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The implications of digitalization on future electricity market design

Abstract

This Energy Insight explores the interplay between the decarbonization and digitalization of the electricity sector. While decarbonization has been studied extensively, there has been less attention paid to the digital transition. Not only can digital technologies improve efficiency and reduce operational costs, they also can enable new energy ecosystems, create new business models, and accelerate the energy transition.

The driving question of this Energy Insight is whether, and if so under which conditions, the economics of decarbonization and digitalization would make them converge and deliver synergies, or whether they could end up deterring each other's development. We provide insights to this question on three aspects: industry structure, ultimate products, and pricing. We use an inductive methodology to develop four propositions and two corollaries that are the logical consequences of blending these economic characteristics. These are discussed in the context of electricity market design in the UK and the European Union.

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1. Introduction

This paper seeks to conceptualize the interactions between the energy transition/ decarbonization and the digital transition in the electricity sector. While the decarbonization of electricity has been thoroughly studied (see for example, Blazquez et al. 2020 among many others), very little has been said about the transition towards digitalization and its wider impacts[1]. Digital applications—such as digital platforms, artificial intelligence, big data, robotics, Internet of Things—have the potential to change how the economic sectors operate and how their products are made. In the electricity sector, digital technologies play a transversal role as they can not only improve operational efficiency and reduce production costs, but they can also enable new energy ecosystems, create innovate business models, and accelerate the energy transition itself. The driving question of this paper is therefore whether—and if so, under which conditions—the economics of decarbonization and digitalization would make them converge and deliver synergies, or if they could end up deterring each other's development. We provide insights to this question by focusing on three aspects: industry structure, ultimate products, and pricing.

Digitalization of electricity is part of a broader process of technological change. Digitalization refers to the process of using digital technologies to perform activities that previously used non-digital tools; new activities that have been enabled due to the rapid diffusion of these technologies; or future applications with the potential to reshape business and regulatory structures. Digitalization can be thought of as increasing the interaction and convergence between the digital and physical worlds. It has three fundamental elements (IEA, 2017):

- Data: increasing volumes of data due to declining costs of sensors and data storage.
- Analytics: rapid progress in advanced analytics and computing capabilities allowing production of useful information and insights from raw data.
- Connectivity: exchange of data between humans, devices, and machines (including machine-to-machine) through digital communication networks.

Research on the impact of digitalization in the energy sector has focused primarily on its impacts on efficiency. Incremental efficiencies in energy management due to digitalization would, all things being equal, lower the price of electricity relative to other goods. This would create an income effect as consumers have more disposable income, and a substitution effect between electricity and other goods. Both effects can lead to a rebound effect resulting in an overall increase in total energy consumption. Lange et al. (2020), for instance, investigate the potential influence of digitalization on energy consumption, and find that energy demand rises with the development of the digital industry. Usman et al. (2021) used panel data to analyze the influence of digitalization on energy use in South Asian economies, and conclude that accelerating the development of digitalization can improve energy efficiency, but would lead to an overall increase in energy consumption.

Existing electricity sector infrastructure and equipment are often incompatible with digital systems. Along with high costs and uncertain returns on investment, this can impede this technology diffusion, despite their benefits. These challenges are also present in the energy efficiency literature. For example, Jaffe and Stavins' (1994) identifies market failures and behavioral barriers that hinder economically rational investments in energy efficiency.

An additional focus has been on how digitalization technologies can help to efficiently integrate intermittent renewable sources. For instance, Shahbaz et al. (2022) examined the potential relationship between the digital economy and energy transition using panel data of 72 countries. They find that a 1 per cent increase in the digital economy—measured as a composite index—will boost renewable energy generation by 0.106 per cent.

[1] Andersen et. al. (2021) report that a Scopus search (10 September 2021) contained only 21 records with title words at the nexus between transition, sustainability, and digitalization.

We take a different but complementary strand and analyze the extent to which digitalization can bring about new structures, actors, and regulatory practices that potentially can change, replace, or complement the existing ways that electricity firms and the entire industry operate (Hinings et al., 2018; Osmundsen et al., 2018). For example, digitalization could relax some of the main constraints around which this sector is organized, such as the need for underutilized assets.

