reasoning is that, while today electricity consumption by households accounts for about 30% of the total, it is

[78] https://www.un.org/en/climatechange/paris-agreement

predicted, also based on outlook scenario-analysis[79] to significantly grow in the medium term, due to the relative ease of deploying in this sector, more than in others, the electrification of consumptions. There is also an additional element to be considered when analyzing future trends in household electricity consumption: the electric car. Electrification of transport is another field that has a high maturity level and is seeing rapid adoption. In the EU, rechargeable cars, which include both plug-in hybrid and fully-electric cars, have reached a 22% market share in 2022, and, also due to the 2035 ban on combustion engines[80], are predicted to rapidly grow. These vehicles can be recharged directly at home if the owner has a private parking space/garage or a roadway. Data on private parking is sparse and lacklustre and varies significantly between countries. Some UK data shows that 75%[81] of owners have a private place to charge the car, while an EU survey *Pasaoglu et al., (2012)* [82] shows that more than 30% of car trips start from a private premise or private parking area. In any case, even considering a conservative estimate of 30%, at-home charging will play a relevant role in the future and will shift a portion of transport-related energy consumption to households. The key point I want to make here is that residential electricity consumption is an extremely relevant share of the total, that can and should be leveraged through demand-response, to balance the variability of renewables, and instead, today is mostly ignored.

Obstacles – why it hasn't been done

Implementing demand response in households is a complex task, according to industry players[83], gathered through the interviews with Enel X, obstacles are both on the regulatory and technical sides. Smart metering with high-frequency sampling is needed to deploy any kind of dynamic fee and regulatory authorities should not have provisions prohibiting dynamic fees. On the other side, a strong limitation is linked to the costs that occur to enable the appliances, on a technical level, to have dynamic activation, load reduction or dynamic activation. While the cost of these implementations is quickly amortised when deployed in energy-intensive businesses, energy consumption from a single

[79] https://www.iea.org/data-and-statistics/charts/electricity-demand-by-sector-and-scenario-2018-2040

[80] https://www.reuters.com/business/autos-transportation/eu-lawmakers-support-effective-ban-new-fossil-fuel-cars-2035-2022-06-08/

[81] https://www.field-dynamics.co.uk/25-drivers-no-off-street-parking/

[82] Pasaoglu, G., Fiorello, D., Martino, A., Zani, L., Zubaryeva, A., & Thiel, C. (2014). Travel patterns and the potential use of electric cars–Results from a direct survey in six European countries. *Technological Forecasting and Social Change*, *87*, 51-59

[83] Based on interviews conducted with managers from Enel X

household appliance is generally pretty low and thus the initial cost would not be recouped. Luckily, another parallel trend can partially solve this issue: smart homes and connected appliances. Most of the latest models of home appliances, from fridges to lightbulbs to washing machines to HVAC systems, are implementing network connectivity, generally through Wi-Fi, to enable smart features like connection to a companion app, voice-assistant activation and data analytics. This connectivity could also be used for demand-response-based smart activation or deactivation. While this sounds good in theory, some key technical limitations preclude this solution from working. Firstly, all connectivity solutions currently implemented use proprietary and non-standardised technologies.

Chapter 6 - The solution

What if you could have all your energy-consuming appliances automatically shift their load during the hours of the day when electricity prices are lower, based on updated wholesale market data? Or even more, by optimising the load to directly use the energy from your behind-the-meter solar panel. This could be done by leveraging the connectivity of intelligent smart-home appliances. The electricity retailer who designs the offer could provide to the customers a smart home hub that can be connected to the appliances, possibly through a standardised, LAN-based protocol (Matter), that can activate, deactivate or modulate their load, based on market price data. The customer could use the smart home hub directly, or a companion app, to set preferences.

Connectable appliances

It is foreseeable a use case scenario for every appliance in the home. In what follows, I present different scenarios, starting from the most energy-intensive ones.

Heating and cooling (HVAC)

Electric heating and air conditioning can be set to automatically modify the temperature by one or two degrees (celsius), based on energy prices. The user can set, directly from the home hub or its companion app, a range of temperatures he wishes the HVAC system to operate at, and then, based on data from the day-ahead market prices, the home hub modulates in this range. Even more, if the user sets a higher heating temperature value in the evening than in the rest of the day, the system could pre-heat the home in the afternoon if prices from day-ahead market outcomes are significantly lower in those hours than during the evening, as often occurs due to solar PV impact. If energy prices are higher, instead, the system reduces the thermostat. The same principle could work in reverse with air-conditioning.

