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WHAT IS SMART ABOUT CONTROLLING ELECTRIC ENERGY SYSTEMS? VIRTUAL POWER PLANTS AND THE DIGITIZATION OF THE GRID

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ABSTRACT

Energy systems are said to be subject to a twin transition of decarbonisation and digitization. Virtual power plants are one part of creating the much proclaimed smart grid, situated at the intersection of electricity production and the electricity transmission. This paper investigates how virtual power plants work by showing their interrelation with the electricity market and the grid. With a focus on the German and European electricity system, the research shows that the market comes first and physic electricity feed-in second. Based on a market ideal, virtual power plants act as an aggregating tool for decentralized energy production and as a regulatory device reacting to supply and demand, albeit the programmes cannot rule out the risk of working against grid stability.

KEYWORDS

Virtual Power Plants, Digitisation, Digitalisation, Electricity Grid, Energy Market, Electricity Market

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Introduction.

"Truly innovative: our sonnenVPP. We are the first and so far only provider in Germany to network private home storage units into a virtual power plant. We are building an energy system with which clean electricity is available exactly when and where it is needed. A system that offers cost benefits for everyone and at the same time reduces the load on the electricity grid."

This is how sonnen, a German company primarily selling electricity home storage systems, looks for customers on its website. However, a scheduled talk with a sonnen staff via phone brings little information on how they operate their virtual power plant. Asking "what exactly is special and unique" after the staff's boastful "our sonnenVPP is very exceptional and no one can copy us" leads to a vague "I don't know, I'd need to check with the technical staff, as I'm working in service here." Similarly, at the smarter E Europe fair in Munich in 2024, Europe's largest exhibition fair for the energy industry, a staff member that focusses on battery sales and customer care wisely redirects technically induced questions to a more knowledgeable colleague.

As Emile St. Pierre has shown through his anthropological research on virtual power plants and ideas of digitizing energy production in Japan [1], several stakeholders in the energy sector and beyond seem to be lacking an understanding of what a virtual power plant is and how it works. Similarly, J.C.M. Siluk and colleagues show, that in cloud-based energy management systems, terminologies, concepts and definitions are used interchangeably, without precision or clear definition of terms like energy hub, smart energy or energy cloud [2]. The smart grid, one of those terms that is inevitably linked with virtual power plants, was in 2016 a central idea of energy system transformation, yet also "mainly a technical vision of engineers and IT experts", an experiment producing knowledge while being tried out [3]. Even seven years on, in 2023, smart grids remain a "vague and enticing imaginary" with different narratives behind it [4]. However, virtual power plants are a precise aspect of the smart grid that has been successfully operating for more than ten years in Germany and other countries. Germany's virtual power plants arguably "offer cost benefits for everyone" and help stabilize the grid. Virtual power plants are said to be a part of the twin transition of decarbonisation and digitisation that energy systems are subject to [5], or liable to three Ds: decarbonisation, decentralization and digitalization [6]. Decentralisation is with the trend to mega wind and solar parks subject to debate and to global investment, yet volatile and smaller units of power generation require a digital control in order to keep the electricity grid stable and secure. We hence see the digitisation of electricity infrastructure through hardware – e.g. through the installation of boxes aggregating several small units of power generation into a virtual power plant – and through software, i.e. of programmes and algorithms that determine and 'optimise' the operation of these decentralised energy production units.

This article examines what comprises this optimisation and what drives virtual power plants. It thereby provides an understanding of virtual power plants from a socio-technical perspective. It analyses the intertwinement of the electric grid system and the electricity market, whose historic development and politically induced design provide for a tight framework within which virtual power plants operate. It is this framework within which stakeholders set up and operate virtual power plants, according to their own premises but aligning it to terms and conditions. The grid, the market and the underlying values and principles hence allowed for virtual power plants to develop in a form that can also raise critique. With its socio-technical perspective, the article sheds light on what drives stakeholders to set up and run virtual power plants and how this form of digitising energy generation and transmission is conceptualised and executed.

