Incentivising and Activating Multi-Purpose Flexibility for the Future Power System

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ABSTRACT

The green transition and the electrification that comes along with it, call for huge investments in infrastructure. Traditional energy systems are operated and planned such that the production follows the demand. Similarly, investment needs in e.g., distribution grids, are typically planned according to the future electricity demand, the number of electric vehicles, and the renewable capacity connected to the distribution grid. However, in the era of high penetration of intermittent renewable energy supply, the focus has to shift towards demand-side flexibility. A pivotal development refers to harnessing and integrating the available flexibility of virtually all types of end-users on all aggregation levels, including from other sectors (cf. the energy-water nexus). Such unprecedented levels of complexity call for massive digitalization of energy systems using data-sharing principles, AI, big data analytics, data-driven digital twins, cloud-fog-edge computing, systems-of-systems, IoT, resilience and user-involvement using apps and Smart Energy Management systems. This paper outlines the large economical benefits of demand-side flexibility both with respect to direct savings related to infrastructure investment and indirect savings for the consumers through cheaper electricity prices and lower grid costs. It is argued that one of the main barriers for the green transition and for achieving these benefits is the existing regulatory framework and most importantly the existing tariffs and energy taxes. Another challenge is the conventional market design which is a barrier for activating flexibility both locally at DSO-levels and in multi-energy carrier settings. The paper will outline principles for proper tariffs and energy taxes as well as new disruptive methodologies needed for integrating flexible assets into energy markets. It will be argued that for a bulk part of the flexible assets, we need to use dynamic pricing, and the actual price should be linked to the real operational challenges and costs of e.g., the distribution grids. A key element is the so-called flexibility function for describing the flexibility of the assets. The methodologies are embedded into the Smart-Energy Operating System (OS), which is a hierarchical framework for coherent digitalization of energy systems consisting of aggregation, forecasting, control and optimization. The framework represents new solutions for activating local flexibility. The framework can seamlessly accommodate different behind-the-meter resources (e.g., electric vehicles, heat pumps, etc.), as the distributed flexibility is activated indirectly simply by broadcasting a dynamically changing price signal, overarching the nature of the distributed resources. This ensures simplicity and transparency while keeping the users in control. The intention is not to replace existing methods for direct activation, but to enrich them through indirect, efficient, and scalable activation of distributed flexibility.

KEYWORDS: Dynamic tariffs, Energy taxes, Demand-side flexibility, Flexibility functions, Smart-energy OS, Digitalization of energy grids

1. INTRODUCTION

In Denmark, the Climate Act of 2020 has set an ambitious medium-term goal, that is a 70% reduction in 2030, relative to 1990. EU's 'Fit for 55' [1] establishes the target of reducing net green house gas (GHG) emissions for all 27 member states by at least 55% by 2030 compared to the 1990 levels. To reach this, electrification will play a key role, accompanied by a continued increase in the share of renewable generation in the electricity mix, aiming at reaching at least 75% renewable installed capacity by 2030 in the EU. Renewable generation will be installed at all levels, from roof-top PV to large off-shore wind farms. As a result of the energy systems' decarbonisation, the systems will shift away from the traditional centralized and top-down operational approach towards weather-driven, decentralized operation.

Classical energy systems planning models use a static, predicted energy demand profile as input. As an important example, the energy systems planning study by Eurelectric [2] concluded that the future investment needs in distribution grids are mostly driven by the final electricity demand, the number of electric vehicles, and the renewable capacity connected to the distribution grid. However, this assessment of the investment needs does not adequately take into account the benefits of demand-side flexibility which can be activated by digital technologies.

For optimally planning the future weather-driven energy system, the renewable energy production characteristics must be considered as the essential input and the final load profile will emerge as a result of various factors e.g. local production, selfconsumption, and demand response capabilities. As a step towards the next generation of energy systems optimization and planning [3] has suggested a new framework, named Frigg, for linking the energy system and consumer's demand response models. In [4] an intensive study of Renewable Energy Communities and their potential impact on the electric distribution grid has been carried out. The results showed that when a battery is located at the beginning of the feeder, then the energy community does not impact the observed minimum and maximum voltage. Moreover, it was found that depending on the energy community's operating strategy the low-voltage grid loading can be reduced by up to 58%.

Also sector coupling at all levels of the energy system, and technologies like PtX, are very important for being able to unlock the needed flexibility and support the future weather-driven energy system in its need for energy storage solutions. Projects focusing on individual aspects of the energy system, such as zero emissions buildings or power systems provide valuable insight, but overlook the efficiency, cost and emissions savings possible with an integrated approach that facilitates flexibility throughout the energy system e.g., by sector coupling and PtX technologies [5].

In an efficient implementation of the weather-driven energy system, demand response solutions must play an essential role [6]. This, however, calls for a focus on digitalization of the energy systems, and intensive use of data-driven technologies such as AI, digital twins, and IoT. Demand-Side Flexibility (DSF), and the ability of the customers to change their consumption intelligently in space and time based on external signals, is a crucial prerequisite for an efficient and fast transition towards a carbon-neutral society.

Examples from simulation and sandbox pilot studies show that savings by activating demand-side flexibility are typically from 10% to 50%; see e.g., [7], [8], and [9]. National projects like Center for IT-Intelligent Energy Systems (CITIES) [10], and the Flexible Energy Denmark (FED) project [11] as well as international projects like SmartNet [12] and ebalanceplus [13] have demonstrated savings in a number of pilot studies. These projects have demonstrated different digital solutions for activating flexibility in living labs.

The power price spikes in 2022 have shown flexibility in consumption at the end-users at scale, with many consumers scheduling e.g., the charging of their electric vehicles (EVs) and washing of their clothes such that they benefit from low electricity prices. This has induced a shaping of the system's demand such that consumption is reduced at times of low renewable energy output. Still, the constant energy tax, seen in many countries e.g. Denmark, reduces the incentive for flexibility. To avoid this, it is purposeful to consider replacing fixed billing structures (including e.g. taxes) to dynamically calculated ones.

Moreover, while dynamic energy prices are beneficial for the system's efficient balancing operations, flexible consumption has not been extensively utilized to curate local, distribution network problems. While distribution system operators have tried to harvest the energy flexibility with time-of-use tariffs, these are only loosely connected to the problems they experience. This will remain the case until electricity prices become time- and location-dependent, reflecting the actual needs of the local grid. Thereby, the end users need to be provided with dynamic pricing signals that reflect both the local distribution grid's problems, as well as the balancing needs of the macroscopic power system.

Thanks to the wide deployment of smart meters in recent years, proper and more granular demand-side pricing is realistic but calls for intensive data-driven methodologies, a disruptive thinking related to local flexibility markets, as well as interoperable mechanisms, as outlined in this chapter. Digitalization and new data-driven methods create new opportunities which will allow also small consumers to provide flexibility and, consequently, all consumers can benefit from lower operational and energy balancing costs. In addition, digitalization has the potential to increase transparency and predictability which again can lead to a positive effect related to trust and fairness. The status and challenges on digitalization of the distribution grids in Denmark is outlined in [14].

Empowering end-users towards uptaking an active role in the energy systems' decarbonization is a pivotal development. We need urgently, both due to climate crises and the geopolitical situation, to empower the end-users to play an active part in decarbonising the energy system. However, the activation of end-user flexibility still faces a sequence of regulatory barriers as well as a few technical challenges. As a result, the potential of demand-side flexibility is frequently an overlooked solution in policy decisions as the key for accelerating a cost-efficient low-carbon transition.

New technologies allow consumers to change consumption, self-produce, and provide self-storage options, which the current tariff is not suited to cope with [15]. In addition, the current regulatory framework contains rules and barriers which hinder flexibility and the green transition [16]. A few of the low-hanging fruits along with the essential barriers will be mentioned in this paper, but the most critical barrier is the existing tax and tariff structures.

As mentioned, demand-side flexibility becomes essential and, regarding the tariffs, we will suggest how to define distribution tariffs in harmony with the physics and the power system markets. Secondly, the paper will prescribe a framework for establishing interoperability between the markets and the components' physics including their aggregated dynamics. Finally, we will briefly touch upon the need for changes of the taxes related to the energy system.