Water heating

Heating water is the most basic form of energy storage, but it's not currently used in a dynamic way. Electric water heaters with boilers/reservoirs represent a great and already widely deployed solution to store energy. Currently, water heaters activate after being emptied of hot water, which is typically after a shower. What if, instead, they could automatically turn in the moment when electricity is cheaper, while taking into account user preferences, thus not diminishing user comfort. A user could set some hours of the day when he wants to be sure that the water heater is full, so he can use the full capacity to have one or more showers (for other household residents). For example, if a user wakes up at 7:00 morning and has a shower, and has set that at 6 PM he wants his boiler to be full, the system could automatically identify the moment in which electricity is cheaper in this timeframe, based on day-ahead market outcomes, or when a rooftop solar panel is producing electricity, and activate the boiler.

Dishwasher and washing machine

The same principle can be applied to appliances, such as dishwashers and washing machines. They can be activated when the prices of energy are lower, using a scheduling mechanism: the user selects the time when he wants the dishwasher or washing machine to end the cycle. For example, a dishwasher could be loaded in the evening, but only activate at 4 AM, when energy prices are lower, so that by 7 AM (hypothetical scheduled moment) the cycle would be finished. Or, a washing machine could be loaded in the morning before going to work and activate at the best moment, to finish before 6 PM.

Electric car charging

For those households which have the possibility to charge an electric vehicle at home, other possibilities open up. By using connected "wall box" chargers, or, even better, directly "connected cars", the charging session could be activated only when electricity gets below a certain price. A user could set a minimum SoC (state of charge) below which the charging would start immediately after plugging in, a margin for unexpected commutes like 35%/40%, but the remaining capacity could only be charged when prices are below a certain threshold. For this example, several technical elements should be carefully considered. The most impactful technical limitation is the fact that the current AC charging standard for EV charging doesn't provide for SoC communication between cars and wall-box chargers. The decision to immediately charge or not, based on the SoC, should be then made "manually" by the user. Otherwise, this charging process could be managed directly by the vehicle, which should then be able to communicate to the energy provider's home hub.

Fridge compressor modulation

Fridges also present opportunities for demand-response implementation. Compressors/heat pumps inside the fridge, which cool the air inside, are not active continuously all the time. They activate and deactivate when the temperature gets respectively above or below a certain threshold. Thermal inertia from fridges could represent another form of readily available energy storage mechanism. In practice, fridges operate between +4° and +6°. This range could be dynamically modified, so that when energy prices are low, the fridge keeps a cooler temperature, around 4°, to have sufficient thermal inertia to then be able to turn off the compressor when prices are higher, until of course the temperature rises above +6°, when it should be activated in any case to preserve the food.

Miscellaneous

A wide range of devices can automatically activate or deactivate based on prices. Air purifiers, for example, don't need to be turned on the whole day, during peak hours they could automatically turn off. The same is true for battery-powered devices. Robot vacuums run on schedule, and can also schedule their charging according to energy prices in a totally transparent way for the final user, which gets the same end result.

Non-schedulable appliances

As we have seen, almost the entirety of high energy-consuming appliances can be scheduled. The only energy-consuming systems that remain outside are the lights, whose share of total energy consumption is significantly decreasing due to the hyper-efficient LED technology and kitchen-related appliances such as induction stoves and ovens. Also, TVs won't fit in this system. Aside from the kitchen-related appliances, both lights and TVs have a low energy consumption. An LED light bulb draws 5W of power, so even big homes with all lights turned on will hardly reach 100W of power drawn from lights. TVs also have a relatively low impact. Even a 55-inch 4K TV[84], with a "G" EU energy rating (the worse possible), has, according to the energy label, a rated consumption of 81kWh/1000h, which equates to 81W of instant power draw. Once again, we are under the 100W threshold. Neither TVs nor lights are going to play a relevant share in future household energy consumption.

Combination with rooftop solar

While this solution can work in every household, for those which have rooftop solar installed, the benefits are even greater. Using directly energy from the panel means increasing, even more, savings,

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[84] https://www.mediaworld.it/it/product/_lg-oled-evo-oled55c26ld-2022-tv-oled-55-in-oled-4k-no-171004.html

using free energy, and being able to pay off the investment more quickly. This solution allows for maximising the energy used from the panels.

Technical implementation

On the technical side, the solution would entail a home hub, that could be a smart display with voice assistant integration, like some solutions already available (Enel X's Homix[85]). The home hub is the "brain" of the smart home and manages demand response. The user can program there the routines and preferred availability moments for the different appliances (Ex: the water heater should be full by 7 AM). The hub also functions as a communication gateway, to dialogue with IoT devices in the Local Area Network. By also being connected to the internet, the Home Hub receives day-ahead price data from the energy retailer, based on the day-ahead market or on custom fees from the retailer. By combining price information and scheduling preferences, it determines the optimal moment for sending the commands to the appliances.

Chapter 7 - Savings potential calculation, different scenarios

The mentioned solution, combined of course with dynamic pricing, could bring relevant savings to the end user since it embraces all the most energy-consuming devices and appliances. To illustrate cost saving for different appliance, in what follows I present the results of data analysis based on secondary data. Detailed calculations depend on the actual variations between peak and off-peak prices.