While some digital applications have emerged within the power sector, other transformative innovations, such as blockchain and digital platforms, originated in the field of computer science. These technologies have been effectively applied to other industries, particularly banking and fintech (Gomber et al., 2018). Although the electricity sector has unique features, such as regulated segments, the underlying technologies are essentially the same, merely applied to different problems. Therefore, one can draw parallels with the experiences of other industries and hypothesize the potential evolution of the power sector. By extrapolating the potential impacts of these digital technologies, we can envision how they may transform the power sector.

No formal modeling is planned in this paper, largely because formalizing co-evolution of technological and institutional systems is quite problematic and is in a nascent stage of development. Instead, this paper uses an inductive, theory-building methodology to develop propositions regarding the energy and digitalization transitions. Through a combination of observations, we launch propositions that are the logical consequences of blending the economic characteristics associated with digital technologies. These ideas could be tested in experiments in subsequent research.

We analyze interactions between decarbonization and digitalization by applying the work of David (1985), Arthur (1989), Unruh (2000), and Foxon (2011), whose common theme is co-evolution. A co-evolutionary approach seeks to identify causal interactions between evolving systems. While digitalization is mainly a technological and economic issue, decarbonization is driven primarily by government policies. This creates a complex set of tensions and interactions that require careful examination. There are various policy options available for decarbonizaton, but once a decision is made, for example to support intermittent renewables, both digitalization and decarbonization can be subject to the kind of analysis offered in this paper.

The structure of the paper is as follows. In section 2 we derive the economic principles of the digital transformation. Based on those economic principles, in section 3 we put forward four propositions that are the logical consequences of the initial premises presented in section 2. In section 4 we explore two corollaries that explore the potential synergies or antagonism between the economic principles of the digital energy transition and decarbonization. Section 5 applies this framework to the discussion of electricity market design in the European Union and in the United Kingdom, and section 6 concludes.

2. Economic principles: digitalization and the power sector

Historians of technology have pointed out that emerging technologies, which later become dominant, determine new ways to organize economic and social activity (Castells, 1996; Brynjolfsson and McAfee, 2014). Not all technologies have these transformative powers. For example, OECD (2005) distinguishes four different types of innovation:

- Product innovation is a novel implementation or significant improvement of a well-known product or service. For example, an innovation that makes it easier to maintain a solar panel.
- Process innovation is the development of a new technology to perform a well-known task. For example, demand forecasting, a known activity, but with better tools such as big data and sophisticated algorithms.

- Innovations can also create new business models, an innovative redefinition of products and services and their monetization. For example, in the UK, Energy Systems Catapult [2] is pioneering the idea of business models around electricity uses such as heating services.
- Innovations can also alter industry structure. A new industry structure might arise when new technologies lead to a change in the supply chain, with either new actors emerging or old actors becoming obsolete. For example, a peer-to-peer market in which prosumers trade electricity (Fuentes et al., 2023).

The first two types of innovation are more incremental (for instance they could result in improved efficiency), while the latter two are more transformative. This paper focuses on how the electricity industry is likely to be transformed due to the emergence of increasing digitalization (the third and fourth innovation types above).

When faced with challenging questions such as these, economists often tend to revert to key economic principles that can help characterize the effect in question. One of the main theoretical constructs to analyze this problem is transaction costs. Coase (1988) argued that transaction costs determine the organization of an industry. The criterion for organizing commercial transactions is assumed to be in two parts: minimizing production costs, and minimizing transaction costs. Due to big data and connectivity, transaction costs—such as search costs and bargaining costs (digital platforms), or policing or enforcement costs (blockchain)—can be drastically reduced. This raises the question of the impact this would have on the way the electricity sector is organized. We discuss this question in relation to industry structure, ultimate products, and pricing.

The traditional business model in the electric power sector is relatively straightforward. Utilities generate electricity and feed it into the grid, so that customers can consume it and pay for volume. In a stylized model, the organization of the electricity sector could be characterized around the following constraints. The industry structure is comprised of 1) a small number of players with 2) large assets. A large proportion of these assets remain 3) idle for long periods of time. The challenge is to minimize its operational costs by taking advantage of 4) economies of scale. Digitalization can relax some of these constraints.

First, digitalization can reduce barriers to entry which allow the participation of more players with smaller assets. For example, digital platforms can enable new markets by connecting smaller producers with buyers. Without the intermediation of these platforms, transaction costs would simply be too high for these actors to participate in such market. This change can transform the power sector into one based less on economies of scale, and more on a modular structure that can be scaled up or down in granular and additive steps. Technologies like blockchain can help observe, design, and tune the activity and signaling of each modular unit.