2. BENEFITS OF DEMAND-SIDE FLEXIBILITY

In a study conducted by DNV [6], the benefits of demandside flexibility are outlined. The input data and assumptions in the study are focused on the 'Fit for 55' objectives [1] and REPowerEU Communication [17]. The study considers only the low- and medium-voltage grids, and hence the study did not take into account the positive energy efficiency impact of DSF activations, nor potential savings from TSO redispatch costs and TSO grid reinforcement costs.

The benefits of DSF are assessed in the savings in the different segments, i.e., wholesale, generation adequacy, system balancing, and grid infrastructure. Altogether, this translates to benefits for the consumers. Today, prices and tariffs typically come in time blocks (often hourly). For tariffs, this is also known as the Time-of-Use (ToU) tariffs. The recent levels and variations of the ToU tariffs are often discussed and criticized. An example is that the abrupt variations of the existing ToU tariffs cause unwanted variations of the grid load. Moreover, location-agnostic ToU prices can cause a simultaneous shifting of loads into low-price times creating significant operational dangers for the distribution systems to which such loads are connected.

According to [6], 'demand-side flexibility' means the capability of any active customer to react to external signals and adjust their energy generation and consumption in a dynamic time-dependent way, individually as well as through aggregation, and it is assumed that they react to a dynamic price-signal. Thanks to the smart meter deployment in recent years, proper and more granular demand-side pricing is realistic but calls for intensive data-driven methodologies and digitalization as outlined in this paper. It is important to underline that the whole benefits of dynamic pricing can be harnessed only when the end-users are equipped with digital controllers, able to react to price changes quickly and without manual intervention.

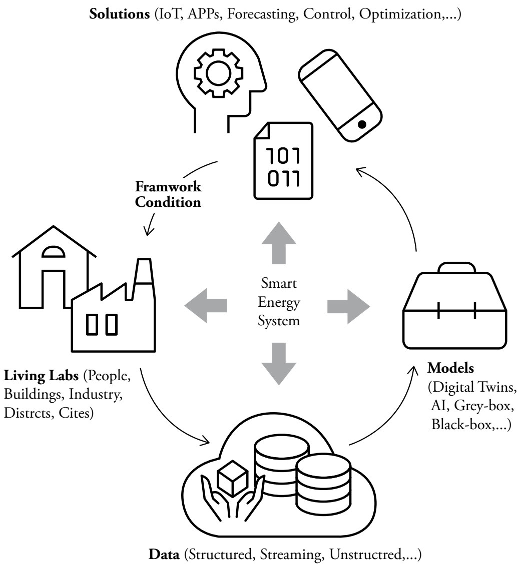

FIGURE 1: PRINCIPLES FOR DEVELOPING AND TESTING SMART ENERGY SOLUTIONS.

Regarding the distribution grid, the study on the benefits of DSF in [6] estimates that 11.1-29.1 billion EUR would be saved annually in investment needs in the 27 EU countries annually between 2023 and 2030. This represents between 27% and 80% of today's forecasted investment needs for low and medium voltage distribution grids.

Moreover, regarding the security of supply and balancing, the results show that efficient activation of demand-side flexibility in European balancing markets in 2030 could save between 43% and 66% of the balancing costs. The analysis also suggests that the energy system in EU in 2030 would lack at least 60 GW of generation capacity to ensure security of supply during highest demand peaks. Enabling 60 GW of DSF would save 2.7 billion EUR annually compared to installing the same amount of peak generation capacity. This would directly benefit consumers with flexible assets, as well as indirectly benefit all customers through cheaper electricity prices due to lower generation costs.

Finally, today the curtailment of wind and solar power is considerable. While 2-3% of RES curtailments is deemed acceptable, today's rather high curtailment levels is an indication of system inefficiency. It is estimated that with demand-side flexibility the renewable energy curtailment would be 61% less (15.5 TWh annually), which will improve the economics of wind and solar energy and increase the availability of decarbonized electricity to consumers.

In the FED and CITIES projects, solutions for activating flexibility have been developed, and tested in a large number of Living Labs. The solutions have demonstrated large costs and CO_2 emission savings, but due to the current regulatory setting, most of the solutions were only running in shorter periods for a verification of the potentials. The principles for development of the smart energy solutions are sketched in Figure 1.

Before a full scale implementation it would be possible to test the digital, data-driven and smart energy solutions in collaboration with e.g., Center Denmark[1], in sandbox or test zones jointly with a next generation of proposals for the regulatory framework as indicated in Figure 1.

3. FLEXIBILITY FUNCTION

For price-responsive customers, prices can be used to control the load as first suggested in [18]. Methods for using experimental data for estimating the energy flexibility of households with a price-responsive load were suggested at least as early as 2009, as part of the FlexPower project [19]. It is shown by [20] how the variations in penalties can be used to shift the load from peak hours to off-peak hours. The authors in [21], [22] went a step further and described how also the frequency and voltage in power grids can be controlled by this method.

However, a model for forecasting how clusters of consumers in e.g., a DSO area will react to a particular sequence of prices is needed. [23] introduced the so-called *Flexibility Function*, which is simply a model which can be used to forecast the response (e.g., the load) as a function of a sequence of incentivizing signals (typically the prices); see Figure 2.

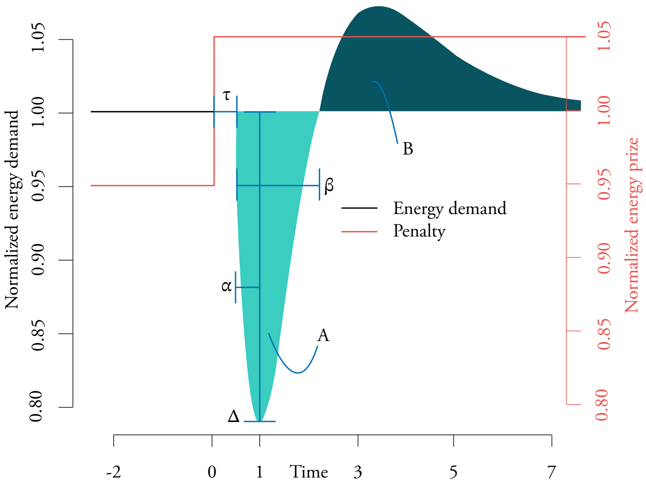

FIGURE 2: FLEXIBILITY FUNCTION (FF). THE FF DESCRIBES THE RESPONSE AFTER A STEPCHANGE IN PRICE.

The flexibility function could be implemented using any type of dynamical model, and it is suggested as one of the fundamental MIMs (Minimum Interoperability Mechanisms) for energy systems [24].

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[1] Center Denmark is a EDIH - European Digital Innovation Hub for Smart Energy Systems. See also https://www.centerdenmark.com

The Flexibility Function shown in Figure 2 is adequate for linear and time-invariant systems. For nonlinear systems, it is shown in [25] that a grey-box model using a set of non-linear stochastic differential equations might be more appropriate. The approach essentially models the flexibility using a battery-like model including a state-variable representing state-of charge. In general, the flexibility function should be considered simply as the link between price and demand.

4. THE REAL COSTS OF DISTRIBUTION GRIDS AND PRINCIPLES FOR PROPER GRID TARIFFS

Here we will focus on distribution grids, but many of the same principles hold also for transmission grids.

There are two overall costs associated with distribution grids:

1. Power losses in transformers and cables due to resistances in the power conducting equipment (energy, i.e., kWh related).
2. Need for investments in the power grid either due to maintenance or needs for expanding capacity (power, i.e., kW related).

Energy losses are easily understood since they are purely physical, and have a well-defined price in the power markets. If, in a particular hour, in a particular part of a distribution grid, there is a loss of 10 kWh, then, the corresponding DSO has to cover this loss by purchasing 10 kWh of energy at whatever the price of the hour in question. Thus, the part of the DSO tariff of this particular hour for this particular part of the DSO grid should be closely linked, if not directly given, by the 10 kWh times the energy price.