Method

To perform calculations, I downloaded[86] hourly prices for the entire 2019 period, and 2022 until the 31st of August, from the GME website. I treated these two datasets (2019 and 2022) separately, to perform a double scenario analysis, one with "pre-pandemic/war" prices, and another with "energy crisis" prices. I then performed some data cleaning on Excel and proceeded to evaluate potential savings through implicit DR. I calculated the value of the average of the three most and least expensive hours of each and every day, and I then averaged out these values. The output was an average energy price value for the three most expensive hours of every day in 2019 and 2022, and the same for the three least expensive ones (whichever they were every day). I then used these values as input for the subsequent appliance consumption calculation. For every major appliance, I estimated

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[85] https://www.enelxstore.com/it/it/smart-home/homix

[86] https://www.mercatoelettrico.org/it/Download/DatiStorici.aspx

the modulable energy consumption and then identified what kind of DR could be used. I distinguished two kinds of DR: “price peak deactivation” and “price dip activation”. For appliances that fell in the first group (ambient heating), I calculated savings with the difference between activating the appliance with peak energy prices, from the previous calculation of the three most expensive daily hours- (no DR) and average prices (DR scenario). For appliances that fell in the “price dip activation” group, I did the opposite calculation, thus assuming that the energy price in the non-DR scenario was the average one, and in the DR scenario the “dip” one, from the three least expensive hours. In the end, I also estimated consumption from non-DR appliances in a fully electrified home and then calculated the savings as a share of the total cost of energy. All consumption data took into account an average household, fully electrified, with efficient appliances and lighting

Calculation process

The first step of the calculation was to calculate the average price in the three least and most expensive hours of every day. To perform this calculation properly, I recursively calculated the 0,125 and 0,875 percentiles. These percentile values equate to 3/24, so exactly three out of the twenty-four hourly data points were greater than the 0,875 percentile, and exactly three were less than the 0,125 price values. For each day I then obtained an average price value of the three least and most expensive hours, columns 6 and 7 in Table 5. I then also performed further calculations to obtain the percentile. This was then meant to use the “AVERAGEIF()” excel function to average out the three.

Data/Date (YYYYMMDD)	Ora /Hour	PUN	0,125 %ile	0,875%ile	Average of values < 0,125%ile	Average of values > 0,875%ile	Delta	Daily Std Dev	Daily Average	Daily CV
20220101	1	170,28	99,36625	203,44125	84,663333	211,7166667	127,05333	40,67569	150,69	26,99%
20220101	2	155,72								
20220101	3	147,09								
20220101	4	91,00								
20220101	5	104,00								
20220101	6	140,60								
20220101	7	147,09								
20220101	8	99,99								
20220101	9	67,99								
20220101	10	95,00								
20220101	11	135,80								
20220101	12	150,70								
20220101	13	155,72								
20220101	14	147,09								
20220101	15	100,00								
20220101	16	155,00								
20220101	17	169,78								
20220101	18	203,10								
20220101	19	205,83								
20220101	20	214,66								
20220101	21	214,66								
20220101	22	203,00								
20220101	23	180,00								
20220101	24	162,44								

Table 6 - Daily averages calculation

The following step was to average out all the daily values of the three least expensive hours "dip hours" and the three most expensive hours "peak hours" (Table 6). This operation was performed in the same manner both on the 2019 data and on the 2022 data. The result of these calculations is displayed in Table 7, which shows the average daily price for the two time periods, plus the average of the average of the three least and most expensive hours for every day. Table 8 shows the final results of the "peak" and "dip" calcluations, from the two datasets (2022 and 2019). The calculation process was the same for both datasets. "Average price peak" indicates the average price of the three most expensive hours of every day in the year; "Average price" is the average of the daily (average) price; "Average price dip" is the average price of the three least expensive hours of each day of the year.

Data/Date (YYYYMMDD)	Ora /Hour	PUN	0,125 %ile	0,875%ile	Average of values < 0,125%ile	Average of values > 0,875%ile	Delta	Daily Std Dev	Daily Average	Daily CV
20220101	1	170,28	99,37	203,44	84,66	211,72	127,05	40,68	150,69	26,99%
20220102	1	151,13	141,76	204,38	127,07	228,83	101,76	31,40	167,21	18,78%
20220103	1	127,00	84,95	271,51	84,13	295,78	211,65	67,02	193,64	34,61%
20220104	1	150,55	119,16	194,36	108,03	201,32	93,29	30,02	166,09	18,07%
20220105	1	142,60	93,50	244,81	79,66	265,00	185,34	59,49	192,54	30,90%
20220106	1	207,15	193,93	254,43	180,52	275,30	94,79	28,07	225,70	12,43%
20220107	1	213,47	205,07	257,79	203,60	267,33	63,73	20,96	233,97	8,96%
20220108	1	218,33	201,79	283,88	201,00	294,99	93,99	28,98	234,47	12,36%
20220109	1	215,00	186,95	243,99	176,78	265,44	88,66	25,84	213,28	12,11%
20220110	1	196,23	192,11	300,40	185,51	307,90	122,38	44,70	252,19	17,72%
20220111	1	204,33	194,35	292,84	186,32	306,19	119,87	40,02	245,24	16,32%
20220112	1	196,65	186,75	284,96	180,65	291,55	110,90	36,58	234,33	15,61%
20220113	1	192,24	188,63	256,98	187,48	267,75	80,27	26,53	223,41	11,87%