In the following, the article – after describing state of research and methods – explains emic views of virtual power plants and shows their intertwinement with the European grid system and the functioning of the electricity market as the two central frameworks for virtual power plants. The article aims at describing, analysing and setting into relation the perspectives of people who operate and work with virtual power plants with the socio-technical regime. Situating virtual power plants within prevailing yet dynamic economic and technical frameworks allows for a better understanding of how virtual power plants position themselves within the system, what shifting power dynamics of steering and controlling electricity production and transmission are at play, and where potential pitfalls are. In other words, the article combines on the ground realities with a bird eyes' view. It does not take to the technical details and programming peculiarities, but brings out the beliefs and impetus of those operating virtual power plants and asks what this, along with the socio-technical frame of virtual power plants, implies for societies and their lived values.

State of research

This social science angle expands and enhances the current state of research on virtual power plants, which is dominated by technical and economic viewpoints. As several review articles show [7–10], research on virtual power plants has over the last ten to fifteen years developed from broad conceptualisations to ever more precise and detailed versions of how to optimize virtual power plants mathematically and algorithmically. They provide a more or less detailed review of the technical advancement of virtual power plants and can be referred to for different categorisations of the currently more than thousand articles on virtual power plants that take to the operational architecture, the optimization of digitally controlled grids or the profit maximization for and through virtual power plants. However, these review articles also show that there is as of now very little academic literature on the social aspects of virtual power plants. One exception is a Dutch research project on virtual power plants that sheds light on community-based ones, showing that the term community virtual power plant is case-study specific, and so are modes of replicating community virtual power plants [11,12]. A study of Australian virtual power plants shows that for individual households or small-scale owners of batteries or solar PV panels to become part of a virtual power plant is a question of financial incentive as well as of giving away control [13]. There are furthermore several studies that investigate the digitisation of energy systems in general, with a view on ethics and society [14,15]. They show that the move towards automated and remote control creates potentially a centralisation of knowledge and realigns data and information transfer. It also raises critical questions of power and control when grid operators, service providers, or market platform operators shift from asset management to service management [16]. The turn to digital technologies has been turning out to be a relevant business model, yet the market is with regards to digitized energy systems not necessarily the best guarantee for net stability [17]. There are more social analysis of smart meters as the user end of a digitized grid, which would allow a remote and automated control of frequency and load [18–20]. Yet analysis of the production and transmission side of digitizing the electricity grid and its social and moral aspects remain scarce. This article, however, focusses on virtual power plants in the way they are understood and put into practice in Europe. The article defines virtual power plants, with reference to [12,21], as a software plus hardware that aggregates supply-side distributed energy resources into one portfolio, allowing for steering and operating these resources in the electricity grid and market as a single power generation unit. The energy resources of virtual power plants are most often, but not only, renewable electricity production units. Virtual power plants can also aggregate fossil based electricity production units, units that produce other forms of energy (e.g. heat), and storage units (e.g. batteries). Virtual power plants have advanced over time and increasing numbers of electricity production units are part of their portfolios [7]. However, they remain as of now a very small part of the electricity system [13], and are hence not or not yet “crucial players in modern power systems” [7], which might be a reason for the limited research on its social realities.

Methods

This article takes to the social realities and wider implications of virtual power plants by investigating how and based on what norms and convictions people operate virtual power plants. Methodologically the research for this article is framed by the socio-anthropological research design of the EnergieDigital project,[1] indicating that the research is conducted inductively rather than deductively, with the aim of understanding the life worlds of people and developing emic, in-depth perspectives rather than providing for statistically relevant representations of the field. This article in particular draws on qualitative empirical social research and is based on seventeen qualitative interviews with people working in or with virtual power plants, as well as several informal conversations, website and document analysis and participant observation at energy exhibitions and industry meetings, conducted between 2023 and 2024. Each interview, conducted in person, via phone or online lasted between one and four hours, was transcribed and coded using QualCoder. The viewpoints expressed and the quotes used in the following[2] provide individual views that people voice. It hence allows those emic perspectives to become heard and to be put into relation with the electricity system within which virtual power plants operate.