Allocating investment costs is not as easily quantified, since the need for expanding the capacity can not be tied directly to the power consumption of particular consumers at a particular point in time. Still, only demand during times when the grid is (close to) having congestion problems is directly contributing to the need for expanding it. Therefore, the need for expanding the grid is decreased by reducing the power consumption (kW) during these times. Using dynamic tariffs that reflect the actual power congestion challenges implies that consumers representing the congestion-inducing consumption are also the ones responsible for the need for grid reinforcements. Such an investment cost mechanism has a built-in fairness of allocating the costs for grid expansions. Consequently, a high power (kW) consumption should dynamically lead to higher local tariffs.

Another typical issue for distribution grids is to ensure that the voltage level is within reasonable limits along the feeder for all local grid areas. If no problems exist, then the voltage related component of the tariffs should ideally be zero. In the case of voltage issues, demand-side flexibility can be activated to control the load. Obviously this also calls for dynamic tariffs. Some details on principles for generating dynamic prices and tariffs will be proposed in Section 7.

The philosophy behind the proposed principles is simply that the dynamic tariffs should reflect the system's needs in such a way that users that cause issues (e.g. congestion) are facing high prices and hence incentivized to contribute to the resolution (e.g. by shifting EV charging), while users that contribute to alleviating or serving the system are rewarded. This naturally incentivizes micro-investments in digital technologies that automate DSF (by creating an attractive return-on-investment) and serve the system.

The suggested procedure might lead to higher dynamic tariffs e.g., in areas with a large number of EVs demanding fast charging. This is most likely areas with people with a high income. In areas with a low electricity consumption there might not be the same need for high tariffs.

Most of the methods outlined in the following for distribution grids will be also apply for transmission grids. Tariffs should reflect the physics, and hence power generated and used within the same distribution grid should not be exposed to transmission tariffs. Such principles should also be implemented e.g. for gas grids. Today biogas is penalized with transmission tariffs even though a minor part of the biogas reaches the transmission system. Both for power and biogas it is important to implement a level of tariffs such that it is incentivized to used produced green energy locally, and not penalised by tariffs for infrastructure that is not used.

5. LOOK-AHEAD INCENTIVES

Energy consumption is a dynamic phenomenon, since a change in consumption at a given time will impact the consumption in the near future as well. Moreover, consumers will need to know tariffs *before* they, or their controllers, decide on their consumption. Thus, rather than solely reacting to the current situation, the DSO tariffs should look ahead, to make tariffs that give the best overall incentives, and with a lead time that is enough for consumers to react. Of course, consumers react to the total prices, e.g. the power prices including taxes and tariffs, and thus, given the energy price, C_t, and tax, T_t, the DSO tariffs should be found by solving for them in the following equation:

$$\mathrm{FF}(C_t + T_t + L(P_t) + E(P_t)) = P_t,$$

where L is the loss tariff and E is the expansion tariff. This equation expresses how the total power price for a given area consists of the energy cost, the tax, the loss tariff and the expansion tariff. Since the tariffs are functions of demand, and the demand a function of the tariffs, this equation needs to be solved, so that the tariffs calculated from the demand P_t, gives an expected consumption of exactly P_t, a fix-point of the flexibility function, FF, which was introduced previously in Section 3.

6. HIERARCHICAL CONTROL FOR SOLVING GRID AND BALANCING PROBLEMS

This section describes how sequential dynamic optimization implemented as controllers in a multi-level or hierarchical control setup, can be used to solve both grid and balancing problems. In order to illustrate how this can be used to activate flexibility also in the residential sector, we will use buildings as an example. Briefly speaking we will describe how the physics (dynamical formulations) of the buildings and grids can be linked to the conventional electricity markets which is characterized by bidding and clearing (static formulations). Subsequently, we shall briefly outline how these principles can be generalised to multi-level and hierarchical control problems.

6.1. CONTROL DESIGN FOR ACTIVATING FLEXIBILITY

In this section, it will be explained how to control the demand of smart buildings by generating prices such that the building reacts and adapts its consumption accordingly. The basic concept is illustrated by Fig. 3, where a smart building, from an external perspective, takes an input (price) and gives an output (demand). Data-driven techniques are used to estimate the Flexibility Function, which then can be used for predicting demand as a dynamic function of price.

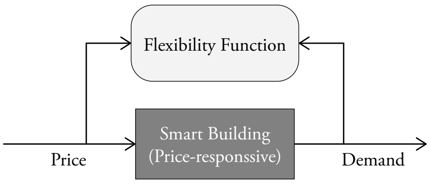


FIGURE 3: THE DEMAND OF A SMART BUILDING CAN BE PREDICTED AS A FUNCTION OF PRICES.

Given a Flexibility Function for the building, a second controller can be formulated where the objective is to control the building's demand according to some criteria, and the decision variable is the price (say, electricity price as a function of time). As shown in Figure 4, the Flexibility Function can be used to generate prices according to some references. The reference could be a desired energy consumption in time. Notice how the demand acts as the feedback to the controller, closing the loop.

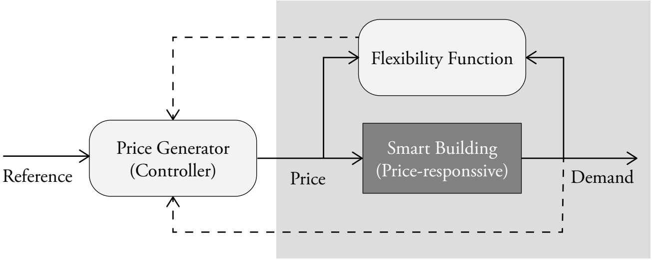


FIGURE 4: USING A FLEXIBILITY FUNCTION TO GENERATE PRICE SIGNALS AND DEMAND AS CONTROL FEEDBACK.

Let FF be the Flexibility Function that takes energy prices as input and gives the building's expected demand as output, while r_l is a reference load profile. Then, a simple upper-level controller (the price generator in Fig 4) can be defined as the following optimization problem

$$\min_{C_u} (\mathrm{FF}(C_u) - r_l)^2, \tag{1}$$

where C_u is the future energy prices. An example of such a controller is the minimum variance controller [26]. Obviously, it might be necessary to impose limits on how much the price can change or requirements on the average value, and a more sophisticated optimization problem than the minimum variance formulation can be formulated, as discussed in [27].

Combining the optimization problem in (1) with a lower level optimization problem of the building's heating system or it's Energy Management System, the Flexibility Function couples the two levels in an elegant fashion:

$$\begin{array}{ll}
\min\limits_{C_u} (\mathrm{FF}(C_u) - r_l)^2, & \text{Upper level} \\
\hline
\min\limits_{u_k} \sum\limits_{k} C_u^{\mathsf{T}} u_k & \text{Lower level} \\
\quad r.t.\ \mathrm{d}x = f(x, u, d, t)\mathrm{d}t + g(x, u, d, t)\mathrm{d}w, & \\
\qquad \Pr(x_{\min} \leq x \leq x_{\max}) \geq 1 - \alpha &
\end{array} \tag{2}$$

where, in this case, the lower optimization problem is formulated as an economic MPC problem [28].

A main reason why the Flexibility Function is considered to be one of the fundamental MIMs (Minimum Interoperability Mechanisms) for energy systems is that the FF is instrumental for interoperability between the building level and the upper level representing the grids and aggregators.

Notice how the two optimization problems are solved independently from each other, thus preserving autonomy and privacy for the building owners while simultaneously allowing a stakeholder (e.g. supplier, aggregator, or balance responsible party) to utilize the energy flexibility. In practice, there are going to be a lot of smart buildings for each aggregator that all have independent control problems and preferences. The development of building energy management systems and smart buildings is left open to competition among commercial stakeholders, while the flexibility function remains agnostic to specific types and technologies of controllers. Finally, this method scales well to this case since the computational burden for the upper-level remains constant — with the Flexibility Function simply representing the expected aggregated response from the relevant cluster of smart buildings [27]. Moreover, on-line identification and adaptive methods can help simplify offering the flexibility services without the need to conduct a study for each resource separately.

