Mapping Innovation in Electricity: A startup approach

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Systematically Mapping Innovations in Electricity Using Startups

Abstract

Technology innovation is recognized as one of the main enablers of sustainable development and the transition towards a low-carbon future. Anticipating innovation trajectories could help decision-makers develop new capabilities to take advantage of incremental and disruptive innovations. This paper maps the current innovation that is taking place in the electricity sector using a bottom-up approach by analyzing the value proposition pursued by startups worldwide.

We compiled a database of 320 startups whose focus is the electricity sector. We classified these startups according to their business propositions in the context of megatrends disrupting the electricity sector. From analyzing this dataset, we find the following. Photovoltaic generation (PV) is the primary technology for decarbonization. Innovation within PV focuses on developing more resistant materials, panels that are easier to install, or maintain. These innovations do not need an updated regulatory-market structure of the industry to be deployed. Digitalization is the key disruptive/breakthrough innovation. It has the potential to reshape businesses and the regulatory-market structure. Storage technologies can be very disruptive for the power sector, but the innovation we observe in storage technology is incremental. This includes batteries that last longer, that charge in shorter periods of time, or that use other less expensive raw materials, or more energy density—more kilowatt-hours per kilogram.
Highlights

- We compiled a database of 320 startups whose focus is centered on the electricity sector.
- We find that Photovoltaic generation (PV) will be the primary technology for decarbonization.
- Innovation within PV focuses on developing more resistant materials and panels that are easier to install or maintain.
- These innovations do not need an updated regulatory-market structure of the industry to be deployed.
- Digitalization will be the key disruptive/breakthrough innovation in the electricity sector as it has the potential to reshape businesses and the regulatory-market structure.
- Storage technologies can be very disruptive for the power sector, but the innovation that we observe in this technology is more incremental than radical.

Keywords

Innovation, Startups, Renewable, Solar PV, Storage, Digitalization, Climate Change
1. Introduction

Technology innovation is recognized as one of the main enablers of sustainable development, the transition towards a low-carbon future and economic growth (Crossan & Apaydin, 2010). Many startups are increasingly focused on developing clean energy technologies. Investors are willing to take risks in these enterprises because of their high growth potential and ability to mitigate climate change. Anticipating innovation trajectories could enable decision-makers to develop new capabilities to take advantage of incremental and disruptive innovations (Kipper, 2021). This paper aims to map innovations and business transformations in the electricity sector using a bottom-up approach.

Many studies have tried to identify technological trends using patent citations (Gress 2010; Li et al. 2011; Yoon et al. 2011; Jun and Park 2013). Other studies have tried to map innovations by statistically reviewing the available literature on the technologies of interest (Faber et.al, 2019; Dall-Orsoletta et. al. 2022). Although entrepreneurs, investors, and companies are well positioned to convert promising technologies into commercially successful products and services, few studies have focused on their business value proposition. We fill that void by analyzing actual innovations originated by startups worldwide in the electricity sector.

A startup is a firm in its early phases but with the possibility of substantial growth. These firms usually transform new ideas into commercially viable technologies. Many startups work in digitalization and consumer products (Colombo and Piva 2008) and increasingly on clean energy technologies, as tackling climate change provides these technologies with high growth potential (IEA, 2021).

One of the main contributions of this exploratory study is the systematic and transparent collection of data and its organization. We compiled a database of 320 startups whose focus is the electricity sector to lay out the evolution of innovation and trace major turning points within this sector. We classified these startups according to their business propositions in the context of megatrends disrupting the electricity sector (Shipworth 2017). The megatrends that we identified are decarbonization, digitalization, decentralization, and electrification. We also classified these startups based on their specific technological domains. We then anticipated their impact on the electricity sector should their business succeed. The collection of startups was compared against key conceptual frameworks of innovation found in the literature. The result is a map of innovation that symbolically position technologies horizontally in reference to one another and vertically against some technological features within the same domain.
This exercise allowed us to put forward hypotheses based on novel knowledge to define new lines of research, business strategies and policy measures. After analyzing this dataset, we put forward the following propositions:

- The future of electricity will be decarbonized and digital. Specifically, solar, artificial intelligence (AI), and energy storage will be the disruptive/new technologies in the electricity sector.
- Photovoltaic generation (PV) is the key technology that will be used in decarbonization efforts. Innovation within PV focuses on product innovation, such as sustained innovation, more resistant materials, easier-to-install systems, increased output, and simpler systems to maintain using the current business model without the need to change the regulatory-market structure of the industry.
- Digitalization is the crucial disruptive/breakthrough innovation. It is a new technology in search of applications in the electricity sector. As such, it has the potential to reshape businesses and the regulatory-market structure. Digitalization trends ‘animate’ markets by reducing the barriers to participation, connecting buyers and sellers through platforms, and decreasing inefficiencies. The regulatory-market structure of the electricity sector needs to be updated to accommodate digitalization.
- Storage technologies can be very disruptive for the electricity sector, but the innovation we observe in storage technology is incremental (problem well defined, domain primarily defined). Storage includes batteries that last longer, charge in shorter periods, or use other less expensive raw materials.
- Many innovations assume a more distributed power system and associated regulatory-market framework.
- Although fewer in number, there are innovative applications in electric vehicles and thermal applications at the home level (heating/cooling).