Why virtual power plants?

It is well known that we need to decarbonise energy production, and that this decarbonisation comes with more decentralised production units, also called distributed energy resources (DER). The German Energiewende may serve as an example: driven by the need to decarbonise energy production, renewable energy production units (especially wind turbines) were technically developed mostly on experimental and informal grounds, while large utilities rather focused on improving and banking on large scale fossil based energy production units. Even though technical innovation in renewable energy generation has leapfrogged since 1990 – increasing generation capacity of a wind turbine from 150 kW to 6 MW onshore and 15 MW offshore – it still needs about 150 of the largest wind turbines to substitute the generation capacity of a standard coal fired power plant. Substitution the 2000 MW of a coal fired power plant with biogas power plants requires about 4000 units, for solar PV a rough calculation arrives at 4000 average industrial roof top PV systems or 10 large solar parks. A substitution of fossil fuel based power plants with renewable ones is on its way: the renewable energy law and its preceding electricity feed in law set the stage for the consequent rise of DER from 1991 onwards [22], allowing the share of renewable electricity production in Germany to increase from 18.934 GWh in 1990 to 272.449 GWh in 2023 [23], contributing to raising the share of renewable energy in the country’s energy consumption to 20.8 %. Similarly, the European Union’s share of renewable energy consumption rose to 23.0 % in 2023 [24]. Pressure from civil society, an increased awareness of climate change and global warming, and a sequential climate legislation that sets targets of 55 % (for the EU and Germany) reduction in greenhouse-gas emissions by 2030, contributed to this significant increase in DER.

Another known fact is that renewable energy is volatile and not available on demand, unless coupled with storage systems. This poses severe challenges for an electricity system, which requires constant balancing of energy input and output, production and consumption, in order to keep voltage and frequency and hence a stable grid that transmits electricity. DERs make this balancing more complex and virtual power plants could theoretically be a solution to handle the ever increasing amount of DERs through aggregating and steering them, an essential part of stabilising the grid and the physical infrastructure. Yet, this, proclaims a sales manager of NextKraftwerke, another German VPP operator, is not their intention.

“It's about increasing efficiency. The legislator has instructed us to introduce this [the VPP] into the market in such a way that the operators have an incentive to use their resources sensibly. And since the electricity exchange follows a simple market principle, namely supply and demand, prices always develop

[1] DFG research project number MU 4925/2-1

[2] All interviews have been anonymized according to the ethical standards agreed upon with the interlocutors.

accordingly. When demand is high, prices are high, when demand is low, prices are low. This means that the incentive for the operator is to produce electricity and use the resources when prices are high, i.e. when demand is high, and to reduce the use of the resources accordingly, i.e. when prices are low according to the exchange. … It is for purely economic reasons, right. You also need to know that we have nothing to do with physics. Actually. NextKraftwerke is not a grid operator, we are purely commercial, and we do have to install technology to be able to control these plants. This is also prescribed by law, i.e. by the Federal Network Agency. And we have to be able to do this, but we don't have to do it and if we do, it's only for purely commercial reasons and not for physical reasons." (Interview 04.01.2024)

The economic side of a virtual power plant that the sales manager stresses, is one central aspect of the way it operates. A chronological view of practically working the virtual power plant is helpful here to understand this thinking and the rational: While conventionally load curves (that fluctuate throughout the day and throughout the year) formed the basis for the following day's net schedule, the virtual power plant operator has at first a look at the market. First thing to decide for is whether the DER's electricity in his portfolio is to be sold as balancing power or not. Balancing power is a form of stand-by modus that grid operators can make use of right away – it needs to be fed into the grid on demand within 30 seconds, 5 minutes or after 15 minutes – when an imbalance actually occurs. Prices for balancing power are auctioned in 4-hour-blocks 24 hours ahead of (potential) delivery time. Only after knowing if the tender is accepted, will the (remaining) potentially produced electricity be traded at the stock exchange's day ahead market. As the name says, trade happens here a day ahead of the actual production and the stock exchange closes at 12 noon. Consequently, the virtual power plant operator, also called direct marketer, knows a day before the electricity is actually fed into the grid what prices it realises. He generates in a second step the net schedule accordingly for all power plants in the portfolio, which will work and feed in electricity the following day in correspondence to the schedule.

