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RESEARCH AND ANALYSIS

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Location choice for large-scale battery manufacturing plants

Exploring the role of clean energy, costs, and knowledge on location decisions in Europe

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Abstract

Driven by an increase in the demand for battery electric vehicles, the location of large-scale battery manufacturing plants, that is, gigafactories, has become a substantial and burgeoning topic in academia, policy, and industry. This study contributes to this debate by examining how a country's specific battery manufacturing costs and knowledge and the environmental impact of its energy mix affect the choice of location for gigafactories in the European Union. We found that France, Latvia, and Germany are suitable locations when equally balancing costs, knowledge, and energy. However, our results also showed that no country leads in all three dimensions, suggesting that there is no single best location to set up gigafactories. Instead, the choice will depend on the battery manufacturer's requirements. Here, we contribute an analysis of various combinations of costs, knowledge, and energy to identify suitable locations. Moreover, we provide a sensitivity analysis to test the robustness of our framework and to explore whether countries with a clean energy mix, such as Sweden, become suitable locations. The findings of our study will assist battery producers in identifying a suitable location for their gigafactories and will provide the basis for policymakers to attract battery manufacturing by directing investments into clean energy.

KEYWORDS

batteries, battery manufacturing, gigafactory, industrial ecology, location choice, sustainability

1 | INTRODUCTION

Reducing anthropogenic greenhouse gas (GHG) emissions has become a key issue for many countries in response to global climate change. The 27 countries in the European Union (EU), for instance, have agreed to achieve a share of renewable energy of at least 32% and reduce GHG emissions by at least 40% by 2030, compared to emissions in 1990. Due to their use in electric vehicles and stationary renewable energy storage solutions, lithium-ion batteries (LIBs) play an important role in achieving climate and energy targets (Duffner et al., 2021a; Mohr et al., 2020). Consequently, the demand for LIBs is expected to significantly increase globally, from 160 GWh in 2018 to more than 1000 GWh by 2030 (Pillot, 2019). Meeting this increasing demand is estimated to require an investment of at least €20 billion in the EU alone, corresponding to 10 to 20 large-scale LIB manufacturing plants, or the so-called gigafactories, in Europe (Beuse et al., 2018). Because the construction of gigafactories is associated with substantial and irreversible investment costs, selecting an optimal location is an important strategic decision for battery producers.

Previous studies on foreign direct investment (FDI) have explored how factors, such as host country risk, labor costs, and the firm's internationalization experience, affect the choice of the location of firms in general (Li et al., 2018) and specifically in the context of industries, such as the automotive (Colovic & Mayrhofer, 2011), pharmaceutical (Gray et al., 2011), and semiconductor (Henisz & Macher, 2004) industries. Because industry characteristics are an "integral determinant in shaping firms' overseas location decisions" (Jain et al., 2016, p. 309), scholars increasingly call for a greater contextualization of location research (Ghemawat & Thomas, 2008; Meyer, 2015; Teagarden et al., 2018) which is a notion that has been emphasized for many years in the industrial ecology field (Jensen et al., 2011; Lifset & Graedel, 2002; Lowe & Evans, 1995).

However, in the context of LIBs, research on the influence of different factors on the choice of location is still rare. In one of the few studies on this topic, Brodd and Helou (2013) compared the manufacturing costs of battery cells in China and the United States, but their study focused on 18650 LIBs, which are commonly used in small portable devices, such as television remote control devices. Focusing on the production of LIBs for electric vehicles, Duffner et al. (2020) considered cost-related aspects, such as energy and material costs, and knowledge-related aspects, such as the availability of a vibrant pool of talented scientists and engineers, which battery producers may have to access to support the development of process innovations to improve factory operations, in their analysis of location choices in Europe. However, while the location study by Duffner et al. may help guide location decisions for gigafactories, it leaves another important factor unexplored; namely, a country's energy mix. A country's energy mix is an important supply-side factor, as battery production is energy intensive. For example, Tesla's gigafactory in Nevada, USA, with a planned annual LIB cell production capacity of 35 GWh, is estimated to require up to 65 kWh of electricity per kWh of LIB cells (Kurland, 2019). Whether the energy required to produce LIBs comes from fossil fuels, such as coal or gas, or clean energy sources, such as wind or sunlight, is important for the overall potential of LIBs to contribute to achieving a more sustainable future. However, the effect of an individual country's energy mix on the choice of location for energy-intensive LIB production has not yet been explored. The present study aims to fill that gap.

In this study, we extend the two-dimensional cost–knowledge framework for battery plant location described by Duffner et al. (2020) by exploring the environmental impact of energy production as a third dimension, alongside the previously identified determinants of location decisions. Our results show that, when equally considering the environmental impact of energy production alongside costs and knowledge, countries with a clean energy mix, such as France, Latvia, and Germany, are suitable locations for gigafactories. However, our results also showed that no country leads in all three dimensions, suggesting that a good performance in one dimension may mask a relatively poor performance in another. In other words, there is no single best location to set up a gigafactory. Instead, the choice of location depends on the battery manufacturer's requirements, and by analyzing combinations of energy, costs, and knowledge, we identified various suitable locations that manufacturers may want to consider. For example, Latvia leads in both the cost–energy and cost–knowledge rankings. Moreover, by providing a sensitivity analysis of the new energy dimension, we tested the robustness of our framework and showed that France may be a suitable choice when a country's energy mix is weighted above 40%, whereas Sweden becomes a suitable choice when clean energy becomes the single most important factor in choosing a location for a gigafactory.

By taking a systemic approach that combines the economic perspective of Duffner et al. (2020) with a new environmental perspective, we contribute to a more comprehensive framework for the study of location decisions. Our framework may support policy and practice by providing a quantitative approach that uses public data to guide factory location decisions.