The paper is organized as follows. The first section discusses the methodological challenges and steps we followed to construct the database and derive insights in more detail. The second section establishes the theoretical framework of our analysis. The third section presents our key results. In the fourth section, we benchmark our results against the innovation gaps we identified to help facilitate the energy transition. The last section summarizes our findings and concludes.

### 2. Materials and Methods

Anticipating future technologies requires both quantitative and qualitative approaches. For instance, many technological forecasts use qualitative methods such as Delphi, which consists of surveying a panel of experts to arrive at a group opinion (Mitchell 1992; Yun et al. 1991). Other studies use quantitative models (see, for example, Indukuri et al. (2008), Jun et al. (2010), Jun and Uhm (2010), applying simple statistics and graphical approaches
(Jun, et al. 2012). This paper uses both quantitative and qualitative approaches, as detailed below.

Databases are used as objective data for technology forecast models and future scenarios (Bengisu and Nekhili 2006). In light of this, we compiled a multi-regional database of 320 startups from 36 countries that focus on new technologies in the electricity sector (see the appendix for the list of countries). To reach these 320 startups, we performed internet searches with neutral keywords such as “startups,” "electricity,” and “innovation.” Internet searches have been used in the literature to build databases (Agrawal et al. 2002; Blair et al. 2002; Brophy and Bawden 2005). We used four languages for these searches: English, Arabic, Chinese and Spanish. To reduce biases, we avoided searching for specific technologies. The searches returned companies referenced in newspaper articles, received public or venture capital funding, won competitions, or were acknowledged by industrial bodies as firms to follow. We then verified the existence of these companies by visiting their websites and Twitter accounts, which were also recorded in the database.

From these searches, we constructed the database by recording the self-description of the startups’ business models. We benchmarked these descriptions against four consensus megatrends in the electricity literature (see Table 1). Some of these firms could fall into more than one megatrend, but we select the dominant or more relevant one for each business case.

**Table 1. Megatrends in electricity, based on startup innovation**

<table>
<thead>
<tr>
<th>Trend</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decarbonization</td>
<td>This megatrend pertains to carbon and other greenhouse gas emissions reductions in the electricity sector. It includes efforts that decouple electricity production or consumption from carbon emissions.</td>
</tr>
<tr>
<td>Digitalization</td>
<td>This megatrend applies IT and other digital technologies developed outside the industry to the electricity sector. Current applications employ artificial intelligence and newly created data to enhance efficiency in processes, but also developing of new products and services and the emergence of new players in the industry.</td>
</tr>
<tr>
<td>Distributed</td>
<td>This megatrend refers to technologies that challenge the concept of a vertically integrated sector. Instead, they develop the possibility for geographically distributed producers and consumers using locally produced electricity.</td>
</tr>
<tr>
<td>Electrification</td>
<td>The use of electricity in economic sectors traditionally consumed other fuels such as gasoline and heating oil.</td>
</tr>
</tbody>
</table>

Source: Shipworth (2017)
We then categorized the startups’ specific technological focuses based on their self-description (see Table 2). Some startups may combine one or more technologies. Schnaars et al. (2008) argue that technological convergence happens when two or more different technologies combine to create an entirely new product and market. In our case, we record if the startup relies on more than one technology to achieve its value proposition. For instance, some startups use PV solar plus batteries or focus on electric vehicle (EV) batteries, EV networks, or the coupling of artificial intelligence and renewable sources.

Table 2. Technological Domains used to classify electricity startup innovation

<table>
<thead>
<tr>
<th>Circular economy</th>
<th>Digital Platforms</th>
<th>Artificial Intelligence</th>
<th>Solar PV</th>
<th>Services</th>
<th>Comfort</th>
<th>Buildings</th>
<th>Local energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Data</td>
<td>Electric Vehicles</td>
<td>Storage</td>
<td>Blockchain</td>
<td>Water</td>
<td>Alternative generation</td>
<td>New fuels</td>
</tr>
<tr>
<td>Geothermal</td>
<td>Transmission</td>
<td>Wind</td>
<td>Other renewable</td>
<td>Smart meters</td>
<td>Storage aviation</td>
<td>Hydrogen</td>
<td>Solar plus batteries</td>
</tr>
<tr>
<td>Demand management</td>
<td>Microgrids</td>
<td>DER</td>
<td>Nuclear</td>
<td>Fossil</td>
<td>New fuels</td>
<td>Efficiency</td>
<td>IoT</td>
</tr>
<tr>
<td>EV- Storage</td>
<td>Ocean</td>
<td>Biomass</td>
<td>Gas</td>
<td>Low voltage</td>
<td>EV-Digitalization</td>
<td>Robotics</td>
<td></td>
</tr>
</tbody>
</table>

We then anticipate startup technologies’ impact on the sector, assuming they are successful. For example, if innovation focuses on lowering the cost of PV solar, *ceteris paribus*, there would be more deployment of PV solar. We assigned keywords to our database that capture these impacts.