The electricity market

The foundation for this form of electricity trade – and for economics being the prime incentive for virtual power plants and their operation – is the European energy market. In the European Union, a total of 2,700 TWh electricity was consumed in 2023; Germany being the EU's single largest consumer at 20 % of this amount [25]. This electricity is traded either over-the-counter, i.e. in direct contracts between producers and utilities or large-scale consumers or at the electricity stock exchange. About 718 TWh were traded at the European Energy Exchange EEX in 2023 [26], indicating that about three quarters of the electricity is traded over-the-counter.

The EEX was founded in 2002 as part of the European agenda of liberalizing the electricity economy. Liberalising the electricity markets comprised a fundamental change from regional monopolies based on concession contracts to a liberal European internal energy market. Prior to the late 1990s, we can talk of electricity oligopolies, with utilities owning and operating both power plants as generation units and the grids, with demarcated borders in the form of concession contracts – giving them power to set consumption prices (albeit being controlled by state agencies). The neoliberal agenda of the EU envisioned a competitive, market-driven electricity economy, pushing for this with several laws and regulations from 1996 onwards: the European Parliament passed three 'Energy Packages' between 1996 and 2009, making way for an energy market that is "competitive, customer-centred, flexible and non-discriminatory" [27]. Liberalising the market was based on the idea that competition brings higher economic efficiency, lower electricity prices and increased private investments.

However, these efficiency gains and economic benefits were hardly realized, as liberalization in a functioning market leads only to competitive, not to low prices. The idea of a larger, because more interconnected and hence stable and more efficient grid, at times led in combination with free electricity trade to collision with physical reality: an example is an Austrian pumped storage utilities buying cheap wind energy from Northern Germany, but grid line bottlenecks across the alps preventing the actual transmission [28]. This electricity then needs to be redispatched. This means that even though the electricity has been bought, traded and calculated (mostly a day ahead to the actual delivery), it cannot be transmitted. The grid operator, in order to avoid an imbalance in frequency or an overload of grid lines and transformers, looks for alternative electricity sources or orders a reduction of demand, making use of the abovementioned balancing power. The costs for the redispatch are allocated to the consumer. The same goes for the costs to tackle such problems through grid expansion: they, too, are allocated to the consumer.

Furthermore, privately operated infrastructure is often subject to an economic logic of short-term profits, which tends to postpone or avoid altogether long-term investments. In consequence, not only have electricity prices for end-consumers increased since the liberalization of the electricity market, but in some cases led to compromises in security of supply as well as national economic harm (examples prove this for the USA, less in the EU [29,30]). The current assessment of the liberalization is hence a mixed one: "Price reductions have not materialized, the markets have become more complex and states have repeatedly intervened in the market structure and distorted it due to the national strategic importance of energy and electricity. Massive subsidies for renewables and decarbonization - important and correct directions - will continue to influence this market" [31]. At the same time, an internationalized, European electricity market is physically as well as commercially reasonable, as it can support energy security through interconnectivity – albeit this would arguably work better with a trading system that calculates not only amount of electricity, but energy security and transmission as well.

But energy security and grid serviceability, as the modus operandi of virtual power plants indicates, come only after marketability. Virtual power plants are a business model operating within a liberalised electricity market. This liberalised market argued with efficiency and lower prices, yet failed to deliver on this promise. It is a core part of a neoliberal political agenda and market logic that has been prominent over the last decades, in parts with problematic consequences for workers, nature, end users, and society as a whole [32–35]. It is based on a market ethics that sees market contracts as the most efficient and most ethical means to organize society. In these logics the state plays a vital role by re-organising institutions, thereby allowing for a tangled web of state-regulated oligopolies, profit-orientated enclaves and pseudo markets. Note, however, that even Adam Smith said that the sovereign is responsible for infrastructural provision. Infrastructure is beyond the capability of private capital [36]. However, with neoliberalisation, we see an assignment of prices to phenomena that were previously shielded from market exchange or for various reasons [37], and financial rather than social objectives define what a public good is. Virtual power plants operate within this framing, and as the abovementioned statement of the virtual power plant operator shows, have adopted the logics. Virtual power plants are not only set up as viable business models, but their practice of running also follows the logic of market first, and physics second.