2 | LOCATION CHOICE LITERATURE

2.1 | Foreign direct investments and location choice

The choice of location for the setup of a new manufacturing facility in a foreign country, is a key decision of multinational enterprises (MNEs) when engaging in FDIs (Melo et al., 2009; Owen & Daskin, 1998). By expanding to foreign locations, MNEs seek to benefit from location-specific competitive advantages (Rugman & Verbeke, 1992). Meanwhile, location decisions affect the development of MNEs because they are usually complex and difficult to reverse. Since location economics was introduced by Dunning (1958), studies (Buckley & Ghauri, 2004; Lu & Beamish, 2001) have endeavored to explain location-specific advantages, explore the process and effects of FDIs, and develop frameworks to support firms in making location decisions (Duanmu, 2012; Flores & Aguilera, 2007; García-Canal & Guillén, 2008; Nielsen et al., 2017; Xu et al., 2021).

On the supply side, studies have traditionally focused on cost advantages when identifying optimal locations for firms (Lee et al., 1981; Mair et al., 1988; Moses, 1958; Weber, 1929), but some studies have also explored the role of knowledge (Alcácer & Chung, 2007; Vereecke et al., 2006) and access to factor pools (Alcácer & Chung, 2014). On the demand side, previous studies have considered factors such as market size, growth, and productivity (Belderbos & Sleuwaegen, 2005; Enright, 2009; Flores & Aguilera, 2007; Kumar, 2001). Moreover, previous studies have also explored institutional factors, such as the legal and regulatory environment of a country (Alcantara & Mitsuhashi, 2012; Kang & Jiang, 2012); home market factors, such as the market and industry structure (Martin et al., 1995; Pak & Park, 2005); and the firm's internal factors, such as its international experience and its resource base (Belderbos & Sleuwaegen, 2005; Jain et al., 2013).

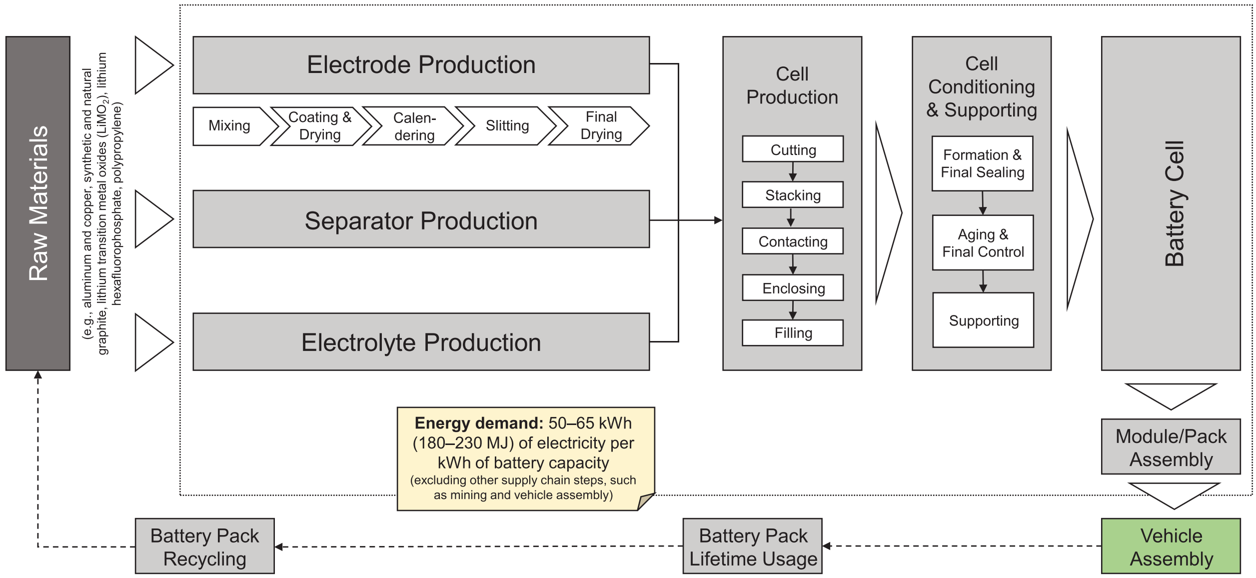

FIGURE 1 Large-scale LIB production ("gigafactory") process flow (electrode production: steps for cathode production), using data from Duffner et al. (2020), Kurland (2019), and Tesla (2019)

Moving beyond economic aspects, scholars have recently emphasized environmental issues, especially in the context of manufacturing firms (Dou & Sarkis, 2010; Gelhard & von Delft, 2016; Kleindorfer et al., 2005; Lin et al., 2018; Sultan & Mativenga, 2019; von Delft & Zhao, 2021) as FDIs may, for example, impact a country's energy consumption (Udi, Bekun, & Adedoyin, 2020; Udi, Bekun, & Sarkodie, 2020) and its ecological landscape (He et al., 2017). Hence, there is a need to put location decisions into a broader perspective to create greater value beyond the firm, or as Chen et al. (2014, p. 2) conclude: "it is becoming increasingly necessary for manufacturing firms to include all aspects and dimensions of sustainability in manufacturing facility location decisions."

2.2 | Battery cells and manufacturing locations

Despite LIBs being the current benchmark for rechargeable battery technologies, LIB manufacturing at scale has several challenges, because of the variety of materials required (Blengini et al., 2017; Li et al., 2020; Wentker et al., 2019) and cell design-related issues (Hettesheimer et al., 2017; Kwade et al., 2018). The major parts constituting LIB cells are the cathode, anode, separator, and electrolytes (Andre et al., 2017; Arinicheva et al., 2020; Whittingham, 2004). Various raw materials are used to produce each battery. For example, thin sheets of aluminum are used as the current collector for the cathode, while lithium transition metal oxides, with metals such as nickel, cobalt, and manganese, are commonly used as positive active materials. In battery production, raw materials are first transformed into their constituent parts via numerous steps and this is followed by cell production and cell conditioning (Duffner et al., 2021b). Battery cells are combined into modules and then into battery packs, which are finally assembled in an electric vehicle. Figure 1 provides an overview of the various interlinked processes in LIB manufacturing.