We used these keywords to perform text clustering and word cloud analysis. We conducted text clustering analysis using patent titles because they contain information that represents product-level technological fields (Zamir et al. 1998; Koller and Sahami 1997).

To analyze the nature of each startup’s innovation, we match their self-description with the theoretical framework discussed in the literature review. For example, we classify each startup according to whether its business case is focused on product, process, business model, or industry innovation (OECD 2005). We also categorize them using the framework proposed by Chesbrough (2003), which focuses on whether problems and domains are well-defined. We do the same with the framework proposed by Pisano (2015), which focuses on whether there is an existing technology or business model.

The classification of some entries was straightforward. The use of more resistant materials is an example of product innovation in PV solar. Process innovation occurs when a new technology is available to perform a common task. For example, using artificial intelligence or big data to forecast electricity demand, which many firms already use, can improve...
accuracy. In other cases, however, the classification was not straightforward, and we needed to adjust the framework. For instance, rather than using the label “new marketing method” proposed by the OECD, we use the umbrella of “business innovation.” This category includes marketing, new ways to deliver services, and financial innovation in service delivery, i.e., pay-as-you-go for PV solar. We also reinterpreted the OECD’s label “new organizational method” as innovations that have the potential to change the sector’s structure. For example, electricity services traded on platforms are a new element in the industry.

A single startup could be classified in multiple ways (the OECD has four options, Chesbrough two and Pisano three). We analyzed these classifications to arrive at a clearer view of technological trends and be able to make comparisons between them.

2.1 Limitations

Our approach has several limitations. Perhaps the main limitation is that it is impossible to know the universe of startups worldwide, and therefore, our analysis cannot be interpreted as a statistical representative sample of startups, but a convenience sample. The viability of this type of sampling depends on the particular research question and the population of interest (Bhutta, 2012). In general, it is an acceptable tool when research is exploratory (Faugier & Sargeant, 1997; Penrod, Preston, Cain, & Starks, 2003). However, there are inherent biases when using this tool. For instance, using internet searches limits participants to those detected by the Google algorithm. Specifically for this problem, we tried to circumvent this potential bias by expanding the languages of search to four of the most widely spoken languages in the world. However, we are potentially omitting startups from leading innovator countries like Germany, Japan or South Korea that may have startups that are only publicized in their native languages. Still, our approach is a systematic and transparent search that can be refined in future work, for example if this search is replicated in subsequent years.

Another limitation that may impact the way how we identify trends is that we give each startup the same weighting. For instance, we do not weigh them by their funding. There are pros and cons to this decision. Perhaps the startups that received more funding had more promising ideas. However, investors could also be backing energy startups to balance their investment portfolios across sectors. Alternatively, venture capitalists could also be interested in acquiring part of the technology to be used for something else and not for the end use that startups propose. A deeper analysis would be needed to analyze the weighting of specific startups, and we suggest that this could be the subject of future research. Nonetheless, by giving startups the same weighting, we are able to establish potential trajectories or trends in innovation that could eventually come to fruition, which is the objective of this paper.
Successful startups not only depend on the development of improved technologies but also on factors such as managerial skills, better strategies, good timing, and perhaps changes in society’s preferences. It is, therefore, possible that some startups will not cross the valley of death not due to their technological potential but because of inadequate management, insufficient funding, or even bad luck. Our approach does not capture these factors. Still, our underlying assumption is that the more startups focus on specific technologies, they will likely become the industry standard.

Another limitation is that some technologies can be used in combination. To keep things simple, we do not analyze any potential technology combinations. This strategy helps us to have a consistent narrative about how the future of electricity might unfold at the cost of a less accurate prediction. By the same reasoning, we do not analyze the potential innovation that would occur with the interaction between startups and incumbents. Of course, incumbent firms also improve their value proposition through innovative products and services.
3. Literature Review

Two clear research streams frame our research question. The first is how to categorize innovation and technologies, and the second concerns the role of startups and other players in the innovation process.

3.1 Innovation Categorizations and Mappings

Innovation is a continuous process that helps companies to develop products and processes. The goal behind innovation is to increase productivity or commercial performance, such as improvements in product quality or increased production capacity (OECD 2005).