Second, digitalization can increase the flexibility of the entire system by enabling integration across the different parts, including supply and demand. Interoperability would allow the exchange of operational information in real time between equipment anywhere in the energy system, reducing inefficiencies, improving reliability, and lowering costs. What is different is that flexibility allows consumers and producers to respond instantaneously to changing market conditions. For example, when the energy price is too high, the demand for energy will reduce, which in turn would reduce not only prices but also quantities. If flexibility limits to infinitum, it could relax the constraint of having underutilized assets to meet peak load requirements that occur over very short periods of time throughout the year. In this way, digitalization can change the way in which grid maintenance costs are covered. If tariffs are set at the rate of return, having less capital expenditure would reduce overall tariffs. Also, digital grid-enhancing technologies could increase the utilization of existing capacity without putting operations at risk. This is important at a time when physically increasing capacity is becoming more difficult. However, this could raise new concerns around cybersecurity.

[2] Energy Systems Catapult, https://es.catapult.org.uk

Third, the electricity sector is organized upstream and downstream in segments of the value chain that follow the flow of power: generation, transmission, distribution, retail. The boundaries between these activities are clear. Digitalization can, however, blur the physical boundaries of this value chain (IEA, 2017). New segments could arise, such as prosumers, while others could emerge, such as aggregators. Since a firm exists to internalize transaction costs, the interplay of these two forces will determine the extent of vertical integration of the new electricity industry, which in all probability will be more fragmented as there are less transaction costs to absorb. But as digitalization also breaks down the boundaries of silos, for instance the boundaries between electricity and transport, this can lead to a new horizontal integration of firms, to take advantage of economies of scale.

A fourth element is that digitalization can redefine the ultimate products of the electricity sector and launch new ones (OEF, 2016). Economic theory establishes that transaction costs would determine what a firm should produce internally, and what it should purchase in the market. When transaction costs are negligible, buying rather than making (firms versus markets) will normally be the most effective means of procurement (Williamson and Masten, 1999). Observations of the effects of digitalization on other industries show that the value proposition of some new firms is to take out of the firm some activities that can now be standardized due to digitalization. Unbundling of a firm's activities can lead to an electricity sector where new firms offer hyper-specialized products and services.

In addition, digital data can be characterized as an externality, as everything an individual does in the digital space can be recorded, including shopping habits and the actual purchasing process: what was considered, and was left not to buy[3]. Data generation will continue to grow exponentially. On the upside, with so much data available, it is possible to design tailor-made products according to a variety of consumer preferences. On the downside, however, the market can become prone to demand discrimination. The same pattern applies to big data (aggregation) which can lead to tailor-made products, but also to demand discrimination (fragmentation).

The fifth element of this section is about costs and pricing. Digitalization shares the same cost structure with some renewables: large upfront costs, and negligible marginal costs afterwards. How to deal with close to zero marginal costs is problematic in economic theory. For instance, it can break down the criteria of profit maximization, where prices are equal to marginal cost. Having prices equal to zero is an anomaly though, as the role of prices is to signal scarcity. The zero marginal cost structure of digitalization is even more problematic. While the physical network is constrained by congestion, digital networks are not. This characteristic makes digital networks prone to network effects, which can lead to concentration and market power. A zero marginal cost service can therefore lead to an industry structure with market power.

3. Propositions

Based on the economic characteristics of digitalization, we put forward the following propositions.

Proposition 1: Digital transition will bring about a tension between fragmentation and aggregation in the value chain

Digital technologies such as blockchain can enable smaller actors to participate in the electricity market by lowering transaction costs and entry barriers. This would create market opportunities that were costly to undertake—or completely forbidden due to high transaction costs. This phenomenon will likely result in further fragmentation of the industry value chain, leading to a greater number of actors with narrower responsibilities. But in order to be profitable for a new player, these potential transactions need to be very frequent to compensate for limited revenue inflows. The emergence of new players with smaller units would require a third party coordinating their activity, perhaps through a digital platform. This new

[3] 'The world's most valuable resource is no longer oil, but data', *The Economist*, 6 May 2017. www.economist.com/leaders/2017/05/06/the-worlds-most-valuable-resource-is-no-longer-oil-but-data

entity would aggregate consumption and production of a group of customers and interact with the system operators in real time.