Overcoming the complex challenges of LIB production requires manufacturers to combine expertise from various disciplines, including chemistry, physics, and engineering; invest in production and R&D activities; and develop cell design competencies. These requirements create barriers against new entrants into this industry. Against this background, large-scale LIB production is currently dominated by a few large companies, such as BYD, CATL, LG Chem, and Panasonic.

In recent years, numerous new gigafactories have been planned in the EU. In the first localization phase, the focus was on Eastern European countries, such as Poland (LG Chem) and Hungary (Samsung and SK Innovation), but there is currently a localization trend toward Central and Northern Europe. Prominent examples are CATL, Tesla, and Volkswagen (VW), which are building gigafactories in Germany, and Northvolt, Freyr, and Morrow, which have opted for Sweden and Norway. This shows that several factors influence the choice of LIB production location.

2.3 | Battery cell production and clean energy mix in the EU

Given that LIB production is energy intensive, manufacturers may want to choose a location where the energy required for LIB production comes from non-fossil fuel sources, such as wind or photovoltaic solar energy, to avoid a negative impact on the climate, human health, and biodiversity, and to prevent resource depletion (Adedoyin et al., 2020; Zurano-Cervelló et al., 2019). In this study, we defined the environmental impact of a country's energy mix as the extent to which a given energy source (1) produces GHG emissions, (2) damages human health, (3) damages biological ecosystems, or (4) causes resource depletion. For example, compared to fossil fuels, clean energy sources produce less GHG emissions (Akella et al., 2009; Amponsah et al., 2014). In comparison to their fossil counterparts, clean energy sources also cause less damage to biological ecosystems, as they cause less terrestrial acidification (and hence, less loss of plant species due to a decrease in soil pH); less damage to human health, because their production is associated with lower levels of respiratory diseases and various types of cancer; and less damage to resource availability (Chen et al., 2017; Prehoda & Pearce, 2017).

For these reasons, LIB manufacturers are increasingly considering the environmental impact when making decisions about gigafactory location. For example, the car manufacturer, Mercedes-Benz, explains that it is "pursuing the goal of CO_2 neutrality along the entire (battery) value chain [...] CO_2 neutral production of battery cells is an important component" (Mercedes-Benz, 2021). Consequently, the firm invested in battery production at its carbon-neutral locations.

More broadly, the energy mix in many EU countries is currently changing as part of the transition toward a more sustainable future, prompting energy producers to reduce their dependency on fossil fuel markets, while simultaneously decarbonizing the current energy mix (Grubler, 2012; Markard, 2018; Victoria et al., 2020). However, there are substantial differences between the EU member states. For example, whereas 60.1% of Sweden's current energy consumption (production + import) is from clean energy, only 11% makes up Luxembourg's overall energy consumption (Eurostat, 2021). Hence, from a clean energy perspective, some EU countries seem to be a more suitable choice than others.

In our study, we considered sunlight, wind, rain, tides, waves, and geothermal heat as clean energy sources, as well as nuclear power, which previous studies have identified as a low-carbon energy source (Lenzen, 2008; Menyah & Wolde-Rufael, 2010; Vaillancourt et al., 2008). For example, the US Department of Energy (2021a) argues that "nuclear is a zero-emission clean energy source." Moreover, while burning coal is frequently associated with severe adverse health effects, nuclear power generation is less toxic and, hence, causes less damage to human health. However, nuclear power is clearly not without disadvantages (e.g., radioactive waste), and whether it is a clean energy source is the subject of debate in the academic literature (Adamantiades & Kessides, 2009; Karakosta et al., 2013; Pearce, 2012) and policy (EU, 2021). However, given the need to decrease GHG emissions, while meeting the increasing demand for energy at scale, and given that this is the first study accounting for the energy mix in the choice of location for LIB manufacturing, we considered nuclear power as a clean energy source.

3 | METHODS

To identify suitable locations for large-scale battery manufacturing plants, we combined the cost and knowledge modeling approach of Duffner et al. (2020) with an assessment of the environmental impact of energy sources used during LIB production (Ellingsen et al., 2014; Hawkins et al., 2013). Environmental impact assessments are commonly used to quantify the burden of a system or product with regard to GHG emissions, the impact on human health and biological ecosystems, and the availability of resources (Dehghanian & Mansour, 2009; Huijbregts et al., 2017; Wey, 2005). Before we discuss each of the variables used in our study in more detail, in the next paragraph we first describe how we created country-specific performance rankings.

We used the *z*-standardization function for rankings and leader segmentations (see Supporting Information S1 section 1 for more details). This function ensures that the values for the three dimensions of costs (*C*); knowledge (*K*); and environmental impact of the energy source, hereafter referred to as energy (*E*), which have different units and data ranges, fall within a common scale (denoted by a mean = 0 and a standard deviation = 1). This function was first applied to our indicators (*ind*) separately, where *i* denotes the individual countries (see Equation 1). The dimension values (*dim*) were then calculated as the sum of the z-standardized indicator values divided by the number of indicators (*n*) forming the respective dimensions (see Equation 2). To rank the countries with low total costs and a high share of clean energy at the top, we multiplied our calculated dimension scores for costs (dim_C) and energy (dim_E) by (−1). Country-specific dimension values were then added to give rise to the indices (*I*), costs and knowledge (*CK*) and costs, knowledge, and energy (*CKE*) (see Equations 3 and 4). An overview of the indicators and dimensions of the EU-27 can be found in Supporting Information S1 sections 3-4.