7. MULTI-PURPOSE CONTROL

In the previous sections the upper-level controller has taken the load reference as input and then generated a sequence of prices that, given the known flexibility dynamics as represented by the Flexibility Function, will provide the wanted demand. This setting is appropriate if we want to establish demand-side load management, which could be useful for peak-shaving or for maximizing self-consumption e.g., in the case of local PV production.

The sketched methodology is, however, easy to generalize to other situations. Let us for instance consider the problem of voltage control with a reference voltage $r_{voltage}$. Then, the voltage controller can be defined as the upper-level controller

$$\min_{C_u} (\mathrm{FF}_{voltage}(C_u) - r_{voltage})^2, \quad (3)$$

where the $\mathrm{FF}_{voltage}$ is a flexibility function describing the dynamical relations between prices and voltage for the considered low-voltage distribution area.

Power transformers are one of the most costly assets in power grids. Due to increasing electricity demand and levels of distributed generation, they are more and more often loaded above their rated limits. Transformer ratings are traditionally set in a controlled environment with conservative margins. In [29] it is demonstrated how to set up a digital twin model for transformers which can be used for *Dynamic Transformer Ratings*, such that the transformers dynamically can be overloaded up to 60% without any risks for damages. In combination with hierarchical controllers as outlined here, the setting can be used to postpone costly investments and ensure safe operations of the transformers.

Until now the purpose of the low-level controller has been to minimize the operational cost, but also the low-level controller can be changed. If, for instance, the real-time CO_2 emission linked to the electricity consumption is used as the penalty signal, then the controller will minimize the carbon footprint of the system. This example of low-level controllers are used e.g., in [30], [31] for controlling the temperatures in summerhouses with a swimming pool such that the carbon footprint is minimized.

As explained in [30] and shown in Figure 5, by changing the cost function, the low-level controllers can be used for

1. cost minimization,
2. carbon footprint minization, or
3. energy efficiency optimization.

A goal of a modern regulatory framework would be to incentivize electricity consumption at periods with low carbon electricity production; it would be advantageous to ensure that the dynamic prices are designed such that the costs are low when the emission is low. Unfortunately, this is not the case today. An example is, as also explained in [7], that wastewater treatment plants could save up to 50% on their emissions, but the current regulatory settings prevents this. Here a main problem is that taxes are not properly linked to the emission.

8. CONTROLLERS AND MARKETS

Ultimately the purpose of the future smart energy system is to establish a connection between the controllers operating at local scales, and high level markets operating at large scales. This includes coupling sectors and establishing dynamic markets to reflect an increasingly dynamic supply and demand of energy. Essentially a spectrum of all relevant spatial aggregation levels (building, district, city, region, country, etc.) has to be considered. At the same time, the established markets and controllers must ensure that all power systems (on all temporal and spatial scales) are balanced. Consequently, data-intelligent solutions for operating flexible electrical energy systems have to be implemented on all spatial and temporal scales.

To address these increasingly important issues, several solutions have been proposed in recent years. Some significant solutions are Transactive Energy, Peer-to-Peer, and Control-Based solutions, as described in [32], and [33], while computational issues also need to be addressed by leveraging the whole spectrum of computational resources (namely, edge-fog-cloud) [34].

Traditionally, power systems are operated by sending bids to a market. However, in order to balance the systems on all relevant horizons, several temporal-specific markets are needed.

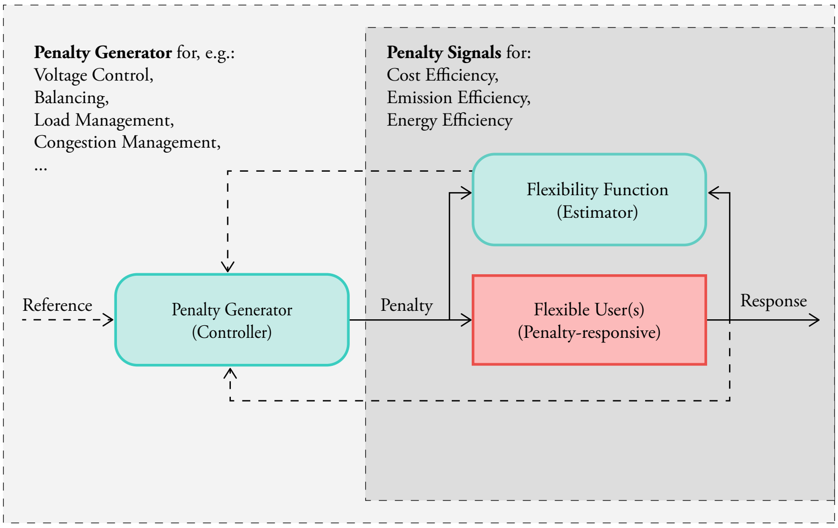


FIGURE 5: HIERARCHICAL CONTROL FOR UTILISING FLEXIBILITY

Examples are day-ahead, intra-day, balancing and regulation markets. The bids are typically static and consisting of a volume and duration. Given all the bids, the so-called supply and demand curve for all the operated horizons can be found. Mathematically, these supply and demand curves are static and deterministic. *Merit order dispatch* is then used to optimise the cost of generation. However, if the production is from wind or solar power, then the supply curve must be stochastic, and the demand flexibility has to be described dynamically - e.g. by the introduced Flexibility Function. Consequently, it is believed that it is necessary to introduce new digitised markets, which are *dynamic and stochastic*. Also instead of using a large number of markets for different purposes (frequency, voltage, congestion, etc.) and on different horizons, we will suggest to use concepts based on the Flexibility Function and stochastic control theory; exactly as described in the previous section for the two-level case. We call this the Smart-Energy Operating-System (Smart Energy OS) [22], [31], [24].

If we zoom out in space and time, i.e. consider the load in a very large area on a horizon of days, or maybe next day, then both the dynamics and stochasticity starts to matter less (and might be eliminated), and hence we can use conventional market principles as illustrated in Figure 6. If we zoom in on higher temporal and spatial resolutions (like for instance a house), the dynamics and stochasticity become important, and consequently we will suggest to use the control-based methods for the flexibility as discussed previously. This implies that in real-time the link is handled simply by a one-way communication or broadcasting of a price-signal, and the consumer can simply self-dispatch according to prices, without any further complications e.g., having to submit bids.

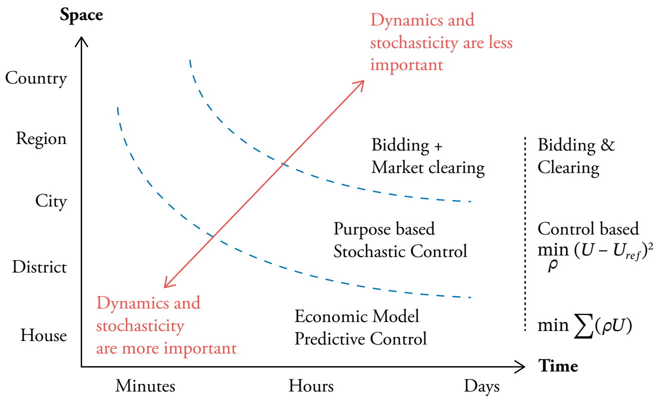


FIGURE 6: HIERARCHICAL CONTROL AND MARKETS.

The simplicity of broadcasting price signals for activating demand-response needed e.g., for a distribution system operator,implies that basically all appliances can contribute to unlocking the needed flexibility at the relevant spatial and temporal coordinates. At the same time the end-user can easily set up local preferences in their Home Energy Management Systems (HEMS) in a weighted combination of a focus on e.g., comfort, costs, emission and energy efficiency [35]. A comprehensive model, integrating these concepts into a TSO-DSO coordination framework is presented in [36].

Basically, the setup distributes the computational effort across many levels of the hierarchy. Similarly, the Home Management Information Systems (HMIS) can be used to provide information about the aggregated flexibility which can be offered from a particular building, and for energy communities similar aggregation principles apply.