Innovation can be classified into four types according to the outcome (Kleinknecht and Reijnen 1993):

1. An improved product or service.
3. A new marketing method.

Other innovation indicators could be product components, products and services, and infrastructure. Chesbrough (2003) another classification. The author notes that commercial research results may vary depending on whether or not the problem and the technological domain are well-defined. Thus, the author proposes a two-by-two matrix with three entries to categorize innovation, as shown in Table 3.

Table 3. Types of innovation according to the problem and technological domain

<table>
<thead>
<tr>
<th>Problem</th>
<th>Well defined</th>
<th>Not well defined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well defined</td>
<td>Sustained innovation (PV solar panels)</td>
<td>Disruptive innovation (digitalization-blockchain)</td>
</tr>
<tr>
<td>Not well defined</td>
<td>Breakthrough innovation (decarbonization storage)</td>
<td>Blue sky</td>
</tr>
</tbody>
</table>
For this paper, we reinterpret Chesbrough’s framework in the following way. We say a problem is well defined when the objective is unequivocally clear. For instance, decarbonization aims to reduce emissions, in line with the Paris Agreement’s objective to keep the global average temperature increase to 1.5 degrees Celsius above pre-industrial levels by 2050. Another megatrend is the electrification of those sectors that currently use another energy source. Motivations for electrification include carbon footprint reduction, new advantages for consumers, or decreased costs. The objectives of some specific technologies are also evident. For instance, solar technologies need innovation to produce more electricity, to make them easier to install and maintain, or to produce more resistant materials. Chesbrough (2003) argues that innovation is only possible when the domain and the problem are well-defined.

Chesbrough (2003) contends that disruptive innovation occurs when the problem is not well-defined, but the technological domain to solve it is. For example, digitalization technologies, including artificial intelligence and blockchain, were not explicitly designed for the electricity sector but are generic technologies in search of applications. In contrast, Chesbrough (2003) observed that breakthrough innovation occurs when the objective is definite, but the domain is not. Energy storage technologies could be a good example of this. Although the objective of energy storage is clear – we want storage technologies, either portable or stationary, that charge faster, last longer, are cheaper, etc. – it is as yet unclear which technological domain this can be realized in, i.e., there is not yet a dominant technology. While Chesbrough does not examine the case where neither the problem nor the domain is well defined, we label these cases "blue sky innovation.” We observe some of these cases in digital technologies.

Another innovation categorization was developed by Pisano (2015). He builds on Chesbrough’s work and proposes a taxonomy that includes whether technical competencies (i.e., whether there is a proven technology) and business models exist for new technologies.

The existence of business models and technical competencies are partially addressed in Chesbrough’s classification. Pisano examines whether the processes to deliver a service or sell a product exist in the electricity sector or elsewhere. For example, some technological innovation is focused on using alternative ways to generate electricity at the utility scale, i.e., the electricity would be sold either by a utility or in the wholesale market. The business model already exists and is independent of the new technology. However, there could be some cases where technology innovations force entire industries to redefine their products and services and how they monetize them. In such cases, the business models do not yet exist.
The combination of business models and technologies leads to the classification in Table 4.

Table 4. Taxonomy of business models and innovation

<table>
<thead>
<tr>
<th>Technical competences</th>
<th>Business models</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>Existing</td>
<td>Not existing</td>
<td></td>
</tr>
<tr>
<td>Routine innovation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not existing</td>
<td>Radical innovation</td>
<td>Disruptive innovation</td>
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</table>


Pisano conceptualizes routine innovation as that which permits existing technical competencies to be used in an existing business model. A radical innovation, however, is when a firm operates within an existing business model but has to develop new technical competencies (Gomber, et. al., 2018). The author does not consider the case where technical competency exists, but there is not yet a business model. This technology might work but is waiting to find a market or demand.

3.2 Entrepreneurship, Market Structure, and Innovation

A startup is a newly created company searching for a repeatable and scalable business model (Blank 2010; Spender et al. 2017), which is more likely to develop product innovations and register more significant innovation than established firms (Criscuolo et al. 2012).

The nature of startups has essential implications for our analysis. For instance, we expect startups to concentrate on technologies at the early stages of development and less on more mature technologies like transmission, natural gas, coal, or wind. We also expect that startups focus more on technologies that have the potential to disrupt industry structure than incumbent firms (Johnson et al. 2008; Girotra and Netessine, 2013). Thus, our findings can be framed within the sustainability transition literature that focuses on how initial technological niches emerge into market niches and then toward regime shifts (Kemp, Schot, and Hoogma 1998; Schot and Geels 2008). Our analysis of startups focuses on their bottom-up approach – more atomized, small-scale, and entrepreneurial in their approach to innovation – as opposed to the top-down approach of large, well-established firms.

The regulatory framework in which new businesses and technologies also operate matters since, in the electricity sector, regulations determine, to a large extent, permissible business models. Cambini et al. (2016) analyze the impact of deregulation on innovation on existing technologies. They find that new patent applications are filed soon after deregulation and that these patents are directed at reducing vertical integration. Nesta et al. (2014) investigate the effect of environmental policies on innovation under different levels of...
competition. The authors find that renewable energy policies enable green innovation in liberalized energy markets.