These new aggregators would create value by coordinating different groups of users. Aggregation in digital platforms takes place at the data layer. Low transaction costs in the virtual world make it possible to aggregate demand faster and more widely than players in the physical network industries (Montero and Finger, 2019). A digital platform can gain competitive advantage via efficiencies acquired with direct, indirect, and data network effects. A network effect is when the buyer's willingness to pay increases as the number of buyers or sellers for the business grows. If network effects are big, the winner captures the entire market. The consequence is that network effects can lead to concentration and market power in the emerging aspect of the electricity value chain. The paradox is that network effects would increase barriers to entry that were originally reduced in the early stages of digitalization.

In terms of the industry structure, an aggregator would reverse the initial granular fragmentation of the value chain by aggregating players. The extent to which this would occur depends on the marginal benefit compared to the marginal cost of aggregation for an individual agent. In any case, it will still fragment the sector, when compared to the original arrangement of the power sector, simply because there would be a new player in the value chain.

Proposition 2: Digitalization can lead to a modular electricity sector versus economy of scale

Digitalization is a virtual technology—it cannot be touched. Yet it can bring about changes in the physical infrastructure landscape. While the electricity sector was conceived to have large assets to achieve economies of scale (companies experience cost advantages when costs are spread over a larger amount of goods), digitalization empowers more modular electricity production.

Modular production permits smaller producers to enter the market without losing cost competitiveness. The implication is that economies of scale, achieved by increasing the size of firms, are no longer the ultimate necessary condition. Instead, the system can be transformed into a modular one where it can be scaled up or down. This could be done at a cheaper cost, as units are smaller; more quickly, as construction time is less for a smaller unit; and closer to the system's needs, as capacity changes are more granular. Perhaps the cost competitiveness comes not as a cost per unit, but because additions can be made at smaller scales, reducing capital costs.

Another characteristic of the electricity sector was that physical and economic signals travelled only in one direction, from generation to consumption. Connectivity, data, and automatic responses facilitate signals to travel in both directions, often referred to as flexibility.

The question that emerges is: what would the electricity sector look like if flexibility limits to infinitum? To begin with, there would be less need for excess capacity. The implication of this impact of digitalization is that the power sector can become leaner, with less excess capacity overall. On the upside, with a leaner capacity, tariffs can be reduced. On the downside, cybersecurity becomes a bigger issue, especially as there is less margin for error.

Proposition 3: Zero marginal costs requires new ways to price electricity services

The cost structure of digital technologies can be characterized by marginal costs that are negligible, while the entire production cost is effectively a fixed cost. Technologies with these characteristics are difficult to integrate into traditional markets designed for textbook supply and demand curves, which assume positive and increasing marginal costs. Having zero marginal costs is problematic because its economic meaning is one of abundance, rather than resource constraints. For example, in contrast to physical networks, which after a certain point can become congested or stop taking new users, digital platforms have more capacity, as the marginal cost of adding one more user can be close to zero, and the fuel used to run these platforms (that is, data) is a non-rival in consumption.

Neoclassical economic theory establishes that firms maximize profits at the point where marginal revenue equals marginal costs. In some cases, this is the point where price equals marginal costs. If the marginal cost is zero, prices should therefore be zero for the mathematical identity to hold. The economic intuition behind prices is that they should signal scarcity. A price equal to zero sends signals of unconstrained resource, which does not make economic sense, as resources are scarce by definition. The neoclassical criterion of profit maximization would break down. Does this mean that the neoclassical criteria no longer hold?

We argue that the neoclassical condition still holds, but the relevant scarce resource changes. Often, technological advances relax bottlenecks in production. If this argument is taken to an extreme, digital advances would reduce bottlenecks to almost zero, leading to the false conclusion that the sky is the limit. But resources are scarce by definition. In order to make neoclassical theory work, marginal costs have to be based on the scarce resource that is next in line, not the one that technology has made more abundant. This problem can be characterized as a two-step production function. In this type of function, in the first stage, inputs are transformed into intermediate goods, which are then used as inputs in the second stage to produce the final output. The total production cost is the addition of each step. Since the cost function is the inverse of the production function, the total cost is the addition of all costs, where only one has a marginal cost of zero.

The consequence is that volumetric charges can be replaced by transaction fees, marginal cost, commission, or subscriptions. Similar to a mobile phone contract, ways to price this type of function could be through subscriptions, or two-part tariffs where one component covers fixed costs and the other covers incremental production. With this cost structure, electricity could be traded in long-term fixed prices schemes that reflect the willingness to pay for access to reliability, which is the constrained resource.