$$z_{ind_{j_i}} = \frac{ind_{j_i} - \overline{Ind_{j_I}}}{sd_{ind_{j_i}}} \tag{1}$$

$$dim_{k_i} = \left(z_{ind_l} + z_{ind_m} + \cdots\right)/n \tag{2}$$

$$I_{CK_i} = dim_{C_i} + dim_{K_i} \tag{3}$$

$$I_{CKE_i} = dim_{C_i} + dim_{K_i} + dim_{E_i} \tag{4}$$

3.1 | Data acquisition for the cost and knowledge dimensions

We followed the method described by Duffner et al. (2020) to calculate the cost and knowledge dimensions. For the cost dimension, Duffner et al. used a battery cell manufacturing cost model that considers more than 250 parameters related to product characteristics, technical observations, operating conditions, and factor costs. This process-based cost model covers a wide range of parameters that are necessary for large-scale state-of-the-art Li-ion pouch cell production. The model derives the total costs by combining fixed and location-specific variable costs. Fixed costs include machine, building, maintenance, and overhead costs, whereas the variable cost comprises labor, energy (excluding taxes and levies), and material costs. The model assumes that the costs of sourcing raw materials and machines are identical in all countries. The relevant dedicated costs include labor, energy, and building costs (Duffner et al., 2020). An overview of the aggregated cost indicators for individual countries is provided in Supporting Information S1 section 3.

The knowledge dimension in the study of Duffner et al. (2020) combined several indicators based on a country's academic outputs and available human resources, which reflect the country's competencies for battery production. We updated the research output data reported by Duffner et al. (2020) by following their approach of searching for relevant publications in the Web of Science database. To determine the locations with an appropriate supply of skilled labor, we built on the approach used by Duffner et al. (2020), but we used up-to-date datasets, because some of the materials used by Duffner et al. (2020), such as the Global Human Capital Report, which was discontinued in 2017, are no longer available. We used the Human Capital Index published by the World Bank in 2020, which ranks countries on how well they are developing their human capital. Furthermore, we used the recent number of students in science and engineering degree programs to account for the size of a country's talent pool. Data were obtained from the Eurostat database. Supporting Information S1 section 4 provides an overview of the knowledge indicators.

3.2 | Analysis of the energy dimension

To identify the countries that offer an adequate energy mix for energy-intensive LIB manufacturing, we assessed the environmental impact related to the production of 1 kWh of electricity and considered the following parameters.

We considered anthropogenic GHG emissions, because they are a major cause of the greenhouse effect and, as such, contribute to climate change. We used the average GHG emission factors of the EU-27 countries' electricity grid mixes and obtained data from the International Energy Agency's Emissions Factors 2021 (IEA, 2021). While GHG emissions are often the main focus when assessing the environmental impact of energy production, there are other parameters that also determine ecologically sustainable production. Instead of exclusively focusing on GHG emissions, we also accounted for the burden on human health and the biological ecosystem, and the availability of resources associated with energy production (see Supporting Information S1 section 2 for more details). For these three parameters, we followed the method described by Huijbregts et al. (2017), who translated emissions and resource extractions into a limited number of environmental impact scores. Their model, known as ReCiPe, is frequently used for life-cycle impact assessments (LCIAs), which measure the environmental impact of a product across its entire life cycle, from extraction to disposal.

The data (see Supporting Information S1 section 5) used to analyze damage to human health, damage to biological ecosystems, and resource scarcity were obtained from the EcoInvent 3.8 database using ReCiPe 2016 (endpoint hierarchy) LCIA methodology available in SimaPro in accordance with ISO 14040/44. Together with the aforementioned GHG emission data from the IEA (2021), we derived the per-capita energy models using SimaPro. We used the system expansion approach in SimaPro to include the impact of the side products of the specific power generation methods.

4 | RESULTS

4.1 | Clean energy performance rankings

In this section, we present the results of clean energy mix analysis. The column labeled "Energy" in Table 1 shows the performance of the EU-27 countries when considering our four environmental parameters for location choices; namely, GHG emissions, damage to human health, impact on biological ecosystems, and resource scarcity. Both the rank (#) and the corresponding dimensional score (dim score) are displayed. Furthermore, for comparison with the data reported by Duffner et al. (2020), Table 1 also shows the performance of the EU-27 countries in terms of cost (*C*) and knowledge (*K*) dimensions.

When only considering energy, Sweden (*dim* score = 1.47) and France (*dim* score = 1.36) were the top-performing countries, as they both have a very low dependence on fossil fuels. France benefits from a 72% nuclear and 20% renewable energy share, while Sweden has a 41% nuclear and 54% renewable energy share. As these energy sources produce fewer emissions and use fewer resources compared to fossil-based energy sources,

TABLE 1 Overview of the analyzed dimensions energy, costs, and knowledge (country codes following ISO 3166-1 alpha-2)

	Energy (*E*)		Costs (*C*)		Knowledge (*K*)	
Country	#	*dim* score	#	*dim* score	#	*dim* score
SE	1	1.47	22	−1.04	5	0.43
FR	2	1.36	21	−0.98	2	1.29
FI	3	0.89	18	−0.77	15	−0.04
BE	4	0.89	25	−1.25	9	0.19
DK	5	0.81	27	−1.83	13	−0.02
AT	6	0.69	24	−1.14	7	0.34
ES	7	0.40	15	0.02	4	0.54
HU	8	0.30	6	1.02	24	−0.81
LU	9	0.29	19	−0.83	19	−0.32
IT	10	0.21	16	−0.61	3	0.88
PT	11	0.21	10	0.65	14	−0.04
NL	12	0.21	20	−0.88	6	0.35
LV	13	0.20	3	1.18	12	0.10
IE	14	0.19	23	−1.09	8	0.26
SK	15	0.18	12	0.54	25	−0.81
DE	16	0.12	26	−1.41	1	2.33
HR	17	0.10	4	1.18	20	−0.53
SL	18	0.06	13	0.54	10	0.19
RO	19	−0.19	2	1.23	27	−1.11
LT	20	−0.22	7	1.02	23	−0.67
CZ	21	−0.39	8	0.91	17	−0.29
BG	22	−0.46	1	1.55	22	−0.57
EE	23	−0.51	9	0.76	16	−0.12
GR	24	−1.34	11	0.60	18	−0.32
PL	25	−1.35	5	1.12	11	0.12
CY	26	−1.94	17	−0.61	21	−0.54
MT	27	−2.16	14	0.12	26	−0.83