Table 7 - Daily price data

Price data		
0,382	€/kWh	avg price peak ('22)
0,311	€/kWh	avg price ('22)
0,253	€kWh	avg price dip ('22)
0,067	€kWh	avg price peak ('19)
0,052	€kWh	avg price ('19)
0,040	€kWh	avg price dip ('19)

Table 8 - Price data calculation results

Granular calculations per appliance

With an average daily price per "price slot" (peak, average, dip) I then evaluated the savings potential of every single appliance, based on consumption data, and assumptions on usage based on statistics. For each appliance, I identified the type of load shifting: "from average to dip" or "from peak to average". For the first type I calculated the yearly savings by not devices at "random" times of the day, without DR, thus considering the average price, but in "optimised" times of the day, thus considering the "dip" price. For the second type, savings are estimated by calculating the difference in cost of using the appliances with "average" prices rather than with "peak" prices. I then estimated the savings percentage, which is dependent on the variability (CV) of the energy prices, and the type of load shifting. In the calculations, only the "shiftable" load of the appliance was taken into consideration. For some (water heating, EV car charging, dishwasher) it was assumed to be 100%, while for others (fridge, ambient heating) it was calculated on usage scenarios.

HP ambient Heating		
Results		
600	kWh	yearly consumption in "peak" prices
2022		
229,43	€	cost "NO DR"
186,70	€	cost "DR"
42,74	€	Saved
19%		% savings
2019		
40,10	€	cost "NO DR"
31,40	€	cost "DR"
8,70	€	Saved
22%		% savings

Table 9 – Ambient heating savings

Water heating		
Results		
1314	kWh	yearly consumption
2022		
408,87	€	cost "NO DR"
332,69	€	cost "DR"
76,17	€	Saved
19%		% savings
2019		
68,76	€	cost "NO DR"
52,30	€	cost "DR"
16,46	€	Saved
24%		% savings

Table 10 - Water heating savings

Dishwasher/Washing machine		
Results		
657	kWh	yearly consumption
2022		
204,43 €		cost "NO DR"
166,35 €		cost "DR"
38,09 €		Saved
19%		% savings
2019		
34,38 €		cost "NO DR"
26,15 €		cost "DR"
8,23 €		Saved
24%		% savings

Table 11 - Dishwasher/Washing machine savings

EV car charging		
Results		
1487,36	kWh	yearly consumption
2022		
462,81 €		cost "NO DR"
376,59 €		cost "DR"
86,22 €		Saved
19%		% savings
2019		
77,83 €		cost "NO DR"
59,20 €		cost "DR"
18,63 €		Saved
24%		% savings

Table 13 - Electric car savings

Fridge		
Results		
35,88	kWh	shifted away from peak
35,88	kWh	shifted from average to dip
2022		
24,88 €		cost "NO DR"
20,25 €		cost "DR"
4,64 €		Saved
19%		% savings
2019		
4,27 €		cost "NO DR"
3,31 €		cost "DR"
0,97 €		Saved
23%		% savings

Table 12 - Fridge savings

These data show that the two electricity consumptions that can benefit the most from this type of DR are electric vehicle charging and water heating. Of course, the savings, in absolute value, afforded from DR essentially depend on the total amount of energy consumed and on the amount of shiftable consumption. In this sense, it should be noted that ambient heat pump heating affords fewer savings due to the fact that the shiftable load is not 100%. Also, for these calculations, a "traditional", non-heat-pump-based water heater was taken into consideration, due to its lower prices, high installed base, and ease of retrofit with a "smart plug". Detailed information on the consumption assumptions is available directly in the attached Excel file.

To perform a more detailed estimation of the percentage reduction on the energy bill, I estimated consumption from other non-modulable appliances, summed it to the modulable component, and estimated savings. I didn't use "average household data" since the scenario I'm analysing considers a home with renewed (connected) appliances, where energy consumption are shifted from fossil sources (gas heating, petrol-powered car etc…) to electrified devices. This model of energy consumption, as mentioned before, is going to significantly grow in relevance in the next thirty years. At the same time, with a growing share of renewables, variability is likely to grow more, increasing the relevance of such a system.