Proposition 4: Digitalization leads to unbundling of products and hyper-specialization

One outcome of digitalization observed in other industries is the standardization of parts that are sold separately from the whole product. Take education, for example. As Spence (1973) notes, education serves the purpose of acquiring new knowledge, and signaling to the market other skills such as perseverance and networking. Digital platforms such as edX and Coursera[4] offer modules that are part of an MBA course, but that can be more suitable for standardization, such as programming in Python. In this way, a whole MBA can be commercialized in smaller pieces, focusing more on the skills and less on the signaling of experience that a full MBA conveys.

We also observe from experience in other industries that the value of some new products is the unbundling of an unwanted characteristic—the absence of something. Take the example of the food and beverage sector[5]. Ghost kitchens (also known as virtual or cloud kitchens) are an innovative solution to some challenges faced by traditional brick-and-mortar restaurants. A ghost kitchen is a commercial kitchen facility that operates entirely online and does not have a physical dining area for customers. This allows fragmentation of some of the diverse services a traditional restaurant offers. Since ghost kitchens do not have a traditional restaurant storefront, they can be set up in low-cost industrial areas and require less square footage than a traditional restaurant, resulting in significant savings on rent and utilities. Ghost kitchens also allow for greater flexibility in menu offerings, since they can easily switch between multiple concepts or cuisines without needing to invest in additional decoration. This flexibility can help restaurant owners to target different customer segments, experiment with new menu items, and respond quickly to emerging food trends.

An application of the same concept in electricity could be virtual power plants. A virtual power plant is a cloud-based system that aggregates the capacities of multiple decentralized power generators, such as solar panels, wind turbines, electric vehicles, and battery storage systems, to operate as a single, large-scale power plant. It allows utilities and grid operators to remotely monitor and control the power generated by a network of distributed energy resources to balance the electricity grid's supply and demand. In a virtual power plant, the distributed energy resources are interconnected through an

[4] edX, www.edx.org/; Coursera, www.coursera.org
[5] 'Unbundling McDonald's: How the traditional fast food industry is being disrupted', CB Insights, 2022. www.cbinsights.com/research/report/unbundling-mcdonalds/

advanced software platform that enables the seamless coordination and management of their electricity production, storage, and consumption. This technology allows utilities to have greater flexibility in managing the electricity grid, including responding to grid outages, fluctuations in demand, and changes in weather conditions. It can also help to reduce the need for expensive transmission and distribution infrastructure, which can be costly and challenging to build in certain areas.

Finally, as noted above, digitalization can unmask values and consumer preferences that were not possible to record. This can lead to better catering to consumer preferences, but it can also lead to demand discrimination which could reduce consumer surplus. Thus, regulation is important to ensure competition in those segments.

4. Co-evolution of the digital and decarbonization transition

This section analyzes the extent to which the above propositions are, or are not, in harmony with the economic features of decarbonization technologies. We will use the framework of co-evolution discussed in complexity theory by Mitleton-Kelly (2006) and van den Bergh et al. (2011); in economics by David (1985) and Arthur (1989); and in energy by Unruh (2000) and Foxon (2011) among others.

Two systems co-evolve when, while evolving, they each have a causal influence on each other's evolution—the more a technology is adopted, the more likely it is to be further adopted. In this case we refer to situations where aspects of the digital economy would reinforce or deter the decarbonization and transition, and vice versa. There are multiple entries for interaction between these two systems. When both transitions reinforce each other, both would have increasing returns. Four major classes of increasing returns tend to be identified in the literature: scale economies, learning economies, adaptive expectations, and network economies (Arthur, 1989). A possible outcome of the co-evolution of two systems is self-organization in which the interactions of both systems end up creating a new system.

Corollary 1: Transversal versus parallel sectors

Proposition 1 in section 3 states that digitalization would create conditions that tend to aggregate/disaggregate the value chain, both vertically and horizontally. Technological and economic features of renewables would reinforce this effect. Two outcomes can emerge as a result of this interplay. The first is that the emerging value chain would have a transversal (diagonal) structure. A second outcome is the emergence of a parallel structure where old and new industry structures co-exist.