France and Sweden ranked higher than other EU countries and had a significantly higher score than Finland (*dim* score = 0.89). In contrast, countries such as Malta (*dim* score = −2.16) and Cyprus (*dim* score = 1.94), which are highly dependent on fossil fuels, scored low in the clean energy ranking, because energy production from fossil fuels consumes large amounts of non-renewable resources and produces large quantities of emissions per kWh produced. It should be noted that, while a country such as France, which has the second highest production capacity (568 TWh) among the EU-27 countries (total: 3249 TWh), should require more resources to meet its energy demand, it benefits from its low reliance on fossil fuels, making it one of the top performers in this category.

4.2 | Combined performance rankings

Figure 2 and Table 2 show the country-specific results when combining all three dimensions (*CKE*). The different colors in Figure 2 indicate the performance of each country in the energy dimension, with green indicating a high share of clean energy and red indicating a low share. The overall ranking with all three dimensions combined was led by France (index score = 1.66), Latvia (index score = 1.48), and Germany (index score = 1.05); (*CKE* leaders in bold in Table 2). However, as shown in Table 1 and Figure 2, these three countries reached their scores in different ways. Overall, France had a high knowledge score and a high energy score, despite high manufacturing costs (reflected in a low-cost score). In contrast, Latvia benefited from low battery manufacturing costs, combined with a relatively clean energy mix, but only achieved an average knowledge score. Finally, while Germany had high production costs and a moderate score in the energy dimension, it had a very high knowledge score.

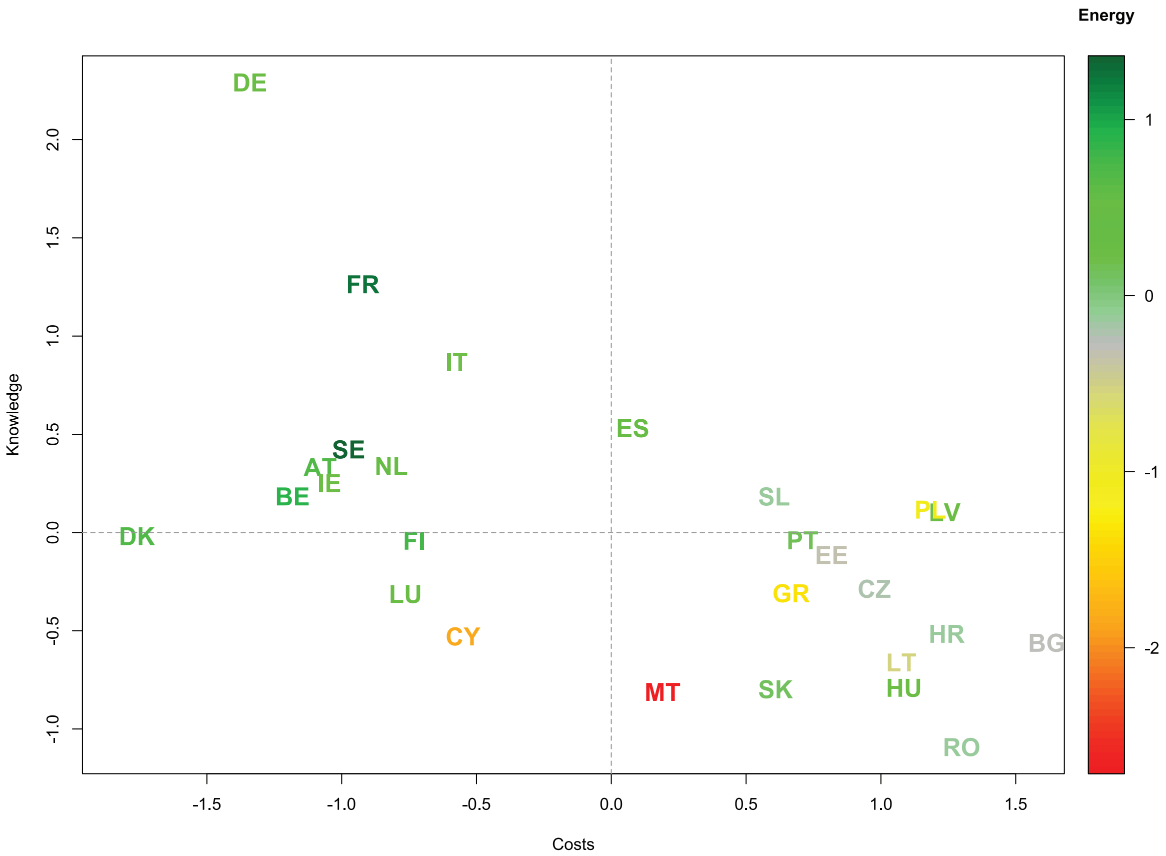

FIGURE 2 Graphical representation of the three dimensions costs, knowledge, and energy (country codes following ISO 3166-1 alpha-2; energy dimension represented with a color code, with green indicating a high share of clean energy and red indicating a low share)

Our results showed that there is no panacea for identifying an optimal location. While the performance in each dimension and the combined performance ranking can inform location choices, trade-offs between the dimensions should also be considered. For example, a country's negative performance in a single dimension may be "masked" by better performance in another dimension, thus making it difficult for decision-makers to assess which countries provide an adequate balance of all three dimensions. Moreover, when making a location decision, a battery producer may decide to disregard one dimension, such as when it has already acquired relevant knowledge, and therefore, make a strategic decision to build a gigafactory in a location that combines low costs with a high share of available clean energy.