The results

By using an implicit DR system with automatic activation, as the one presented before, I have estimated cost saving on the yearly energy bill of 21%, (excluding additional service charges) using 2019 price and variability data. This amounts to an absolute value saving of 61,22€. 2022 energy price data present significantly higher prices, due to a crisis scenario mainly linked to the Russian aggression on Ukraine, with natural gas prices growing tenfold. Being gas generators the marginal generation plants, the price of electricity drastically rose in parallel to gas prices, due to the marginal price mechanism. The available data from January to August of 2022 presents an average price per MWh of 311€, compared to just 52€ per MWh in 2019. In scenarios with high energy prices demand response becomes even more relevant, according to my calculations, the savings enabled by the aforementioned DR system amounted to 286€, despite a lower variability, with a daily averaged coefficient of variation of 19%, compared to 23% of 2019.

Impact on energy load

Based on these estimations, the percentage of the total load of a household which can be shifted through implicit DR is up to 85%. Considering that, as previously analysed, the total share of load from households accounts for 30% of total electricity consumptions, with a clear growth pattern, projecting this solution in a "moonshot" scenario of electrified consumptions and full adoption of implicit DR systems, with a growth of household energy consumptions share around 40%, up to 35% of the total electricity load could be dynamically shiftable based on supply, through price information.

Chapter 8: The Matter Standard

Smart home fragmentation

The current landscape of smart home devices and ecosystems is very fragmented[87]. Every different producer has developed a proprietary app with a proprietary cloud service[88] to which the appliances connect by using the home's Wi-Fi network of the user. This is true both for small devices such as motion sensors, smart plugs, connected light bulbs, and HVAC controllers, but even more for smart appliances like connected fridges[89], dishwashers[90] and washing machines[91]. Amazon[92], Apple[93] and Google[94], starting in 2014, entered in the smart-home world by trying to integrate smart devices with their devices and mainly voice assistants, for easier operation. The big tech platforms, Amazon Alexa, Apple HomeKit, and Google Home (Nest), tried to become aggregation spots for different connected devices from different manufacturers. I can say with confidence that this strategy didn't work out well. These platforms used different connections mechanism to the end device. Amazon and Google, to simplify the process and boost adoption leveraged a server-level interconnect with[95] device manufacturers' proprietary cloud systems. This mechanism has several issues related to security[96], reliability, latency and long-term support. In particular, the reliability of such cloud systems proved weak due to multiple single-points-of-failure: smart home controller to ecosystem provider cloud, ecosystem provider cloud to manufacturer's cloud, manufacturer's cloud to end device. This approach also posed another risk: manufacturers, after a certain period of support for their products, could

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87 https://interpret.la/smart-home-fragmentation-is-holding-back-industry-growth/

88 https://opensource.com/article/20/11/cloud-vs-local-home-automation

89 https://www.bosch-home.com/us/experience-bosch/home-connect

90 https://www.haier-europe.com/en_GB/connectivity/washing/

91 https://www.miele.com/en/com/application-4735.htm

92 https://en.wikipedia.org/wiki/Amazon_Alexa

93 https://en.wikipedia.org/wiki/HomeKit

94 https://en.wikipedia.org/wiki/Google_Nest_(smart_speakers)

95 https://developers.home.google.com/cloud-to-cloud; https://www.einfochips.com/blog/understanding-alexa-skills-and-its-integration-with-home-appliances/

96 https://www.wired.com/brandlab/2017/06/iot-is-coming-even-if-the-security-isnt-ready-heres-what-to-do/

decide to cut the variable costs linked with maintaining the operation of their cloud system, or charge it to the customer.

Apple's approach

Apple adopted a different approach: all connectivity to its platform, HomeKit, had to be handled in the local network[97]. Devices connect to a local hub, an Apple TV or a HomePod, that handled commands directly and enabled the possibility to create routines and automation that are executed automatically based on external parameters. This approach, while working well on a technical level, required product developers to implement this separate control system, thus increasing costs and complexity.

Project CHIP

The fact that there was a multitude of different systems IoT devices should implement was a problem in itself. For this reason, in 2019, the three big techs, joined forces[98], together with the ZigBee Alliance (now Connectivity Standards Alliance) and relevant players in the industry, to create an open standard that could make IoT devices interoperable and secure.

The Matter standard

After two years of development, in 2021,[99] the commercial name, "*Matter*"[100], was announced along with details regarding its functioning. The first aspect that should be cleared is that Matter is an application-layer standard. This means that it provides a common "language" that IoT devices can use to communicate among themselves and with ecosystems for pairing, encryption, receiving and sending of commands. It is NOT a physical or network layer standard, like Wi-Fi, Bluetooth and