The simple setup with a simple broadcast of a price-signal provides directly a possibility for sector coupling and multienergy supply systems, where e.g., air-to-air heatpumps can be used jointly with natural gas heating systems; maybe as a stepping stone away from natural gas. The Home Energy Management System (HEMS) can simply change from natural gas to electricity when the electricity prices are low. This system would accelerate the green transition and offer extra flexibility which will reduce the number of times e.g., wind turbines are stopped by grid operators.

9. MARKET DESIGN CHALLENGES

9.1. MARKET DESIGN FOR ACTIVATING LOCAL FLEXIBILITY

Several projects and initiatives have studied the possibility of controlling e.g., the load in a distribution grid by setting up a local DSO market [12], [37]. However, it has been concluded that conventional market mechanisms are not suitable here [31]. First of all, the number of potential bidders and the market size is very limited. Moreover, even for larger flexible assets, energy flexibility is only of secondary concern. As an example we can consider the conclusion from a series of workshops for wastewater treatment plants organized by Energinet and Center Denmark. Wastewater treatment can be highly flexible, but the primary concern for the operator of wastewater treatment plants is to avoid overflow in the city, the second priority is to keep the flow at the plant below some given values to ensure that the active part of the sludge stays on the plant, while saving money due to energy flexibility is at best a third priority. Given even a small probability of a severe rain event, wastewater plants will not bid into the markets.

The workshops with wastewater treatment plants operators concluded that the price-volume bidding strategy would be difficult or impossible to use for the plant operators. Instead the suggestion was to introduce a specialized aggregator which trades on the electricity markets and then broadcasts a dynamic price signal to the wastewater plants. However, from the wastewater treatment plant's perspective, it does not matter where this dynamic price signal comes from. The up to 50% savings due to flexible operation reported in [7] can be shared between the aggregator and the wastewater treatment plant.

9.2. WHERE DOES THE MARKETS STOP AND THE PHYSICS BEGIN?

Another barrier is the fact that the conventional market design with merit order bidding and subsequently clearing represents a *static problem* but the local flexibility represents a *dynamic problem*, and hence the bidding formats of traditional market mechanisms do not offer enough expressive richness to capture the temporally coupled characteristics of the new market players [38].

Let us for instance consider a supermarket. Here the cooling represents a flexible asset. The problem is however, that if a supermarket has lowered the electricity consumption for the cooling during a given hour, then it might not be possible to offer a similar flexibility for the subsequent hour due to considerations to keeping the goods within the typical temperature ranges (typically below 5-6 degrees Celsius).

Another challenge related to the conventional market structure is that if a given flexibility is bid into a specific market and hence only available for solving the market specific problem, then this flexibility is out of the game for solving other and maybe more critical grid ancillary service problems. In the Smart Energy OS framework the flexibility will be available for solving all grid and balancing service problems. In addition market bidding includes a volume, a price and a time period, but most systems can deliver a lot of power flexibility (kW) in a short period, or less flexibility in a long period [39]. If the price is high enough all consumers will be flexible, and essentially the causality is from price to load flexibility. Finally, the stochasticity implies that a probabilistic assessment of the flexibility are needed in order to provide proper calculations related to resilience and risks.

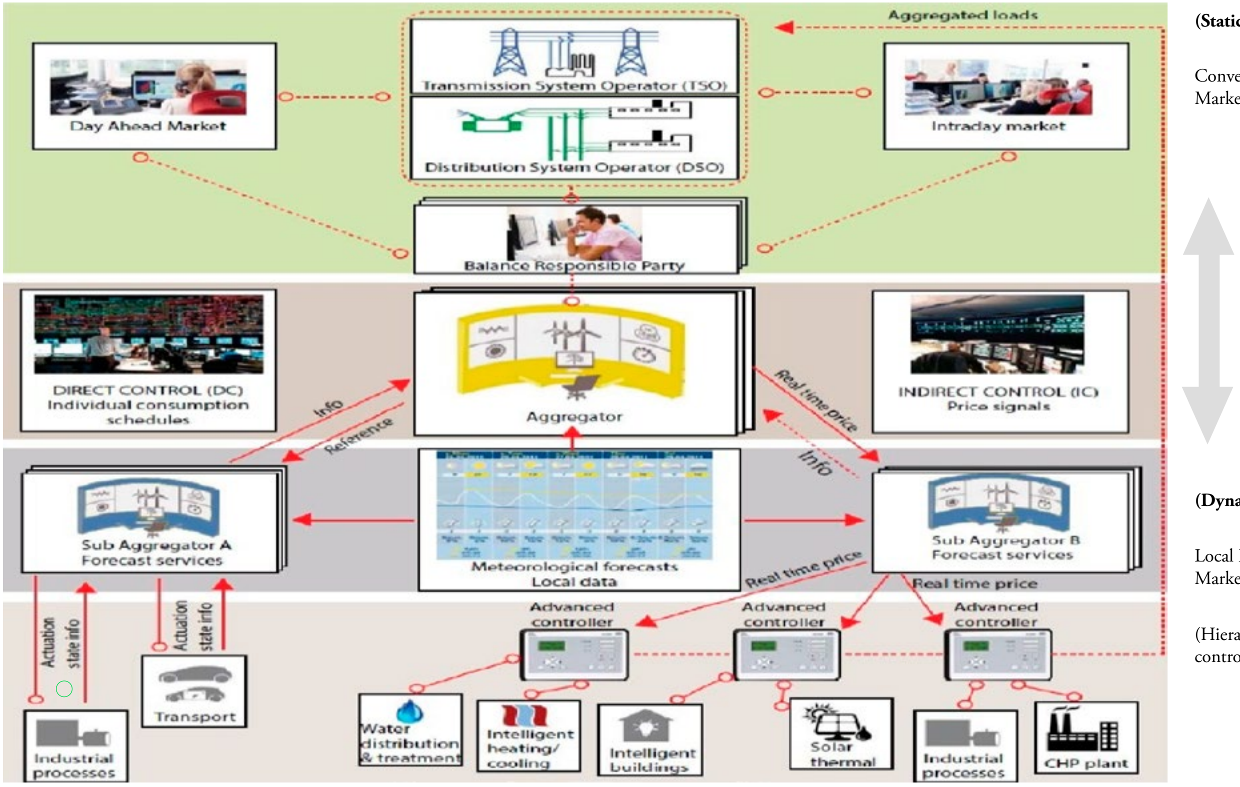
However, it is clear that at higher aggregation levels - e.g., day-ahead at price-zones operated at the NordPool spot market, the existing market mechanisms should be preserved, since they act as an important mechanism to find the overall level for the electricity prices. At that level the dynamics and stochasticity are of less importance and can be ignored.

The conclusion is that we need an interoperability mechanism to define the link between the high level static markets and the low level physics. We will suggest to use the Flexibility Function as a fundamental Minimum Interoperability Mechanism (MIM) for this purpose, and hence for describing the link between the markets and the physics. The MIMs [40] are now becoming an important instrument in the twin transition in Europe and globally the MIMs are approved by ITU and 17 member organisations [41].

10. THE SMART ENERGY OS

Let us consider the outlined principles for forecasting, control and optimisation which constitute the so-called Smart Energy OS (SE-OS), in more detail. The framework used in several projects to develop, implement, and test solutions (layers: data, models, optimisation, control, communication) for hierarchical and coherent operation of flexible electrical energy systems at all scales. See [22, 31, 42] for further information.

An efficient implementation of the future low-carbon energy system requires the electricity demand to follow the weatherdriven energy production at all scales of the power system. In addition the future calls for more coordination between the low and high-voltage system operators and, consequently, there is a need for coherence between actions taken by the TSO and DSOs, who operate at different spatial scales. As an example a new method for hierarchical forecasting of wind power production suggested in [43] has lead to a significiant improvement of



(Static)

Conventional Markets

Linking Markets to Physics

(Flexibility Functions)

(Dynamic)

Local Flexibility Markets

(Hierarchy of controllers)

FIGURE 7: THE SMART ENERGY OS

wind power generation forecasts and at the same time the forecasting hierarchy ensures that the forecasts seen by the TSO and the DSOs are coherent. In [44] similar hierarchical forecasting techniques are used for improved load forecasting in all four price areas in Sweden.