To address this issue, we analyzed combinations of the two dimensions. The two-dimensional ranking for cost and knowledge (*CK*), also shown in Table 2, was led by Latvia (index score = 1.28), Poland (index score = 1.24), and Bulgaria (index score = 0.97). These three countries had average knowledge scores and very high cost scores because of their low production costs. When combining costs and clean energy, Latvia had the highest score (index score = 1.37), followed by Hungary (index score = 1.32) and Croatia (index score = 1.28). These countries may be attractive when high knowledge diffusion is expected or when a company already has a technology lead in their market. When analyzing the combination of knowledge and energy, France (index score = 2.65), Germany (index score = 2.45), and Sweden (index score = 1.90) led the ranking.

4.3 | Sensitivity analysis

As described in the previous section, we derived the overall results by equally weighing the three dimensions of cost, knowledge, and energy. To test the robustness of our study and account for the influence of the new energy dimension in our three-dimensional framework, we performed a sensitivity analysis. For this analysis, we first set the weighting of the energy dimension to zero, labeled as CK in Table 3. We then gradually increased the weighting of the energy dimension to 1000% to achieve a weighting at which this dimension is dominant (in Table 3, *E* represents the rankings based only on the energy dimension). The midpoint, denoted as *CKE*, represents the point within our framework where all three dimensions are weighted equally (i.e., 100% weighting of the energy dimension, as in Section 4.2).

The analysis showed that minor changes in the weighting of energy did not cause major changes in the rankings. When the impact of energy was reduced to a very low value, countries with a good score in this dimension fell significantly in the rankings. However, when the weighting of the

TABLE 2 Overview of different combinations of the analyzed dimensions

#	*CE*	Index score	*KE*	Index score	*CK*	Index score	*CKE*	Index score
1	**LV**	**1.37**	**FR**	**2.65**	**LV**	**1.28**	**FR**	**1.66**
2	HU	1.32	**DE**	**2.45**	PL	1.24	**LV**	**1.48**
3	HR	1.28	SE	1.90	BG	0.97	**DE**	**1.05**
4	BG	1.08	IT	1.10	**DE**	**0.93**	ES	0.96
5	RO	1.04	BE	1.07	SL	0.73	SE	0.86
6	PT	0.86	AT	1.03	HR	0.65	PT	0.82
7	LT	0.80	ES	0.94	EE	0.64	SL	0.79
8	SK	0.72	FI	0.85	CZ	0.62	HR	0.75
9	SL	0.60	DK	0.79	PT	0.61	HU	0.51
10	CZ	0.52	NL	0.55	ES	0.56	BG	0.51
11	SE	0.43	IE	0.44	LT	0.34	IT	0.48
12	ES	0.42	**LV**	**0.30**	**FR**	**0.30**	CZ	0.23
13	**FR**	**0.38**	SL	0.24	GR	0.28	EE	0.13
14	EE	0.25	PT	0.17	IT	0.27	LT	0.12
15	FI	0.12	LU	−0.03	HU	0.21	FI	0.08
16	PL	−0.23	HR	−0.42	RO	0.12	RO	−0.07
17	BE	−0.36	HU	−0.50	SK	−0.27	SK	−0.09
18	IT	−0.40	EE	−0.62	NL	−0.53	PL	−0.11
19	AT	−0.45	SK	−0.63	SE	−0.61	AT	−0.11
20	LU	−0.54	CZ	−0.68	MT	−0.70	BE	−0.17
21	NL	−0.67	LT	−0.90	AT	−0.80	NL	−0.33
22	GR	−0.74	BG	−1.04	FI	−0.82	IE	−0.65
23	IE	−0.90	PL	−1.23	IE	−0.83	LU	−0.86
24	DK	−1.02	RO	−1.30	BE	−1.06	DK	−1.04
25	**DE**	**−1.28**	GR	−1.65	LU	−1.15	GR	−1.06
26	MT	−2.04	CY	−2.48	CY	−1.15	MT	−2.87
27	CY	−2.56	MT	−2.99	DK	−1.85	CY	−3.10

CE, costs + energy; *KE*, knowledge + energy; *CK*, costs + knowledge; *CKE*, costs + knowledge + energy; country codes following ISO 3166-1 alpha-2; CKE leaders in bold.

energy dimension was significantly increased, countries with a clean energy mix topped the ranking, even if they had an average performance in other dimensions (e.g., Sweden moved from 5th to 2nd and Finland from 15th to 7th at a weight of 200%).

We found that, among the top-performing countries (France, Latvia, and Germany) in the overall performance ranking (i.e., where all three dimensions are weighted equally), there were three different outcomes when shifting the weighting of the clean energy dimension. Latvia showed a high performance when clean energy was not weighted in and when it was weighted equally (*CKE*), but its scores gradually decreased when clean energy was weighted above 90%. Germany benefited from a higher weighting of clean energy until the CKE point, but thereafter, it began to gradually rank lower. In contrast, France showed a higher performance with an increasing weight of clean energy. After the CKE point, France remained in the highest position until clean energy was weighted at 1000% or above, when Sweden took the lead.

5 | DISCUSSION

With the increasing demand for LIB electric vehicles, the search for suitable locations to produce LIBs at scale has become an important topic for academics, policymakers, and business practitioners (Duffner et al., 2020; European Parliament, 2018). For example, in March 2021, VW announced that it will have six 40 GWh battery cell production factories in operation in the EU by 2030. The first two of these gigafactories will be located in Skellefteå, Sweden, at the site of VW's partner Northvolt, and at VW's site in Salzgitter, Germany (Volkswagen, 2021). In this study, we explored the factors that influence such location choices for large-scale LIB factories by systematically analyzing the advantages of locations across the EU.