The physics and the actual production of electricity are hence the second step after prices have been set. Prices determine when and where to produce and feed in electricity. The single power plants in a virtual power plant's portfolio work off their plan accordingly. The virtual power plant sends this price-determined plan automatically to the DER, which in turn programmes next days' electricity fed-in accordingly and automatically. The software calculating the best prices and distribution corresponds here with a hardware – a controller box monitoring operation, collecting and sending data, and allowing for remote operation of the power plant. Controller boxes or other technical devices that allow the grid operator to remotely reduce, partially or completely, feed-in power are mandatory for power plants larger than 25 kW. For those large than 100 kW an additional call-up of actual feed-in needs to be technically possible. Controller boxes have thus been turning into a part of the electricity grid infrastructure.

The electricity grid

They are only the latest detailed amendment to the European grid, which in Central Europe is laid out as a single phase-locked grid with 50 Hz frequency, spanning over (parts of) 36 countries [38]. As of 2023, the European grid connected more than 1.074 GW of installed electricity generation capacity [39]. Navigating this capacity and keeping net stability in the sense of assuring that net frequency is at a stable 50 Hz in the European electricity grid is the task of the 40 transmission system operators, responsible for the highest voltage transmission lines. Through network control rooms, they plan, monitor and control the load flow within their region on highest voltage level. Based on the calculation made a day ahead, they check if in reality load curve, net schedules and actual supply and demand for electricity provide for an operating and stable electricity grid system. Similarly, the distribution system operators, responsible for high, medium and low voltage lines, monitor and control electricity flows in their own network control rooms, albeit through directing their attention to keeping voltage. Operating in the network control rooms comprises for the transmission system operators to use balancing power and redispatch, for both transmission system operators and distribution system operators at highest and high voltage level it comprises switching and regulating operations, down-regulating supply and demand or redirecting electricity flows, through de/activating power plants, relay stations and large consumers.[1] This happens in parts automated, in parts through telephone commands and back-up checks (e.g. to ensure that no one is close to a relay station in moments of switching).

[1] This control and regulation is not possible/allowed at medium voltage level (as regards load/consumption); it is allowed at low voltage level (load and feed-in) but not yet technically possible, as hard/software is missing.

Virtual power plants ensure that this operation is still possible in times of a several-fold increase of generation units. Virtual power plant operators secure functioning controller boxes as the relevant , installed hardware for switching or regulating DERs and that the software is able to aggregate the individual DERs into a size that can be traded at the stock exchange and that is operable by the grid operators. NextKraftwerke, for example, reached a size of 10.000 MW installed capacity in 2022. Virtual power plant operators sell the amount of electricity – calculated with monitored data from the DERs they have contracted, weather forecasts, a buffer for divergence, and other data – and allow for an automated release call by the transmission system operator when sold as balancing power, or themselves order the DERs to follow the final net schedule for feeding in electricity. Virtual power plants' software provides for an optimised marketing the day ahead and for a balanced physical use of the DERs according to the accumulated amount sold and budgeted into the grid. To say it in the words of a virtual power plant staff member:

"So we take care of all this small stuff: Do they now stick to the timetable, are they available, etc. Yes, that means we chat with the 2000 biogas plant operators. The TSO (transmission system operator) then has convenient centralised access via us. Says 'I now need 100 MW', and how we then organise this and allocate it behind the TSO's enquiry, so to speak, is something the TSO doesn't have to worry about." (Interview, 03.07.2024).