The study in [45] considers the power grids as a hierarchy consisting of the transmission, distribution, and microgrid levels and develops interfaces among these levels showing how the flexibility at the microgrid level can be activated at the higher levels. In [45] community batteries are considered as a primary source of flexibility. Finally, [36] describes a generic modeling framework towards integrating distributed flexibility across different hierarchy levels and markets for energy management decisions.

The Smart Energy OS principle is using the Flexibility Function as one the fundamental MIMs to ensure a minimal but sufficient interoperability on all relevant levels. For many applications low-cost solutions can be established using mobile phones, smart home management systems, and similar edge computing technologies. Data is typically kept at the edge, and computations are carried out in a *coherent hierarchy* consisting of edge, fog and cloud computing levels with security, privacy, transparency and fairness in mind.

The Smart Energy OS is a hierarchical setup as indicated in Figure 7. At the top level it consists of conventional markets, but at the lower levels it consists of methods for a combined direct and indirect control. The experience at, e.g., the smart energy hub, Center Denmark, is that most of the building related demand response methodologies should be based on indirect price-based control.

At the same time the Smart Energy OS is designed as a hierarchical system for data handling and information exchange frameworks, ensuring a unique coherence across all relevant spatial and temporal aggregation scales, and with a focus on multi-objective criteria like energy efficiency and flexibility.

Conceptually, the Smart Energy OS relies on the Minimal Interoperability Mechanisms (MIMs) roadmap, which aims at providing building blocks for an efficient digitalization of the society in general, and in providing functionality across different but related domains like energy, transportation and water. The intention is not to replace existing market mechanisms, but to accomplish this with a MIMs-compliant framework for an efficient scale-up of local flexibility concepts (e.g., for large-scale integration of wind and solar energy) while supporting local initiatives like district heating and local energy communities.

Data for energy systems forecasting and services is an important example being built upon the Smart Energy OS concepts. Here unique frameworks and data spaces for exchange of information between all relevant aggregation levels have been established. More specifically, the Smart Energy OS concept contains a framework of spatial and temporal hierarchies for ensuring that forecasts of, for instance, the wind power generation are coherent across all relevant aggregation levels, as explained e.g., in [46].

Integrity – including privacy (GDPR), transparency, security and reliability – has foremost importance in the Smart Energy OS, and in all essential cases such issues are dealt with by design in a consistent and verifiable way. For instance, the work in [47] proposes a privacy-preserving, distributed framework for residential demand response. Energy efficiency and flexibility of residential buildings are important examples where design-specific data exchange metrics have been adopted.

A key element of the data exchange framework between, e.g., residential homes and grid operators is the Flexibility Function [23], as previously introduced in Section 3. The Flexibility Function is one of the fundamental MIMs-related features within the Smart Energy OS setup, and it represents a condensed information exchange or interoperability framework which is used, for instance, to create a coherent link between the low-level physics (e.g. the thermal inertia of the buildings) and high-level electricity markets.

The Flexibility Functions are used also for sector coupling and for hybrid energy systems; an example being buildings with both district heating and heat pumps. Finally, the Flexibility Function can be used at all aggregation levels, e.g., for the appliance, the house, the district, the city and larger regions.

Another key element of the Smart Energy OS is the datadriven digital twins or grey-box models. The grey-box models allow for information from real-time data from sensors and measurements to be assimilated into the models in almost realtime, and consequently this improves the forecast and control performance. Moreover, the Smart Energy OS manages to keep privacy-related information at the edge. This is possible due to the fact that the Flexibility Function contains all relevant information for instance for the balance responsible parties as well as for the distribution grid operator.

The Smart Energy OS concepts, and in particular the integrated standard Flexibility Function for activating flexibility at all levels and across all relevant energy vectors, imply that flexibility and interoperability can be obtained everywhere using low cost technology. The simplicity of broadcasting price signals for activating demand-response implies that basically all appliances can contribute to unlocking the needed flexibility at the relevant spatial and temporal coordinates. At the same time the end-user can easily set up local preferences in a weighted combination of a focus on costs, emission and energy efficiency. The overall simplicity of the concepts ensures fast adaptation and stimulates an effective scale up of the use of flexibility and demand response technologies in the market.

In the Smart Energy OS framework, the computations are done at many levels of the system hierarchy. The Smart Energy OS for Power Systems, Home Energy Management Systems (HEMS) and Home Management Information Systems (HMIS) can be used to provide information about the aggregated flexibility which can be offered from a particular building, and for energy communities similar aggregation principles apply. The Smart Energy OS concepts have been demonstrated in several national and international projects like ebalanceplus [9], Flexible Energy Denmark [48], Center for IT-Intelligent Energy Systems (CITIES) [10], and SmartNet projects (EU H2020) [31].

11. DYNAMIC AND STOCHASTIC RESERVE SCHEDULING FOR POWER SYSTEMS

Solving the unit commitment and economic dispatch problem is one of the main responsibilities of power systems operators. Power systems already face important challenges due to the forecast uncertainties for renewable generation, demand response solutions, and behind-the-meter renewable PV generation. As discussed, when introducing the Flexibility Function, these uncertainties are both dynamic and stochastic.

Traditionally, operators have been dealing with uncertainties by committing reserves, i.e., making sure that enough amounts of spare generation capacity are available at every operational timeslot to meet possible demand needs. In systems with high penetration of renewables, even if the energy supply is adequate, there is a significant curtailment of renewables to make room for conventional generators that provide the necessary reserves. While storage and flexibility are envisioned as the remedy to the intermittent and time-differentiated renewable supply, it is far less discussed how they are going to replace conventional generators in the need to procure reserves.

More specifically, and in contrast to generators, storage and flexible demand are temporally coupled, which means that if they decrease consumption in one timeslot they bear a reduced ability to decrease consumption again in subsequent timeslots. This is less problematic when scheduling their consumption profile since, as discussed in previous sections, one can account for the temporal couplings and co-optimize the flexible assets' profile across the whole of a look-ahead horizon. Nonetheless, when it comes to reserves there is the additional subtlety that a committed reserve capacity may or may not be actually used, which makes it difficult to reason about the effect of the dispatch schedule (and reserve commitment) on a battery's stateof- charge or on a flexible asset's inter-temporal energy state and needs.

Specifically, consider a cluster of batteries or EVs with 500 kWh of energy stored at the start of a horizon of K timeslots. Naturally, it is not operationally safe to consider the asset capable of providing 500kWh of reserve in each of the K timeslots, since if some amount of this reserve is activated in one timeslot, it would be depleted and would not be available for the subsequent timeslots. Although this is fairly obvious, notice how it is not the case for generators, and how traditional (per-timeslot) reserve products made for generators do not account for such issues. On the other end, if the flexible asset is allowed to offer its 500 kWh as its total reserve across the K timeslots (e.g. an amount of $500/K$ kWh of reserve in each timeslot), it would be severely underutilized, because it is not really the case that the asset cannot provide more than $500/K$ kWh at each timeslot (it actually can); it is just that it cannot provide a total of more than 500 kWh of reserve activation across the K timeslots.

These two approaches make it clear that traditional reserve products (originally made for generators) are inadequate to capture the flexibility capabilities and characteristics of the system's new players. The first approach compromises the system's security, while the second is over-conservative and compromises the system's efficiency. In the face of these problems, [49] proposes a new notion of reserve that effectively resolves the utilization of storage and flexible demand for optimal unit commitment. The proposition points to the new notion of Energy Reserves, which generalizes the concept of per-timeslot reserves to energy reserves *across* time intervals.