TABLE 3 Results of the sensitivity analysis (country codes following ISO 3166-1 alpha-2)

#	*CK*	3%	10%	20%	30%	40%	50%	60%	70%	80%	90%	*CKE*	200%	500%	1000%	*E*
1	***LV***	LV	LV	LV	LV	LV	LV	LV	LV	LV	FR	***FR***	FR	FR	SE	***SE***
2	***PL***	PL	PL	PL	DE	DE	DE	FR	FR	FR	LV	***LV***	SE	SE	FR	***FR***
3	***BG***	BG	DE	DE	PL	FR	FR	DE	DE	DE	DE	***DE***	LV	FI	FI	***FI***
4	***DE***	DE	BG	BG	BG	BG	SL	ES	ES	ES	ES	***ES***	ES	BE	BE	***BE***
5	***SL***	SL	SL	SL	SL	SL	ES	SL	SL	PT	PT	***SE***	DE	AT	DK	***DK***
6	***HR***	HR	HR	HR	FR	ES	BG	PT	PT	SL	SL	***PT***	PT	ES	AT	***AT***
7	***EE***	EE	PT	PT	HR	PL	PT	HR	HR	HR	HR	***SL***	FI	LV	ES	***ES***
8	***CZ***	PT	ES	ES	ES	PT	HR	BG	BG	BG	SE	***HR***	HR	DK	LV	***HU***
9	***PT***	CZ	EE	FR	PT	HR	PL	PL	HU	SE	BG	***HU***	SL	HU	HU	***LU***
10	***ES***	ES	CZ	CZ	CZ	CZ	CZ	IT	SE	HU	HU	***BG***	HU	PT	PT	***IT***
11	***LT***	FR	FR	EE	EE	EE	EE	HU	IT	IT	IT	***IT***	BE	DE	IT	***PT***
12	***FR***	LT	LT	IT	IT	IT	IT	CZ	CZ	CZ	CZ	***CZ***	IT	IT	DE	***NL***
13	***GR***	IT	IT	LT	HU	HU	HU	EE	PL	EE	EE	***EE***	AT	HR	LU	***LV***
14	***IT***	GR	HU	HU	LT	LT	LT	SE	EE	LT	LT	***LT***	SK	SL	HR	***IE***
15	***HU***	HU	GR	RO	RO	RO	SE	LT	LT	PL	PL	***FI***	BG	SK	NL	***SK***
16	***RO***	RO	RO	GR	GR	SE	RO	RO	RO	RO	FI	***RO***	LT	NL	SK	***DE***
17	***SK***	SK	SK	SK	SE	SK	SK	SK	SK	FI	RO	***SK***	NL	LU	SL	***HR***
18	***NL***	NL	SE	SE	SK	GR	FI	FI	FI	SK	SK	***PL***	CZ	IE	IE	***SL***
19	***SE***	SE	NL	NL	NL	NL	GR	AT	AT	AT	AT	***AT***	DK	LT	RO	***RO***
20	***MT***	MT	FI	FI	FI	FI	NL	NL	NL	BE	BE	***BE***	RO	RO	LT	***LT***
21	***AT***	AT	AT	AT	AT	AT	AT	GR	BE	NL	NL	***NL***	EE	CZ	CZ	***CZ***
22	***FI***	FI	IE	IE	IE	BE	BE	BE	GR	IE	IE	***IE***	IE	BG	BG	***BG***
23	***IE***	IE	MT	BE	BE	IE	IE	IE	IE	GR	LU	***LU***	LU	EE	EE	***EE***
24	***BE***	BE	BE	LU	LU	LU	LU	LU	LU	LU	GR	***DK***	PL	PL	PL	***GR***
25	***LU***	LU	LU	MT	MT	DK	DK	DK	DK	DK	DK	***GR***	GR	GR	GR	***PL***
26	***CY***	CY	CY	CY	DK	MT	MT	MT	MT	MT	MT	***MT***	MT	CY	CY	***CY***
27	***DK***	DK	DK	DK	CY	CY	CY	CY	CY	CY	CY	***CY***	CY	MT	MT	***MT***

Our study extended previous research that considered cost and knowledge factors (Duffner et al., 2020) by exploring the environmental impact of energy production as a third dimension alongside the previously identified determinants of location decisions. In doing so, we contribute to the literature on location choice for FDIs (Alcácer & Chung, 2007; Belderbos & Sleuwaegen, 2005; Enright, 2009; Lee et al., 1981; Mair et al., 1988; Xu et al., 2021) and energy-related issues associated with FDIs, such as an increase in energy consumption (Udi, Bekun, & Adedoyin, 2020; Udi, Bekun, & Sarkodie, 2020), by exploring the role of clean energy, which has not been explored in general or in the context of LIBs in these previous studies. By analyzing the cost, knowledge, and energy dimensions of each EU country, our results showed that France, Latvia, and Germany are suitable locations for gigafactories when considering cost, knowledge, and energy equally. However, as no country led in every dimension, the overall ranking should be interpreted with caution. This is because good performance in one dimension may "mask" poor performance in another dimension. Looking into this issue in more depth revealed a more nuanced picture. Our analysis suggested that there is no optimal choice for a gigafactory in the EU, but rather, it depends on the combination of factors that firms consider most important in their location decision-making.