In short, the virtual power plant combines the energy market and grid system. It provides the hard- and software to calculate and regulate parts of the 9.000+ biogas plants, 28.000+ on shore wind turbines, and about 1.2 billion photovoltaic & storage systems.[1] Using the allowed roles and general ideas, virtual power plant operators are a logical consequence of the way the grid developed and intertwines with the market. This system of optimising energy flows works well, for both the companies and the electricity system, according to the NextKraftwerke sales manager:

"Yes, and it works brilliantly. We are exactly the best example that it works. We've been on the road for twelve years now and have by now aggregated energy from decentralized small-scale generation plants in total from five nuclear power plants, and that's just us, and the grids haven't collapsed etc. Precisely because there are companies like ours." (Interview, 04.01.2024)

Problematic aspects, or: Is it smart to have virtual power plants as part of smart grids?

Indeed, virtual power plants work. For the European grid and electricity market, they are a marketable and technically feasible option to feed decentralised, renewable electricity into the grid. As regards quantity, they are able to replace several conventional power plants, with NextKraftwerke alone replacing about three large coal-fired power plants.

However, virtual power plants are not without problems and several issues remain problematic. For one, the current virtual power plants in operation concentrate on biogas plants and batteries. Both are not volatile electricity source; they don't depend upon the weather but can be turned on and off on demand, with the storage volume of the biogas tank and the battery being the significant limit. To calculate weather conditions for wind and solar electricity is significantly more complex and bears greater potential for divergence. It requires more meteorological data and computing power, bears greater financial risks and less security for the grid. Wind turbines and solar panels can support the grid only through load shedding; in case of strong wind and sun they can be shut off or down-regulated, but not turned on if there is now wind and sunshine. A prequalification for solar or wind parks to contribute to balancing energy will be disproportionately harder to acquire than for (aggregated) biogas plants or batteries.

The second issue is that especially volatile energies, whether aggregated into a virtual power plant or not, do not necessarily contribute to net stability. Quite on the contrary, the way the electricity market is designed right now pays for amounts and quantity, but does not factor in net stability. Yet, the market does not work with an invisible, allregulating hand. The idea that prices generated through demand and supply does automatically regulate electricity input and output might to large parts be right. However, it is also conceivable – especially in markets that sees not only producers and consumers, but brokers, investors and market-makers with their sole interests in generating profit – that price signals are overbid and outbid, crossing a threshold from grid stabilising to grid destabilisation. As Körner and colleagues [17] have shown, the market might not be the best idea for digital technologies in energy systems. The German electricity market on December 14th in 2008 is a good example: incorrect forecasts for the photovoltaic feed-in led to rapidly increasing prices on the intraday market. While in theory these high prices would induce declining demands and balancing power regulating the rest,

[1] Numbers according to [40–42].

in practice the prices for balancing power were too low for traders to act this way. They instead continued to buy and rely on balancing power – more than available – so that the last resort to prevent a black out was to shed load and take large consumers of the grid (ibid: 3). Körner and colleagues hence conclude that all current developments require an adjustment of the market design (ibid: 4). Otherwise, the liberalised or at least a completely uncontrolled market implies here a race towards scale and concentration, as Trahan and Hess point out [14]. This is not per se a negative thing, as it allows for more research and development in order to improve and expand virtual power plants. Sonnen, for example, has been working on software that also incorporates dynamic end consumer tariffs, as well as for integrating electric vehicles' batteries. Yet it is important that this concentration of data, knowledge and control over access to electricity infrastructure does not lead to the formation of black boxes or company secrets preventing grid operators to be able to operate and optimise grid stability. The way algorithms work and steer operation, remains rather vague.

"On software or so on, all these algorithms that are developed, that is of course a trade secret, let's put it that way. So it's clear that NextKraftwerke has employees who program algorithms and try to achieve the highest efficiency and, of course, the highest profitability…. But I can tell you which parameters have an influence. For example, the weather is of course a very, very important point, a very, very important parameter. And of course there are also various weather services that are then consulted. But I can't say what these are and how exactly they all work and what probability calculations are used, but I know that this will be done in such a way that the forecast, especially for wind and PV systems, will of course be prepared accordingly." (Interview, 04.01.2024).