Such a reserve product that is more nuanced around storage and flexibility, enables the new assets to be integrated in the system and replace traditional generators, not only in terms of balancing the system, but also in terms of providing the necessary reserves to support renewables-based energy supply. This effectively means that the system can be operated with fewer generators committed which can lead to more than substantial cost benefits. The study goes on to quantify this effect, on the standardized case study [50], and reports a secure operation of the system at a whopping 10% of the cost of traditional practices. For the European system, this translates to weekly savings in the order of billions of euros, just by changing the reserve products.

12. ENERGY SYSTEM TAXES

12.1. THE COMPLEXITY OF TODAY

Today, the system-related taxes are complex. Historically, the purpose has been to increase the cost of energy to incentivize energy efficiency. The related tax is often called the energy tax. Later on, environmental taxes related to greenhouse gas (GHG) emissions were put in place, such as the CO_2 emission related to fossil fuels, but also other gasses like NO_x and SO_2. In the following, we will also discuss the CO_2*-eq tax*[2]. Figure 8 shows how the taxes today are introduced differently when e.g., coal is used for producing either electricity or heat (district heating).

While these instruments are politically desired, the approach of including them in the form of rigid taxes or levies in the electricity bill hampers the pricing effects of both market signals and an efficient tariff design. According to [51] numerous studies show that a high share of taxes has a strong negative impact specifically on cost-reflectiveness and fairness.

The different ways of introducing the taxes indicated in Figure 8 also exemplify the challenges of the system today. For instance, the industrial sector is typically exposed to a very low energy tax on electricity, and hence excess heat from industry without extra taxes could represent an unfair situation, leading to inefficient use of electricity, as waste heat can be sold off without penalties.

The taxes also depend on the fuel. As an example, biomass is treated as fossil-free fuel, and even in district heating applications, there are no taxes on energy produced by biomass. This seems reasonable if the biomass is produced 'this year and just outside the city', since then we are faced with a local recycling

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[2] A carbon dioxide equivalent or CO_2 equivalent, abbreviated as CO_2-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming

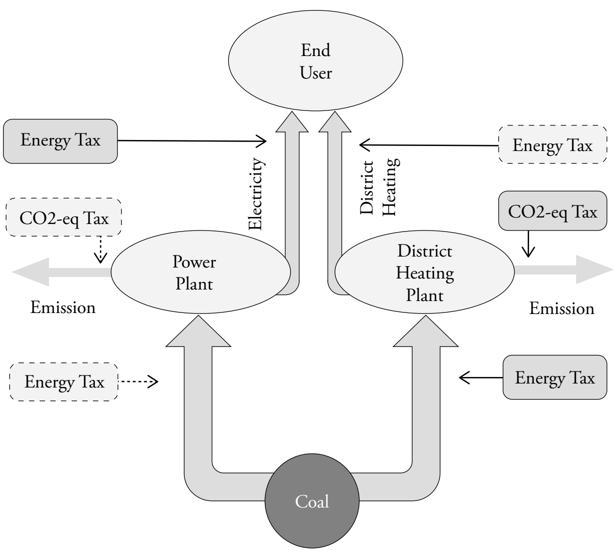

FIGURE 8: EXAMPLE ON TAXES THAT COULD BE INTRODUCED IN CONVERTING COAL TO EITHER ELECTRICITY OR HEAT. THE SOLID LINE BOXES SHOW THE TAXES USED TODAY, WHEREAS THE DASHED LINE BOXES SHOW OTHER POSSIBILITIES FOR TAXATION.

of the CO_2. However, if the biomass is 100 years old trees, imported from overseas, then it is reasonable to consider it partly as fossil-based fuel. As another extreme, biogas delivered by the existing natural gas pipelines is treated as fossil fuel even though it would be possible to make tax exemptions based on certificates. The fact that it is possible e.g., for the industry outside Denmark to use biogas supplied by the existing pipelines, just highlights a taxation problem that has to be solved as soon as possible. A similar paradox is seen for the transport sector, where e.g. bio-diesel is exempted from tax, while biogas is not.

Existing solutions related to green or renewable energy certificates have to be revised. For green gas, including biogas, it somehow makes sense to use green certificates, since the costs for transportation is very low, and we have an existing infrastructure in Europe for long-term storage of gas. However, for electricity a lot of efforts have revolved around renewable energy certificates (RECs), but most of these are no better than green-washing. Once electricity is produced - by a wind turbine or a coal power plan - its source can't be tracked, and when an end-user turn on a light, it is impossible to tell whether that power was generated by the wind turbine or the coal power plant. If not co-incident and co-located with usage, then taxation should be conducted accordingly since for electricity storage options are limited and expensive, and hence timing is of the essence. Some efforts have taken place on establishment of Granulated Guarantee of Origin (GGO). Sector coupling to gas storage and electricity grids would however enable storage of power, which could making offsetting of production and consumption possible at low expense, as for instance the biomassbattery [52], [53]. Some loss of energy is however to be expected in these conversions and they should thus primarily be used to balance the "hard to abate" long-term storages. Balancing of shorter fluctuations are better achieved by demand-side flexibility. If power is produced by gas then the gas storage can simply function as a virtual storage of electricity.

With the increased need for green fuel generated by PtX technologies, we need access to large amounts of biogenic / cyclic carbon for the production of e.g., methanol for transportation and for the industry (e.g., plastic production). Unfortunately, the political short-term goals for 2030 implies a focus on Carbon Capture and Storage (CCS) whereas, instead, more attention should be on Carbon Capture and Utilisation (CCU), as this will incite development of long-term applicable PtX value chains. The experience from the establishment of local value chains is much needed if Denmark has to remain competitive and be able to export PtX. The possible sector coupling between PtX and power markets for arbitrage will require access to large amounts of CO_2, and hence it is recommended to develop large scale CO_2 storage solutions in Denmark.

An ideal taxation should be linked to a penalization of the use of fossil fuels such as natural gas and coal when it is brought into the energy system, while we need to incentivize circular use of biogenic CO_2 since this is going to be a scarce resource when ramping up on PtX and the sooner value chains are in place, the more competitive Denmark will be onward. It is clear that this calls for a careful redesign of the taxation in the energy sector, and here for instance a circular view which includes a focus on the use of CO_2, will be important. The revision of the energy-related taxation in Denmark also calls for a revision of the existing favorable tax rate for electricity consumption above a certain threshold for households dominantly heated by electric sources and schemes that support the use of roof-top PV, selfconsumption, and local energy communities.

Today curtailment of renewable energy is substantial, and this holds for both wind and solar energy. Curtailment is taking place both operationally (e.g., by the TSO) as well as due to the existing sub-optimal rules in the regulatory settings. As an example, we can mention that the maximum production for private wind turbines is 15 kW despite the fact that many turbines can produce much more. Also, rooftop PV production is often curtailed, and it is not allowed to share the power with the neighbours. We need a regulatory setting that can support local energy communities that can optimize self-consumption. Given a proper regulatory design, this would also help resolve grid challenges.

However, the main problem is that taxes are typically rigid or constant, and this is blunting relevant price signals from the market or the network. For instance, for ordinary households, the tax (incl. VAT) represents a large fraction (approx. 60 pct in Denmark) of the electricity price. Even with the suggested revision of the markets and the tariffs, the current electricity tax is so high that the proper system and market-related signals from new markets and tariffs are almost hidden and the incentives for being flexible are almost nonexistent today. A study of tariffs and taxes in Europe ([51]) confirms this by concluding that a main outstanding issue across Europe is the weight taxes take on the electricity bill.

12.2. A TAXATION DESIGN FOR INCENTIVIZING DEMAND-SIDE FLEXIBILITY

Due to the complexity outlined above we will now describe a solution, where the main purpose is to incentivize demandside flexibility. The solution can be considered as a stepping stone towards a more permanent solution which accounts for the complexity outlined regarding the biomass, biogas, the need for CO_2 for PtX, etc.

The energy crisis in 2022 has shown that people are willing and able to react and avoid periods with high prices. Now in 2023 many automatic or semi-automatic smart solutions for rescheduling the load to periods with low electricity prices have been developed.