Digital technologies can tackle bottlenecks of integrating renewable technologies into incumbent structures (for example, integrating wind power into the wholesale market), or they can enable the creation of an alternative sector independent of the incumbent structures (such as peer-to-peer markets). By coupling digitalization and renewable technological and economic features, a possible outcome would be the emergence of a parallel sector, where different market structures co-exist.

Distributed generation technologies, like solar photovoltaics, can bring about a sector with millions of producers (fragmentation). These producers, individually, would have negligible impact on the electricity market. However, if they were able to collude—act in unison—they could leverage their group position (aggregation). Now, negotiating with millions of other producers would be very costly and impractical without digitalization connectivity technologies. Connectivity permits a central coordinator to link, monitor, and control large numbers of individual energy-producing units and pieces of consuming equipment.

The forces of aggregation and fragmentation resulting from distributed decarbonization technologies are being implemented in a power sector that was previously monolithic and designed solely to meet demand. Behind-the-meter investments could therefore lead to the duplication of some generation capacity, which create formal and informal parallel markets. Households that install distributed energy resources can operate in both. They would see a shift in the supply curve to the right, as their capacity is added to the utilities' capacity, resulting in access to more electricity at lower prices. However, households without the means to install new technologies would see a shift in the supply curve to the left, as the cost of providing them with electricity would increase due to the reduced use of fixed-costs assets.

Throughout this process, centralized networks will continue to be the backbone supporting the transition, balancing the overall system. The fragmented part of the value chain would resemble perfect competition because of its number of participants, while the aggregation could be probably best characterized as a monopoly because of the network effects noted above.

Corollary 2: Hyper-specialization and non-zero marginal cost pricing

Renewables' zero marginal cost technological and economic characteristic would reinforce the consequences of digitalization's negligible marginal costs feature. Both effects push forward the argument for pricing services using memberships and two-part tariffs.

Without zero marginal costs, the market operates in the following way. Power generators offer different quantities of electricity at various prices. These bids are ranked from cheapest to most expensive. The market clearing price is set at the marginal cost of production of the last unit sold. Plants with marginal production costs that are lower than the market clearing price will enjoy profits above their marginal costs, which would contribute towards their fixed costs. The marginal plant, the last one needed to fulfil demand, will only be able to cover its variable operating and maintenance cost. Plants beyond this marginal plant will remain idle. This process is repeated at every t-time.

Having zero marginal cost, renewables have priority of dispatch. Renewable energy can generate power from resources that seem abundant (sun and wind). The question is, how to price a product when an increasing share of it comes from an apparently unconstrained resource. Prices would be zero or negative if the decarbonization transition is complete, which clearly is an anomaly. However, the average price of electricity needs to be higher than the average total cost of production to guarantee the deployment of new power capacity. Prices should reflect scarcity, and there is no such a thing as a free resource. Therefore, the source of scarcity must lie elsewhere and a new mechanism has to be designed to capture this.

Electricity is a multifactorial good (Fuentes-Bracamontes, 2016). Renewables cannot produce all these electricity services, but only some of them—for example, zero emissions but not reliability. Thus, to discover this scarcity, markets that incorporate technologies with negligible short-term marginal costs require parallel markets with positive marginal cost. In this case, whereas the energy market is priced based on the cost of production, reliability has its own intrinsic supply and demand, that is, capacity is needed until the point where its marginal costs equal its marginal value (avoiding capacity shortage). Therefore, one can think of the electricity sector as a fragmented sector, one part providing energy services and the other part providing reliability via installed capacity. In addition, a flexible customer may not necessarily require a supply that is 100 per cent reliable. Big data can help identify such customers, who would be willing to accept lower reliability subject to a price compensation. By embracing the idea of economies of flexibility, as opposed to economies of scale that bundle together flexible and fixed demand (Li, 2020), flexible customers are empowered to leverage their ability to negotiate the best deals and freely adapt to intermittent generation without being hindered by passive demand. This resembles the hyper-specialization consequence of digitalization in other industries such as Fintech (Gomber et al., 2018) and Fast Food (CB Insights, 2022).

5. Policy implications

Section 4 assumes that once the economic mechanisms of each transition are identified, the industry structure, firms, and products and processes will respond organically to their consequences. However, policy making often involves intervening in the system to achieve a specific outcome. This section examines the extent to which the framework of analysis proposed in this paper can shed light on key policy questions. This point is illustrated by analyzing the electricity market design proposals currently under discussion in the UK and the EU through the lens of the above propositions and corollaries.