While all companies I talked to stressed that the grid operator has priority access to the DERs and is the prime actor deciding when to regulate and operate these DERs (whose electricity was sold as balancing power), scenarios are conceivable where interfaces don't work, DERs don't execute commands, and virtual power plant operators refute liability.

The final issue to be considered is costs. With the large amount of data generated, transmitted and stored, smart grids and virtual power plants as one aspect of them, are said to reduce efficiency and increase operational costs for grid operators [43]. Distributed electricity systems with more individualised units for production that still rely on a grid infrastructure require skilled work to bring these units together. For executing this work, direct marketeers were introduced as a new role to the energy market. They congregate expertise on the soft- and hardware for aggregating DERs, and this expertise and work is priced into electricity rates. At the same time, direct marketers are subject to an economic logic of growth, necessitating constant customer relations, customer care and sales department. Currently, the owners of DERs pay for the service of virtual power plants, yet indirectly end consumers do: the higher profits virtual power plants make as compared to DERs selling electricity individually will be priced into what the end-consumer pays. Virtual power plant operators are a growing branch of the energy sector, with several hundred people working here, a number likely to increase further.

These and other costs need to be considered carefully when praising virtual power plants as solutions to a decentralised, decarbonised and digitised energy system. Currently, costs are redistributed to the end consumer, either in hidden or in open form. The market with the merit order principle leaves huge space for excess profit, as the energy market crisis in the context of the war on Ukraine has shown: oil and gas companies in Germany made a windfall profit of about 70 billion Euro, while electricity companies (excluding hard coal, gas and oil) made a windfall profit of about 30 billion Euro [44]. Instead of an announced 90 %, the German government only retrieved about 3 billion through windfall taxes, while paying about 9 billion for buffering the costs for end users – who essentially paid the rest of the companies' excess profits. Similarly – but not as severely or significantly – when prices are calculated for auctions and stock exchanges, the incentive for profits is clearly set, which are, if not regulated and capped, also added to the price. The smart meters to be installed in individual end users' homes are another example for redistributing the costs for digitisation: The German government, for example, announced that the yearly costs for smart meters for individual households will be capped at 20 to 120 Euro (depending on electricity amount). The rest of the costs, however, will not show on the electricity bill separately, but is integrated into network charges. Likewise, the costs for expanding the grid in form of cables and the costs for redispatching, which have been rising from 110 million Euro in 2013 to 3.1 billion Euro in 2023 [45,46], are redistributed to the end consumers. While financing a grid infrastructure and investments into what remains a natural monopoly and a basic right is necessary, too little state control might lead to too large margins for private profits.

Conclusions

Virtual power plants are but one digitisation form in the energy sector. They are central for aggregating decentralised renewable energy production units, and allow for a continued use of transmission grids in a liberalised energy market. They are programmed and controlled by comparatively new stakeholders, who got their role as 'direct marketers' in the European energy system. While this can be criticised as another form of capitalising on electricity and consequently raising the prices end consumers pay for electricity, it concentrates development and expertise for IT solutions.

The grid operators also see the need to digitise electricity production and transmission, albeit they don't consider virtual power plants their playing field. They focus on grids in the first place, meaning that bottlenecks and asset management are prime concerns – where digitisation also plays a role. For transmission system operators (and distribution system operators when operating high voltage lines), virtual power plants do the necessary aggregation. Grid operators see their role in data provision for virtual power plants rather than in programming. For distribution system operators (when operating medium and low voltage lines), prime concern is currently the load that charging stations for electric vehicles and heat pumps will generate, requiring severe grid expansion or digital regulation of consumption – albeit in a situation where hardly any monitoring or data gathering is done or hardware installed, let alone digital regulation possible. With several digitisation tasks and demand for significant changes, the question whether to digitise the grid or to bet on copper in or above ground is almost a question of faith for grid operators. Will digital bottleneck management and supply and demand management be a solution that requires increased calculation, algorithms and data processing capacity? Or will digitisation only postpone (if at all) more cable installation? Virtual power plants bank on installed grids and grid-connected decentral DERs, while putting forward a working, financially incentivised form of digitising the grid.

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