This conclusion is in line with the ‘Porter hypothesis’ (Porter and Van der Linde 1993), which challenged the traditional view of environmental regulation. It stipulates that requiring firms to reduce an externality like pollution was akin to increasing costs and thus reducing their profits. Porter and van der Linde (1995) argue that well-designed regulation could enhance competitiveness. Stricter regulation is needed to motivate additional innovation to satisfy new regulations cost-effectively. After all, if there are profitable opportunities for reducing pollution, profit-maximizing firms would already be taking advantage of them. Regulation would also signal promising areas for research and development, which, in turn, would de-risk such R&D investments.

4. Results
This section reports statistics and visuals from our analysis of the startups' database. These statistical metrics help us map innovations in the electricity sector.

4.1 General Results
The clearest trend shown by our analysis is that innovations in the electricity sector focus on decarbonization and digitalization (see Figure 1). The electrification of traditionally non-electric sectors is separate from a significant share of the startup innovation pipeline. However, this megatrend is arguably the most recent of the four (Cleary 2019).

Figure 1. Startup count by megatrend

Source: Fuentes et al. (2022)
More specifically, if the innovation pipeline materializes, the dominant new technologies will be in PV solar, storage, and AI (please refer to Table 4 for the definitions of technological domains and see Figure 2).

**Figure 2. Startup count by area**

![Figure 2. Startup count by area](https://ssrn.com/abstract=4367325)

Source: Fuentes et al. (2022)

### 4.2 By megatrend

In this section, we delve into innovation developments within specific megatrends.

#### 4.2.1 Decarbonization

Of 129 firms with a clear focus on decarbonization, we found that 35% of firms focus on PV solar (see Figure 3). This percentage represents the most significant focus on renewables,
with 11% of firms developing wind technologies and 10% on other general renewable technologies like biomass and hydropower. This finding is in line with the theory that incumbents are more likely to focus on incremental improvements to well-established technologies than startups (Johnson et al. 2008). For example, we would not expect much startup activity in technologies such as nuclear or transmission. This expectation is corroborated by the fact that only eight startups in our database focus on transmission, and only one focus on nuclear. Five focus on using new fuels, such as hydrogen, decarbonized gas, or biofuels, and seven focus on completely alternative generation methods, such as hybrid hydro-wind technologies.

**Figure 3. Where do firms focused on decarbonization concentrate their efforts?**

![Bar chart showing distribution of firms focused on decarbonization](https://ssrn.com/abstract=4367325)

Source: Fuentes et al. (2022)

**4.2.1.1 Domain: PV solar**

As mentioned, PV solar is the critical technology for decarbonization in the startup space. Innovations within PV concentrate primarily on product innovation (OECD 2005) or sustained innovation (Chesbrough 2003).

Sixty percent of the innovations improve one aspect of PV. These are incremental or sustained innovations, as defined by Chesbrough and Pisano, respectively. Most of these startups can operate within well-known business models that do not need new regulations. Some examples include improving materials, such as fire-resistant materials, lighter components, and more efficient materials. Startups also concentrate on improving the installation, maintenance, and operations. For example, they aim to make panels easier to install and standardize components. They also aim to increase the energy productivity of solar panels, for example, by improving solar tracking. Some startups develop more innovative business models, such as ‘solar-as-a-service’ and intelligent platforms to integrate distributed generation. They also aim to reduce information asymmetries by bringing together consumers and producers. Some startups also pair solar with other
technologies such as storage and artificial intelligence. Table 5 summarizes the focus of innovation in solar and provides some examples.

<table>
<thead>
<tr>
<th>Table 5. PV solar innovation focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>Materials</td>
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<td></td>
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<tr>
<td>Maintenance</td>
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<tr>
<td>Business model</td>
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<td></td>
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<tr>
<td>Output</td>
</tr>
<tr>
<td>Localization</td>
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<tr>
<td></td>
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</tbody>
</table>

Source: Fuentes et.al. (2022)

4.2.2 Digitalization

Digitalization seems to be the key disruptive/breakthrough innovation within the power sector because it is a new technology in search of applications. Digitalization is probably the most disruptive megatrend. It can change the industry structure because the technology incentivizes disintermediation. For example, households could trade electricity between themselves using blockchain technologies. It also allows smaller businesses to enter the market as their capital needs are lower than other energy ventures. This trading would create a more atomized electricity sector in terms of the number of companies participating (KAPSARC 2016).

Digitalization startups have the potential to reshape business and sector innovation. If successful, these startups would ‘animate’ markets (Thomas 2018) by connecting buyers and sellers through platforms. However, current regulations need to be updated for some applications, such as network tariff design, to allow for peer-to-peer transactions. We identified 82 firms within the digitalization megatrend. Artificial intelligence is the dominant
technology for startups, with 27 firms using it. This number is almost double the concentration of firms innovating in other domains, including data mining and recording (13 firms), digital platforms (13 firms), and blockchain technology (8 firms) (Figure 4).