Previously in Section 2, it was argued that demand-side flexibility enabled by digitalization and proper design of markets and tariffs could lead to huge savings in infrastructure investments and balancing costs. Similarly, it is shown e.g., in the CITIES project [10] that a proper design of dynamic GHG taxes could lead to up to 50% savings of the greenhouse gas (GHG) emission.

As a part of the CITIES project [10] a National Task Force Committee[3] suggested to redesign the energy taxes such that the consumers are motivated to use more energy when it is green and subsequently less when it is black. Consequently, it is recommended that part of the electricity taxes is scaled according to the specific CO_2 emissions per hour to accelerate the development of solutions for flexibility.

The main principles are:

1. The taxes are linked to the physical conditions.
2. The taxes are linked to the current geographical and temporal variation in CO_2-eq emissions.
3. The taxes are harmonized between the forms of energy.
4. Taxes are harmonized between forms of consumption.
5. The taxes are designed with *a fixed part*, which provides an incentive for *energy efficiency*, and a *variable part*, which provides an incentive for *energy flexibility*.
6. The fixed and variable parts can be scaled so that a desired revenue is achieved; for example, they can be designed such that they are revenue-neutral; but this is a political decision.

See [10] for more information.

The taxation of industrial customers is, in general, lower than for households across Europe, in an effort to keep the industry competitive. Nordic countries like Norway and Finland stand out in this regard, offering the lowest taxes on industrial consumption.

The industry must also be motivated to become flexible, energy efficient and, where it makes sense, also electrified. The aim is to accelerate the green transition in the industry, through a gradual introduction of CO_2 taxes. This requires international support. In a Danish context, the CITIES task force suggested establishing a scheme where these taxes are paid to a fund, which aims to support a transformation of the industry towards being flexible, efficient and electrified. To avoid carbon leakage the outlined principles for CO_2 taxes are designed to allow for a later extension to include life cycle analysis and CO_2-eq total accounting. For example, the life-time CO_2 load for a building will consist of a load which is due to the materials (including the ongoing renovations), as well as a load that is due to the current energy consumption.

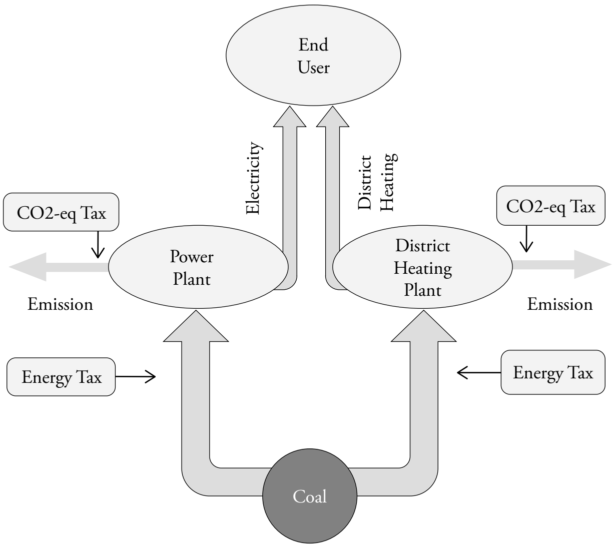

FIGURE 9: ILLUSTRATION OF THE EXAMPLE SOLUTION FOR A STRUCTURE FOR ENERGY SYSTEM TAXES. HERE THE IS AN ENERGY TAX ON THE FUELS WHEN THEY ENTER THE ENERGY SYSTEM, AND A TAX ON EMISSIONS RELATED TO THE FUEL TO ENERGY CONVERSION.

Similarly, the costs and emissions related to waste incineration should also be revised. This should include Scope 3 emissions[4] and e.g., the carbon cycles related to waste handling.

12.3. EXAMPLE SOLUTION

Here we present a concrete example solution, that satisfies 1)-6) in the list from the CITIES Task Force, in a simple manner. This solution would put energy taxes directly on the fossil fuels while CO_2 taxes are put on the CO_2-emissions as illustrated in Fig. 9. This ensures that CO_2 taxes are only levied on actual emissions, since this is what physically drives climate change. The energy taxes have to be put on the fuels, to encourage reducing the amount of the fossil fuel that is consumed. This satisfies 1)-4) by harmonizing forms of production and consumption, while linking everything directly to physics. 5) could be satisfied since putting a fixed tax on all fuels encourages energy efficien-

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[3] Task Force Committee consisted of representatives from: Danfoss, Danish Technological Institute, Grundfos, Ørsted, Green Energy, Tomorrow, Aalborg University, and the Technical University of Denmark

[4] The GHG Protocol Corporate Standard classifies GHG emissions into three 'scopes'. Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions.

cy, while the CO_2-tax varies with CO_2-intensity, and thus is variable, encouraging energy flexibility.

We will, however, suggest to put the energy tax on fossil fuels only to ensure that green fuels, e.g. from PtX, are competitive on the markets. Lastly, as explained in 6), the fuel-tax and CO_2-tax can be balanced, to strike the right balance between energy efficiency and flexibility, while the overall size of taxes can be chosen as to achieve the desired revenue. Notice that taxes could even be negative at times if one wishes the revenue to be zero. We also suggest to consider the solutions outlined for the industry in order to ensure that the industry is competitive also in the future.

Trade in electricity between EU member states and countries in the EU's close vicinity is gaining in importance, and the post-pandemic energy crisis has made it even more significant. Using real-time tools for finding the current CO_2 content of the cross-border electricity flows will be needed, and here tools like Electricity Map [54] can be used. This tool shows live CO_2 data (measured in gCO_2-eq/kWh) including carbon intensity of both import and export.

13. CONCLUSION

This paper describes the challenges, methodologies and benefits for activating demand-side flexibility for an efficient transition to the fossil-free society. It is highlighted that demand-side flexibility in combination with digital technologies and controllers that harness it, can be seamlessly forecasted and activated to readily serve the needs of both the local distribution system and the macroscopic power system.

Investments in expansions of the electricity grids are considerable and unavoidable. However, it is estimated that demandside flexibility can lead to large savings (between 27% to 80%) of today's forecasted investment needs until 2030 for low- and medium voltage grids. Similar large savings are reported for the balancing costs. A prerequisite for a successful implementation of methods for activating demand-side flexibility is that tariffs are linked to the actual operational costs.

Furthermore, we need dynamic taxes that are linked to the CO_2-eq emission within the hour and the use of fossil fuel. Energy taxes should dynamically be on the fuel consumption, and ideally green fuel should be exempted from taxes.

The optimal solution is tariffs and taxes that are linked to the physics. The methodologies described for enabling dynamic tariffs and taxes will successfully pave the way for a plethora of solutions for activating demand-side flexibility at scale.

The solutions outline for the taxes can be considered as a stepping stone towards a solution incentivizing flexibility for the weather-driven energy system. For the future fossil-free society the tax structure must also reconsider CO_2 recycling, biomass, biogas, and Scope 3 emissions. It is important to incentivize recycling of carbon, which will be needed for the production of green fuel at the future PtX plants.

Demand-side flexibility solutions rely on digitalization of the energy grids. In this paper methods for digitalization of the energy grids and data-driven methods are described. It is argued that we need interoperability mechanisms for connecting different flexible assets (smart buildings, supermarkets, wastewater treatment plants, PtX plants, etc.) to the grids and markets. The suggested methodologies imply that the end-user flexibility can be offered in a multi-level hierarchical control for solving essentially all grid and balancing problems. The suggested interoperability mechanisms allow for sector coupling, which drastically increases the flexibility potential.

We need a regulatory framework which supports an affordable, fair, reliable and fast transition to the weather-driven energy system, and most importantly we need dynamic tariffs that are just high enough to solve the issues in space and time. The tariffs should be linked to the physics, and a methodology is described for linking the dynamics of the physical assets to the electricity markets.

For the taxes, an important step forward would be the outline dynamic energy taxes that motivates use of energy when it is green and penalizes use of energy when it is black. The combined approach for dynamic tariffs and taxes is simply a broadcast of price-signals. The procedure ensures that the consumers are in control and in the center. The simplicity is also an important precondition for transparency and trust.

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