The UK and the EU have called for a consultation on market design (BEIS, 2022) to address an energy crisis characterized by high electricity prices, insufficient decarbonization, and high dependence on fuels supplied by unreliable partners. There are two opposing views regarding market design.

One side argues that the microeconomics of the current electricity market design is fit for purpose to address these policy issues, and all that is needed is to allow markets to perform their function, which means accepting periods of volatility and high price levels. The problem does not reside in the economics of market design but in the politics.

The other view takes a stance on completely redesigning the market, with some radical approaches. For example, some propose the creation of two markets, one for electricity 'as available' (variable/zero marginal cost/renewables), and one for electricity 'on demand' (firm/increasing marginal cost/thermal) (Keay and Robinson, 2017). In the same spirit, other authors propose a separation between financial and physical markets, or ways to insulate retail markets from wholesale markets (Grubb et al., 2022), which would decouple short-term electricity prices (efficiency) with long-term signals (investment/decarbonization), or decouple electricity prices from the price of gas.

In all these radical proposals, the common denominator is splitting markets in time or space. Specifically, the two-market proposals are in essence another way to fragment a once-consolidated market and to create parallel markets. The idea is to eliminate price cannibalization between energy sources with different cost structures, namely the zero marginal cost problem. The 'as available' market will be traded by long-term contracts. Our proposition of pricing using subscriptions follows the same logic of detaching the time variable of electricity consumption from prices by making time lags more pronounced.

In this fragmented market, consumers can actually operate in both markets, which is aligned with our corollary of having co-existent structures and parallel markets. Having two markets would provide strong incentives for demand-side flexibility: the price differential between the two would provide arbitrage opportunities for technologies able to shift demand in time. When consumers shift from one market to another, they would also be revealing their preference for flexibility. If this flexibility tends to infinitum due to advancements in digitalization, the 'on-demand' market would become the residual market. They would change from being parallel markets to sequential markets. Since this approach presents a radical way of understanding electricity markets, a wide range of crucial design questions still need to be addressed. Any feasible reforms cannot ignore the foundations of these propositions and their corollaries, and cannot be at odds with the technological inertia of transitions.

6. Conclusions

The future of the electricity sector will be characterized by complex and dynamic changes that will require innovative solutions. This paper seeks to conceptualize the interactions between the energy transition and the digital transition in the electricity sector. Overall, the digital transition will lead to a more efficient and flexible electricity sector, but will require careful consideration of its implications for the industry structure and pricing mechanisms. Digital technologies can also enable new energy ecosystems, help innovate business models, and accelerate the energy transition itself.

Based on a transaction cost approach, we offer insights in three areas: industry structure, ultimate products, and pricing. The digital transition in the electricity sector will lead to a vertical fragmentation in the value chain, but also to horizontal integration with other sectors such as transport. While digitalization may increase fragmentation and market power in the value chain, it can also create new opportunities for smaller players, and reduce excess capacity. Additionally, new smaller players are expected to enter the market, competing in a modular fashion rather than based on scale. This may lead to competition in some segments, while others may be prone to increased market power. Digitalization can redefine the ultimate products of the electricity sector, launching new ones, but since some segments may have zero marginal costs, this would require a new approach to pricing and packaging.

Digitalization and decarbonization technologies can interact and co-evolve to create new systems that can further transform the energy sector. We use the framework of co-evolution to analyze the potential outcomes of this interaction, and suggest two corollaries. The first corollary discusses how the interaction between the two technologies can lead to the emergence of a transversal or parallel value chain structure. The second focuses on hyper-specialization and non-zero marginal cost pricing, and suggests that the zero marginal cost of renewable energy would require a new mechanism to capture scarcity sources.

This framework can help analyze relevant policy questions such as the consultation on electricity market design in the UK and EU. The framework aligns well with the proposal of a two-market approach that would encourage demand-side flexibility and incentivize firms to create hyper-specialized products.

This paper argues that digitalization has the potential to revolutionize the electricity sector by disrupting its existing industry structure, enabling new products, and ultimately improving overall industry performance. A pertinent question that needs to be addressed in future research is the reverse question: whether there are certain industry structures and legacies in terms of regulation and infrastructure that facilitate or hinder digitalization. As the electricity sector continues to evolve and integrate digital technologies, it is critical to consider how industry structures can either support or impede innovation.

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