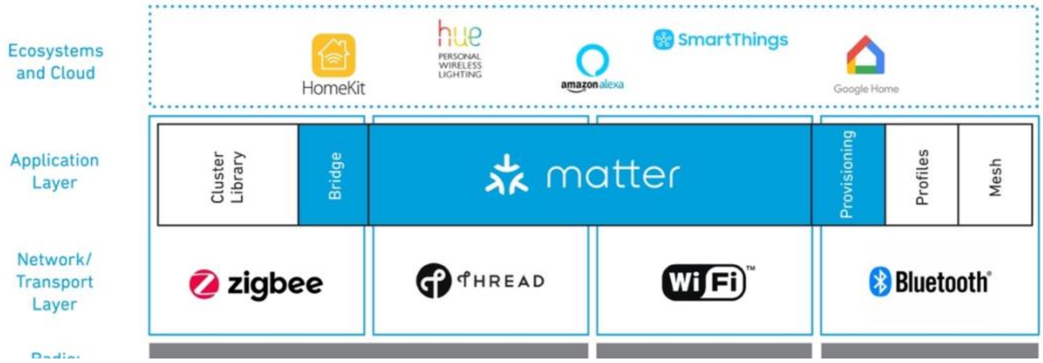

Figure 3 - Matter layer. Source:Qorvo

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97 https://developer.apple.com/documentation/homekit

98 https://www.apple.com/newsroom/2019/12/amazon-apple-google-and-the-zigbee-alliance-to-develop-connectivity-standard/

99 https://www.pocnetwork.net/technology-news/project-chip-becomes-matter-in-a-new-rebrand/

100 https://csa-iot.org/all-solutions/matter/

ZigBee; it works on top of those standards, by leveraging the IP networking protocol. Any physical-layer standard that supports IP can be Matter-compatible.

Matter works in Local Area Networks, in a similar fashion as HomeKit. One of its key strengths is the “multi admin[101]” feature, this foundational capability allows for multiple ecosystems to control a single Matter device. A Matter smart light bulb can thus be paired at the same time with Apple HomeKit, to control it via your iPhone, and with Google Home, to turn on the lights via voice command. This is also a huge opportunity for other competitors in the smart-home ecosystem landscape: a smart-tv manufacturer could enable all Matter-compatible light bulbs to connect to the TV and change their brightness according to the type of content displayed, or, an energy retailing company to provide a hub that controls energy-consuming appliances to enable demand-response.

Technical details

To pair with Matter devices, ecosystem providers should have a “Matter controller” device in the LAN, this is the “Hub” that sends the commands to the paired devices. This drastically increases security, since smart-home devices dialogue with the controller only after a “zero-trust”[102], public-key encryption process, that ensures no device can be controlled without explicit permission (pairing), and all communication remains confidential and encrypted. The standard provides a set of compatible devices and supported command types, in the first releases it only includes a small number of device types and commands, but the CSA aims to cover all device types in the smart home over time. Since the standard is first conceived as a solution for voice-assistant compatibility, the list[103] of device types and controls available in the initial release is focused on sensors, lights, and thermostats.

Why Matter for DR

Some of the key issues mentioned above on costs, incompatibility and accessibility of decives, which hinder the implementation of demand-response in households can be effectively solved with wide compatibility and inexpensive technical solutions. Other approaches have relevant shortfalls: developing proprietary, cloud-based, interfaces between the energy retailers and each and every appliance manufacturer requires a relevant effort from both parties, it might work for a transitory period, for a limited number of big appliance manufacturers and energy companies. Also, leveraging a purpose-built standard for IoT brings advantages in compatibility, multi-admin, reliability and security.

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[101] https://csa-iot.org/newsroom/matter-multi-admin/

[102] https://csa-iot.org/developer-resource/white-paper-matter-security-and-privacy-copy/

[103] https://developers.home.google.com/matter/supported-devices

DR implementation

While the standard is currently designed for automation and controls, rather than energy management or demand-response, already some scenarios can be deployed with the 1.0 release. HVAC systems with Matter smart thermostats could already work to provide implicit demand response, paired with an energy-retailer smart-home hub. Of course, this is a single category of devices considering all those envisioned in the previous session. My vision is that all the above-mentioned products (washing machines, water heaters, EV chargers…) could be included in the standard, with specific standardised controls for energy management. For example, the Matter standard for smart fridges could have a "temperature range" variable, that can be controlled by DR devices.

Future development: "steering the CSA to energy management"

While today the Matter standard is mainly meant for DR applications, I foresee a great opportunity to "steer" the standard toward energy management. A relevant number of participants inside the CSA are involved in energy management or are energy companies, namely, Voltalis[104], ConnectedResponse[105], Aclara[106], Pietro Fiorentini S.p.a.[107], Powerley[108], Lazzen[109], EDF[110], Xcel Energy[111], Tesla[112], Duke Energy[113], EDMI[114], Geo[115], LandisGyr[116], EnelX[117], Schneider Electric[118] and others are all members from the energy sector of the CSA that have their core-business in the energy sector. Several of these mentioned members, like EDF, Xcel Energy are energy companies that don't even have a smart-home lineup of products. Clearly, the interest of these stakeholders is on widening the effort of the CSA and Matter standard to comprehend energy management. The alliance

104 https://www.voltalis.com/

105 https://connectedresponse.co.uk/our-services/

106 https://www.aclara.com/

107 https://www.aclara.com/

108 https://powerley.com/

109 https://www.sh-liangxin.com/

110 https://www.edf.fr/

111 https://my.xcelenergy.com/s/state-selector?return=%2Fs%2F

112 https://www.tesla.com/

113 https://it.wikipedia.org/wiki/Duke_Energy

114 https://www.edmi-meters.com/

115 https://geotogether.com/

116 https://www.landisgyr.eu/

117 https://www.enelx.com/it/it

118 https://www.se.com/it/it/

is an open effort, that can be joined by any company, and offers different tiers of membership participation and involvement.