Figure 4. Startups focused on digitalization work in the following areas.

Source: Fuentes et al. (2022)

4.2.2.1 Domain: Artificial Intelligence

Artificial intelligence technologies focus on optimizing operations and increasing efficiencies. About 37% of AI applications focus on balancing the grid, which can be done by forecasting supply and demand more accurately using granular data. Applications also monitor line faults and speed up repairs. Some AI technologies enable EVs to operate as virtual networks. Another important area AI facilitates is demand response and the flexibility it brings to the market. Finally, planning of investments is another area where AI can use granular and abundant data to improve demand forecasting. Eleven percent of firms have this focus.

These applications can be considered business-as-usual activities performed with novel technologies that deliver better results. Perhaps the most innovative aspects of AI are its ability to enable markets by improving trading opportunities and creating markets by intermediating supply and demand. AI applications also help facilitate more distributed energy, especially in homes. These applications would enable homes to perform activities that used to be the traditional functions of utilities. Table 6 summarizes these findings.
Table 6. Primary applications of artificial intelligence by startups

<table>
<thead>
<tr>
<th>Item</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>AI to balance grid</td>
</tr>
<tr>
<td></td>
<td>Monitor and repair flawed lines</td>
</tr>
<tr>
<td></td>
<td>EVs as virtual grid</td>
</tr>
<tr>
<td></td>
<td>Optimization</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
</tr>
<tr>
<td>Demand response</td>
<td>Facilitate demand management</td>
</tr>
<tr>
<td>Planning</td>
<td>Predictive software for planning</td>
</tr>
<tr>
<td></td>
<td>Improved forecasting tools</td>
</tr>
<tr>
<td>Market enabler</td>
<td>To improve and facilitate trading</td>
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<tr>
<td></td>
<td>Market creation</td>
</tr>
<tr>
<td></td>
<td>Intermediary</td>
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<tr>
<td></td>
<td>Platforms</td>
</tr>
<tr>
<td>Optimization</td>
<td>Less waste</td>
</tr>
<tr>
<td></td>
<td>Lower costs</td>
</tr>
<tr>
<td>Local energy</td>
<td>Cloud-based asset management</td>
</tr>
</tbody>
</table>

Source: Fuentes et al. (2022)

4.2.3 Distributed

Energy storage is by far the most dominant technology in the distributed megatrend, with 43% of firms within the distributed energy space developing this technology (see Figure 5). Energy storage is followed by other technologies that facilitate the use of distributed energy and microgrids. See Figure 6 for more details.

**Figure 5. Areas pursued by distributed energy-related startups.**

Source: Fuentes et al. (2022)
4.2.3.1 Domain: Storage

Although storage technologies can be very disruptive for the power sector, as they would allow the decoupling of supply from demand, innovation within storage startups seems incremental (the problem is well defined, and the domain is defined chiefly). For example, startups are developing batteries that last longer, charge faster, and are cheaper. Some innovation in storage technologies experiments with new materials, which would help reduce the storage cost, enhance its life, and improve charging and discharging times. These technologies facilitate the integration of renewables into the grid by reducing the problem of intermittency.

4.2.4 Electrification

Within electrification, the dominant trend is the transition to the electrification of cars (EVs), buildings and heating (see Figure 6). Most innovations within this megatrend are a combination of technologies, and EVs are usually paired with storage. The electrification of heating (a comfort market) is usually combined with digitalization and data to understand household behavior to improve comfort and lower costs.

Figure 6. Electrification is focused on the following areas.

Source: Fuentes et al. (2022)

Fifty-four percent of startup electrification efforts are associated with EVs. The innovations focus on the intersection between storage and batteries, networks (charging and discharging), AI (when to charge), and connectivity, as illustrated in Figure 7.
4.3 Types of Innovation
Seventy-nine percent of startup innovation focuses on improving products (e.g., more resistant materials, lighter materials, more output per unit) or existing processes (e.g., forecasting demand with more potent statistical capabilities using more data). Fifteen percent of businesses combine some elements of innovative business models (the way services are delivered or repackaged), and even fewer, 5%, have the potential to change the industry structure (adding new elements to the value chain) (Figure 8).

Figure 8. Startup value propositions fall into these categories.

Source: Fuentes et al. (2022)
Figure 9 reinforces the idea that startups focus mostly on incremental innovation.

**Figure 9. Most startups focus on sustained innovation**

![Bar chart showing the distribution of startups focusing on sustained, disruptive, and breakthrough innovations.]

Source: Fuentes et al. (2022)

Most startups focus on sustained innovation. We find that most startups have defined technologies and look for applications. From our observations, only 5% base their value proposition solely on an innovative business model (see Figure 10).