When firms consider knowledge and energy to be important factors, our results showed that France, Germany, and Sweden were the most suitable locations. Given the importance of accessing knowledge resources in location decisions and the increasing relevance of clean energy production, countries leading the knowledge–energy ranking may offer advantages for battery producers. This is because a decrease in overall costs is, in the short and medium terms, more likely than an improvement in both knowledge and energy dimensions. To illustrate this point, consider that the overall cost of production has a variance of only 3.74, ranging between a maximum value of US$97.9/kWh and a minimum value of US$91.5/kWh. Thus, the total cost may be reduced through the use of system optimization or through government incentives. In such a scenario, the balance of the presented framework will tip in favor of leaders in the knowledge–energy ranking.

When firms consider cost and energy, our results suggested that Latvia, Hungary, and Croatia may be suitable choices for locating gigafactories. These countries may be attractive when high knowledge diffusion is expected or when a company already has a technology lead in its market. For example, knowledge diffusion between EU countries may be supported by the relatively free and unbureaucratic movement of talent between EU countries, in which case, firms may want to focus on cost and energy factors in their location decision-making. However, knowledge, especially in the context of high-tech industries, is known to be "sticky" and knowledge transfer has numerous barriers (Sun & Scott, 2005; Szulanski, 1996). Therefore, even if firms use our cost–energy ranking to inform their location choice, a cost–energy location strategy should not be pursued alone, while disregarding knowledge.

To test for robustness and account for the effect of the new clean energy dimension on our three-dimensional framework, we also performed a sensitivity analysis. The results showed that our study was robust to medium changes in the weighting of the energy dimension. This suggests that battery producers and policymakers may use our framework, even if the weighting of clean energy is moderately increased or decreased. For example, it may be used when a company has not yet decided how much to weigh clean energy, or when it is not yet clear whether or to what extent environmental regulations favor the use of clean energy in LIB production. In this case, our results suggest that France is a suitable location choice, because it is the highest-performing country in our analysis and is stable against medium to large variations in the weighting of clean energy.

This study is the first attempt to consider the cost, knowledge, and environmental impact of a country's energy mix in location choices for gigafactories. As such, it is not without limitations, which may represent research opportunities. For example, as our study was limited to the EU, we recommend that future studies consider additional regions, such as the US or UK, in the analysis of location choices. Future studies should compare specific regions or federal states within and between countries. For example, in the United States, substantial differences exist between the energy mixes of different states (US Department of Energy, 2021b), suggesting that not all states may be suitable for energy-intensive LIB production. Similarly, in Europe, we recommend that future research moves beyond aggregated country-level data and provides a more fine-grained analysis of location choices. For example, in the United Kingdom, Scotland generated 90.1% of its consumed energy (30 TWh) from renewable sources in 2019 (Scottish Government, 2020), making it a potentially attractive location for gigafactories.

Future research could also consider how changes in countries' energy mixes affect location choice over time. Such a temporal dimension would allow future research to consider how governments' commitments to expanding clean energy production over the following decades changes our rankings. For example, our results showed that Germany currently ranks 16th in the energy dimension, but the new German government has recently proposed accelerating the transition toward clean energy production, aiming for 80% of Germany's energy generation to come from renewable sources by 2030 and to phase out coal by 2030. Future research should study how such changes affect location choice.

In our study, we implicitly assumed that battery producers rely on national grids to source their energy, instead of setting up clean energy production at the site of their factories. While investing in the ownership of clean energy production has certain advantages, it comes with several economically important disadvantages, such as: (1) higher upfront investment costs (including time to plan and setup energy production) that would need to be justified to shareholders, (2) additional operative expenditures resulting from the maintenance of energy production, and (3) additional complexity resulting from compliance with the host country's regulations for energy producers. Therefore, in our study, we assumed that it is economically more effective for gigafactory operators to subcontract clean energy production to specialized energy companies and, consequently, to source clean energy from a third party. However, we could not answer the question of what level of clean energy demand of a gigafactory is optimal for outsourcing or integrating energy production. Future research may address this limitation and explore when it is optimal for battery producers to invest in on-site clean energy production. Future research should also explore the availability of, or access to, clean energy in specific regions, as opposed to an analysis of country-level energy mixes, in making location decisions for gigafactories.

Future research should also address concerns regarding our measures. In our study, we focused on important supply-side factors, such as the energy needed for production. Future research may extend our framework by considering demand-side factors, such as proximity to the market. For example, proximity to a major battery pack and/or electric vehicle assembly plant may affect the cost dimension in our framework. Analyzing such demand-side factors may complement our supply-side-focused study and will be especially informative for established car producers, which may consider co-locating new battery factories and existing vehicle assembly plants.

Another opportunity for future research is on the knowledge aspect. Following Duffner et al. (2020), we used publications as a proxy for the attractiveness of a country's research landscape in our knowledge analysis, but future research may also include patents as an additional proxy for knowledge and technology transfer (Aaldering et al., 2019; von Delft, 2013). Regarding our clean energy measure, we included nuclear power as a clean source of energy, but future research may, instead, focus on renewable energy sources, given the potential disadvantages of nuclear energy and the ongoing debate about whether it is a clean energy source. Moreover, we recommend that future research should consider additional cost measures. For example, following Duffner et al. (2020), we assumed that raw material costs are identical for all EU countries and, hence, we focused on energy, building, and labor costs. However, there may be differences in raw material costs between countries; hence, we recommend that future studies consider additional upstream process costs. Similarly, our analysis did not consider the costs of other downstream processes, such as recycling. Therefore, future research may extend our model by considering country-specific costs and sustainability aspects of LIB recycling.

DATA AVAILABILITY STATEMENT

The aggregated data that supports the findings of this study are available in the supporting information of this article. The raw data sources are listed in the methods section of this article and are openly available at Duffner et al. (2020), https://doi.org/10.1016/j.jclepro.2020.121428; Web of Science, https://www.webofscience.com; and Eurostat, https://ec.europa.eu/eurostat/data/database. Data on GHG emissions are available from the IEA, https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021. Restrictions apply to the availability of the IEA data, which were used under license for this study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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