Participating in the CSA

Four participation tiers are provided by the CSA: Associate, Adopter, Participant and Promoter.

Associate

The base tier, which is free of charge, allows companies to rebrand already approved white-label products and obtain the licence to sell products under their brand with the Matter label and certification.

Adopter

Adopters are members that directly develop Matter products, and perform the certification process.

Participant

Participant-tier members take part in the development of the standard, by participating in working groups, and by contributing to the definition of use cases, specifications and test procedures. They have vote power and are involved in member meetings. To enter this tier only a 20.000$ yearly fee is required, for a company less than the yearly cost of a single intern. Companies in this tier have relevant power to influence the future development of the standard, with minimal financial effort, confirming the feasibility of a "steering" effort of the CSA towards energy management.

Promoter

Promoters are the alliance members in charge of leading the standardization effort. They receive a seat on the board of directors and have all the other participation and decision rights as the "Participant" tier.

Energy Management: the "Silver bullet" for IoT

IoT shortcomings

While smart-home IoT devices have been growing in the last few years, mass adoption is still far. A reason for this limitation is that "smart" functionalities are considered "nice to haves", and not essential features for a new device. Companion apps have often relatively limited functionalities, with questionable usefulness. Starting a dishwasher from an app doesn't provide any real user value by itself. Often, connectivity to smart appliances is added to gather usage data from the device, or for marketing reasons to sell the device with the "smart" buzzword printed on the box, rather than to provide meaningful value to the user. After some confrontations and interviews[119] with industry players, a key insight was the low usage of smart connectivity on "traditional" appliances. It was claimed that less than 1/3 of users who bought a smart washing machine from a renowned German brand, actually connected it to the network.

Energy management value proposition

Energy management, in particular, the demand-response efforts can instead provide a "killer use case" for IoT: automatically shifting the load to get relevant savings on the energy bill is a compelling value proposition, even more, if customers perceive the message that their load helps the environment by using more renewable electricity, potentially directly from their rooftop solar, reducing the need of deploying highly polluting peaker plants, and facilitating the deployment of more renewable production. Agreement from industry players on these considerations is strong, as expressed by company representatives I discussed with at IFA 2022[120].

Chapter 9 - Stakeholders interest map

To steer a standard body towards a new technical implemetnation, a wide consensus of industry players would be needed. With this stakeholders interest map I want to demonstrate that both the existing members, cross industry, could benefit from such a solutuon, and new ones involved in energy management could enter the CSA. The following conisderations are also informed by interviews I conducted with involved members at IFA 2022[121]. Using IoT to power demand-response provides a great opportunity for every involved stakeholder, plus it provides a comprehensive increase of efficiency to the overall energy market, helping achieve the sustainability targets.

End users

Every successful project should first and foremost focus on the value it provides to the users, its "value proposition". A customer-centric approach is nowadays the mantra of all the most successful companies and start-ups. A "smart DR" solution, as the one conceptualised in chapter 5, allows customers to have, by just signing a contract and connecting the energy-retailer-provided home-hub to their appliances, relevant savings in the energy bill. Sustainability is also becoming a key driver of customer decisions. With a properly done communication effort, energy retailers can explain the positive impact that using such a system has, which goes beyond the opportunity to get "only

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[119] Guest lecture from https://www.valantic.com/en/ at "Emerging Electronic Business" course, Uni Köln

[120] https://b2b.ifa-berlin.com/en/

[121] Ibid.

renewable electricity", as some retailers[122] already offer, but actively helps the grid to get more renewable capacity installed. For users with rooftop solar, such a solution is a no-brainer, it allows maximise their investment, reduces their dependency on the grid, and maximises sustainability.

Energy retailing companies - differentiation

Today, energy retailing companies have limited differentiation potential. Almost all contracts provide an indexed price to the PUN, with a small surcharge. Some have discounts for the first months, some have more peculiar plans, like the above-mentioned "Ore Free"[123] from Enel, but in the end, all offers are mostly similar. The differentiation potential comes from additional services sold together Sorgenia[124] for example, bundles electricity and gas together with fibre-optics broadband internet connection. While bundling can be effective for lock-in purposes, offering an integrated energy-management solution that connects to home devices, reduces costs, and boosts sustainability can be seen as a significantly more relevant differentiation element. Also, providing a connected home hub opens the door to a wide array of smart-home services that can provide value to the user and monetization opportunities.