**Figure 10. Categorization of startups (per Pisano)**

![Bar chart showing the distribution of startups focusing on routine, blue sky, radical, and disruptive innovations.]

Source: Pisano (2015); authors.

Twenty-seven percent of the innovation in decarbonization and distributed technologies focuses on the combination of product (OECD 2005) and sustained-routine (Chesbrough 2003) innovation, as defined in the methods section, i.e., improving one technological factor or making incremental innovations.
The largest share of digitalization startups (43%) focus on business model innovation, and these are disruptive (the same technology is applied to different problems) and ‘blue sky’ models. Digitalization is also used to make processes more efficient, with 18% of the startups surveyed focusing on this area. These startups perform an existing activity, like forecasting demand, but in a more optimized way. The most significant focus of electrification startups is on process-sustained routine, according to the classification used in OECD (2005), Chesbrough (2003), and Pisano (2015) (see Figure 11).

**Figure 11. Firms by business model**

Source: Fuentes et al. (2022)

### 4.4 Validation of results

This section discusses the extent to which our approach to map innovations in electricity is valid. A map is a simplification of reality. Its objective is to give a sense of direction. A source of validation is, therefore, the extent to which a map is helpful for the purpose it was created. In this case, the research problem is to identify those key technologies that are transforming the power sector to help decision makers to plan accordingly and take full advantage of these changes.

Mapping is an operation that associates elements of a given set in one domain with one or more elements from a second dimension. We map four megatrends in the innovation ecosystem and their corresponding technologies, and assess their importance in relative
terms, and not necessarily in absolute values. One important aspect is therefore to verify if the ranking of megatrends or technologies would vary, in case the size of the sample changes. We tested this by cross-validating multiple samples.

We randomize the entire list of startups, and then divided in half and tested if our key results still hold. Table 7 shows the share of each megatrend in each randomized sample and compares it with their share in the total database. We did not find much variation in the actual shares, and in the ranking.

Table 7. Share of megatrends in two randomized samples and the total database.

<table>
<thead>
<tr>
<th>Megatrend</th>
<th>RAND 1</th>
<th>RAND 2</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decarbonization</td>
<td>38%</td>
<td>43%</td>
<td>40%</td>
</tr>
<tr>
<td>Digitalization</td>
<td>27%</td>
<td>26%</td>
<td>26%</td>
</tr>
<tr>
<td>Distributed</td>
<td>22%</td>
<td>23%</td>
<td>22%</td>
</tr>
<tr>
<td>Electrification</td>
<td>14%</td>
<td>9%</td>
<td>12%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Then we tested whether the two randomized samples were statistically different. We assign numbers 1 to 4 to each megatrend in alphabetical order to each entry in the database and calculated their means and standard deviation. The P-test is above .05, which means that the null hypothesis is not rejected as the difference between the means of both samples are not significantly different from one another (Table 8).

Table 8. The means of two randomized subsets are not significantly different

<table>
<thead>
<tr>
<th></th>
<th>RAND 1</th>
<th>RAND 2</th>
<th>P(T&lt;=t) two tales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.11</td>
<td>1.96</td>
<td>0.12</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.07</td>
<td>1.02</td>
<td></td>
</tr>
</tbody>
</table>

We performed the same test by individual technologies and observe that results are stable when the sample size changes (Table 9).
Table 9. Share of the main 4 technologies in two randomized subsets

<table>
<thead>
<tr>
<th>Megatrend</th>
<th>Random 1</th>
<th>Random 2</th>
<th>Whole set</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Solar</td>
<td>17%</td>
<td>19%</td>
<td>18%</td>
</tr>
<tr>
<td>Storage</td>
<td>11%</td>
<td>13%</td>
<td>12%</td>
</tr>
<tr>
<td>AI</td>
<td>9%</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>EV</td>
<td>7%</td>
<td>6%</td>
<td>7%</td>
</tr>
</tbody>
</table>

5. Discussion

Our dataset suggests that multiple innovation pathways are occurring in the electricity sector. At first glance, most of the innovation is coming from within the electricity sector, as the decarbonization megatrend and PV solar have the highest share of all technologies in our database. This trend would align with the “technological substitution pathway” suggested by Geels and Schot (2007). According to these authors, this trajectory occurs “when a disruptive change destabilizes the existing regime, enabling previously developed niche innovations to break through and replace existing models”. This trend is consistent with what we observe when clean technologies displace dirtier ones.

Digitalization developments, however, come from outside the electricity sector. The electrification of vehicles is driven outside the electricity sector, as it is usually a joint effort between storage developers and car manufacturers. This combination is closer to the “de-alignment and re-alignment” pathway suggested by Geels and Schot (2007). This path occurs when there is an ‘avalanche change’ – when changes are significant, sudden, and divergent, changing the landscape. If niche innovations are insufficient to become the new standard, multiple niches co-exist and compete for resources until one becomes dominant. When this occurs, the system realigns itself around this new dominant technology.

Our database also contradicts Verbong and Geels’ (2010) main conclusion about sustainability transitions in the electricity sector. When analyzing the transition pathways and their implications for grid infrastructure, they argue that a scenario dominated by distributed generation and local infrastructure was the less likely of the three scenarios they considered. The authors argue that this scenario was unlikely because it involved significant restructuring of the electricity sector and was more dependent on external developments
and decisive policy intervention. Our database shows that since 22% of startups focus on the distributed megatrend, their scenario could materialize in the midterm.

According to the IEA, the priority of energy innovation is cost reduction since this would help scale up low-carbon technologies irrespective of market or policy conditions. Our findings show that startups are tackling this priority. Besides reducing costs directly, innovations also focus on improving performance and thus reducing unit costs. These trends are happening in PV solar, storage technologies, and AI, with the latter focused on improving the efficient use of resources. According to our theoretical framework, startups focus on product or process improvements, which are sustained or routine innovations.

Although both innovation and investment strategies call for multidisciplinary and diversified investments, to diversify inherent risks in this activity, our survey of startups is heavily concentrated on a few technologies: solar, storage, and AI. However, multiple solutions can still be found by intersecting these areas. For instance, some startups combine technologies (solar and storage or EV-storagetransmission). We also observed efforts to pair products or foster business model innovation, i.e., how to price, repackaging and deliver service technologies. Still, very few startups we surveyed are pursuing completely radical approaches, except those whose focus is on the electrification of heating in buildings.

This mapping of technologies can also help us to conclude the value of theoretical frameworks. This dataset reveals some limitations of the output-based innovation literature. For instance, product innovation can take different forms, each with different implications. For example, Gigasolar’s innovation of lighter solar panels (materials) and Vortex’s bladeless wind turbines are categorized as product innovation. Digitalization also breaks this output-based model. For example, should we treat digitally recording data as a product, as input to a process, or both? Is a digital platform a product in itself, a process by which consumers and producers interact, or both? Is software a product used to make a process more efficient or both?

Regarding geography, the 320 startups that we analyze come from 36 countries. At first glance, it seems as if innovation is global, focusing for example, on PV solar, storage, and AI. However, these startups are concentrated in the United States (U.S.) (20%), United Kingdom (U.K.) (14%), Europe (20%), and China (21%) and represent very few developing countries except for India. We observed that startups in the U.S. and Europe focus more on digitalization than other technologies. We also observe that in the U.K., the decarbonization of buildings is a key focus, and many startups focused on the ‘comfort markets’ are based here. Firms from Gulf Cooperation Council countries and the Middle East focus almost exclusively on deploying PV solar. China’s startups focus on storage for power systems, EV
batteries, and the manufacturing of EVs themselves, something we do not find outside the incumbent automobile firms in the U.S. or Europe.

6. Conclusions

This paper offers a systematic approach to mapping future technology trends in the electricity industry based on analyzing the business proposition of 320 startups worldwide. Innovations in the electricity sector focus on decarbonization and digitalization. More specifically, solar, AI, and storage are dominant technologies being developed by startups.

From our analysis, PV appears to be the critical technology behind decarbonization efforts. Innovation within PV focuses on product innovation such as sustained innovation, more resistant materials, making PV easier to install, enabling more output, and making it easier to maintain. This innovation is being done within the same business model within existing regulations of the electricity industry.

Digitalization is the critical disruptive/breakthrough innovation. It is a new technology in search of applications in the electricity sector. As such, it has the potential to reshape businesses and the regulatory-market structure. Digitalization tends to animate markets by reducing market barriers to participation, connecting buyers and sellers through platforms, and eliminating inefficiencies. To successfully utilize this innovation, the sector needs to update its regulatory-market structure to accommodate new business models.

Storage technologies can be disruptive for the power sector, but the innovations we observe in storage technologies are incremental (problem well defined, domain primarily defined). These include batteries that last longer, that charge quicker, or that use less expensive raw materials. These findings can help governments and firms plan technology policies under rapidly changing industry conditions.

This paper has some limitations that we aim to address in future work. The dataset is a snapshot of the electricity sector’s current innovation landscape. It could be transformed into a dynamic tool by tracking startups’ progress in subsequent years, with the advantage that we now have a basis and initial metrics. This future work would allow us to monitor, for instance, the rate of firms’ success and survival and their ability to attract funding through different instruments. It would also enable us to enhance our analysis by tracking the direction, intensity, and magnitude of electricity innovation. Future research can also try to reduce biases with multiple samples, in the same vain of convenient sampling, using additional tools like Twitter or LinkedIn.
7. List of References


Temple, James. 2019. “How a new class of startups are working to solve the grid storage puzzle”. MIT Technology Review. October 10th, 2019