Savings-sharing

But this is not all, by shifting their customer's load to hours when prices are lower, retailers will, in turn, purchase electricity when it's cheaper. Retailers don't necessarily need to transfer all the savings to the end user since a limited saving incentive is sufficient to deploy such a solution. Retailers, for example, could set fixed-priced dynamic slots, that enter in validity depending on the wholesale market price. For example, three price slots: Cheap (0,20€/kWh), Medium (0,35€/kWh) and Expensive (0,55€/kWh) alternate during the day. The "medium" price tier would be the standard fee when wholesale prices are in a range around the mean. (eg: 20-45€/kWh). The two other tiers only activate in those hours when the price goes below a certain threshold. The "cheap" one, in particular, only activates when wholesale prices are equal to or below 0,20€/kWh, to allow energy companies to increase their savings, the higher the lower the prices are. On the other side, the "cap" of 0,55€/kWh would give more peace of mind to customers. This solution would seem like a zero-sum game: what the energy company gains with the "low" fee, is needed to compensate for the losses linked to the "high" fee; but it isn't. Since demand is actively being shifted towards the cheapest hours, and away

[122] https://www.iberdrola.it/

[123] https://www.enel.it/it/luce-e-gas/luce/offerte/ore-free

[124] https://www.sorgenia.it/

from the most expensive ones, losses are minimised and gains are maximised. This is just an elaborate commercial offer to perform "savings sharing" with the end user, while at the same time simplifying the proposition and providing a price-cap mechanism. It simply leverages the fact that customers are more sensitive to high prices than high discounts. A 12% reduction in costs from the "medium" to the "low" price slot is sufficient to justify the (automatic) load shifting, and increasing it to 20% (hypothesized as the maximum saving) does not provide a significant additional incentive to end-users. At the same time, customers appreciate having a "risk reduction" mechanism, in this case, implemented by a price cap.

Explicit Demand-Response

While all the construction of this solution has been concentrated on implicit DR, when adopted at scale it could also provide opportunities for explicit DR. An energy retailing company with a relevant amount of connected appliances for (implicit) DR could also participate in the transport-operator Explicit DR bids. Of course, the modulable capacity offered should be a fraction of those allowed by implicit DR, since end users should always have the possibility to manually turn on their appliances. At the same time, for the law of large numbers, it's extremely unlikely, if not impossible, that all users switch off their DR systems at the same time, during an explicit DR event. What could be done without the user even noticing is to use the same hardware/software infrastructure to respond to explicit DR events, by reducing consumption in key moments: increasing fridge temperature range, shifting the planned activation of the dishwasher/washing machine, delaying EV charging schedule, rising/lowering HVAC temperature.

Appliances and IoT devices manufacturers

Key stakeholders in this equation are IoT device manufacturers. As mentioned before, implementing energy management could meaningfully boost interest in smart-home solutions, shift demand towards connected products and even boost appliance sales in absolute value, by giving users a reason to upgrade, and, crucially, increase the share of users who actually connect their appliances to the network, to offer them additional services and retrieve analytics data.

Governments: an enabler for a higher share of renewable without costly storage

Governments around the world are interested in finding ways to accelerate and facilitate the decarbonization of electricity. A problem often faced is the replacement of easily modulable fossil generation with non-programmable renewables, ensuring energy grid stability and reducing end users' energy bills. An implicit demand response system deployed at scale could alleviate all of these problems at the same time, without any significant additional cost, considering that the "connected appliance" trend is already ongoing, and no specific new hardware other than an already present networking module (Wi-Fi[125] or Thread[126]) would be needed.

Energy producers: favouring investments in renewables

To tackle the "duck curve" issue, which inhibits the installation of new renewables (Solar PV in particular) an inexpensive solution to shift demand would be game-changing. Today, with a high share of renewables, supply exceeds the demand in the hours of maximum PV production, pushing energy prices close to zero, and thus zeroing the remuneration of potential new installed solar PV capacity. By shifting up to 35% of the total electricity load from "peak" hours to "off-peak" hours, it allows for the installation of more non-programmable sources that can be used dynamically.

Conclusions

Variability in daily energy prices can be both a threat and an opportunity. Renewable energy generation will significantly grow in the upcoming years, due to economic convenience and decarbonization targets. With it will come a relevant increase in variability, that has the potential to spark the development of game-changing energy technologies. Implicit demand response for households is at the same time the simplest one to imagine, but probably the hardest to implement. In this thesis, I tried to provide a way to facilitate this implementation, while analyzing and calculating the savings potential and indicating additional opportunities for the actors involved. The idea is to set a path that can benefit an "ecosystem" of actors involved in different markets, from IoT to appliances to energy retailers, by agreeing on a common technical standard. Time will tell if this solution actually succeeds, but, based on this analysis, the stakes are pretty high.

[125] https://www.wi-fi.org/

[126] https://www.threadgroup.org/

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