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# Economic efficiency analysis of an investment strategy based on oversizing the installed capacity of photovoltaic and wind farms beyond their grid connection capacity

*Paweł Włoch*

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**Abstract:** In the context of the ongoing energy transition, one of the major challenges is the increasing difficulty of securing new grid connection capacities for renewable energy projects. The aim of this study was to analyse the potential for oversizing the installed capacity of wind and photovoltaic power plants beyond their agreed grid connection capacity. The evaluation was performed using an indicator-based analytical framework combined with an assessment of improvements in the efficiency of the existing grid connection. The results clearly demonstrate that oversizing generation units beyond the contracted grid capacity constitutes a rational investment strategy, improving the utilisation of the connection point and exerting a positive impact on the overall economic performance of the project.

**Keywords:** Wind energy, photovoltaics, system oversizing, grid connection utilization

## Introduction

The energy sector is currently one of the most dynamically evolving areas of the economy. As part of the ongoing energy transition, national energy systems are undergoing structural transformation aimed at reshaping the energy mix—a balance of various electricity generation technologies used to meet demand. Table 1 presents an overview of the generation technologies currently operating within the Polish National Power System (Krajowy System Elektroenergetyczny, KSE).

**Table 1.** Installed capacity of generation units operating in the Polish National Power System (Krajowy System Elektroenergetyczny) as of June 2023.

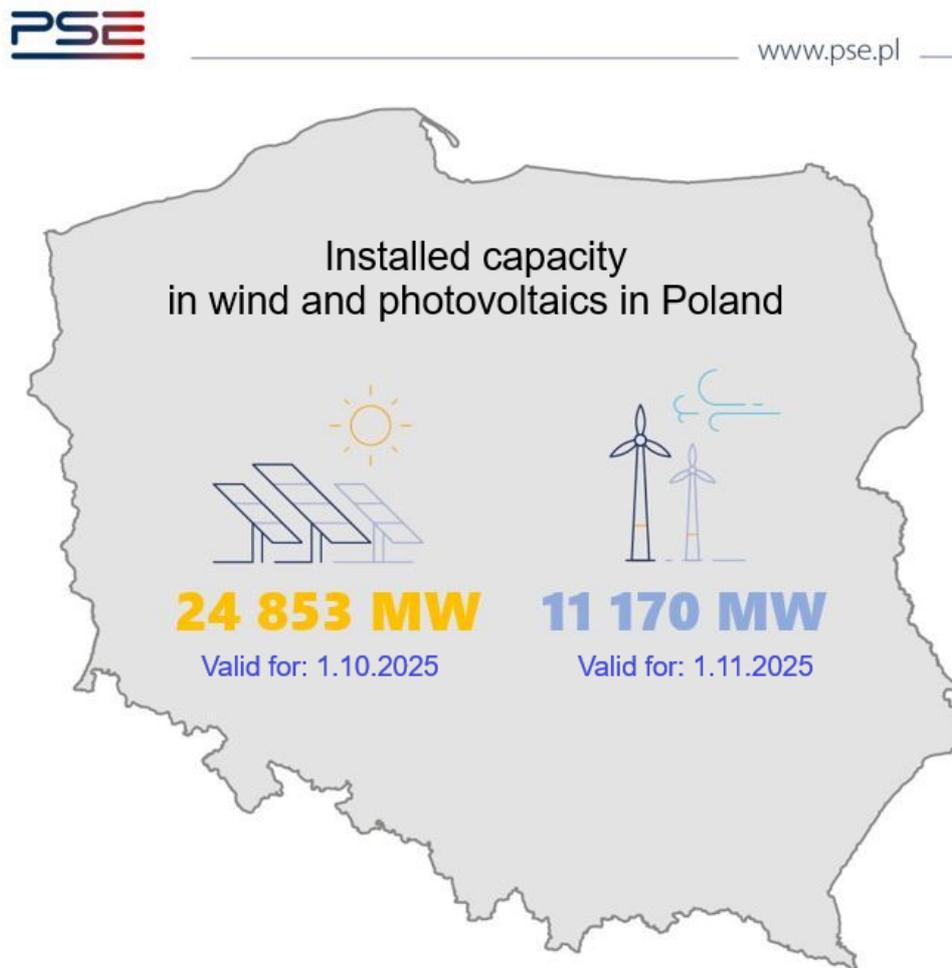
Generation technology	Capacity [MW]
<b>JWCD</b>	<b>27 770</b>
<i>Hard coal</i>	<i>16 114</i>
<i>Lignite</i>	<i>8 249</i>
<i>Gas</i>	<i>3 407</i>
<b>nJWCD</b>	<b>8 773</b>
<i>Hard coal</i>	<i>7 450</i>
<i>Lignite</i>	<i>128</i>
<i>Gas</i>	<i>1 195</i>
Hydro power plants	2 504
Wind turbines	9 698

Photovoltaics	16 190
Biomass	275
Heating oil	747
Coke oven gas	158
<b>Sum</b>	<b>66 115</b>

Source: own elaboration based on data from PSE S.A.

Considering current trends—particularly the drive to minimise the environmental impact of human activity-significant emphasis is placed on the development of renewable energy sources, including wind and photovoltaic power generation. According to data published by the transmission system operator, Polskie Sieci Elektroenergetyczne S.A., at the beginning of 2024 Poland had over 10,000 MW of installed wind capacity and nearly 18,000 MW of installed photovoltaic capacity.

**Figure 1.** Installed capacity of wind and photovoltaic power plants in Poland



Source: [www.pse.pl](http://www.pse.pl), accessed: 01.12.2025.

A key challenge of the energy transition is reconciling the ambitions of the energy sector with the current condition of the power system. According to the report of the Supreme Audit Office (Najwyższa Izba Kontroli) titled “*Development of the Electricity Distribution Network*”, in the first half of 2022, 99.3% of all applications for new grid connections were rejected. This raises a fundamental question: *How can new generation capacities be integrated when obtaining additional grid connection capacity is increasingly unlikely?*

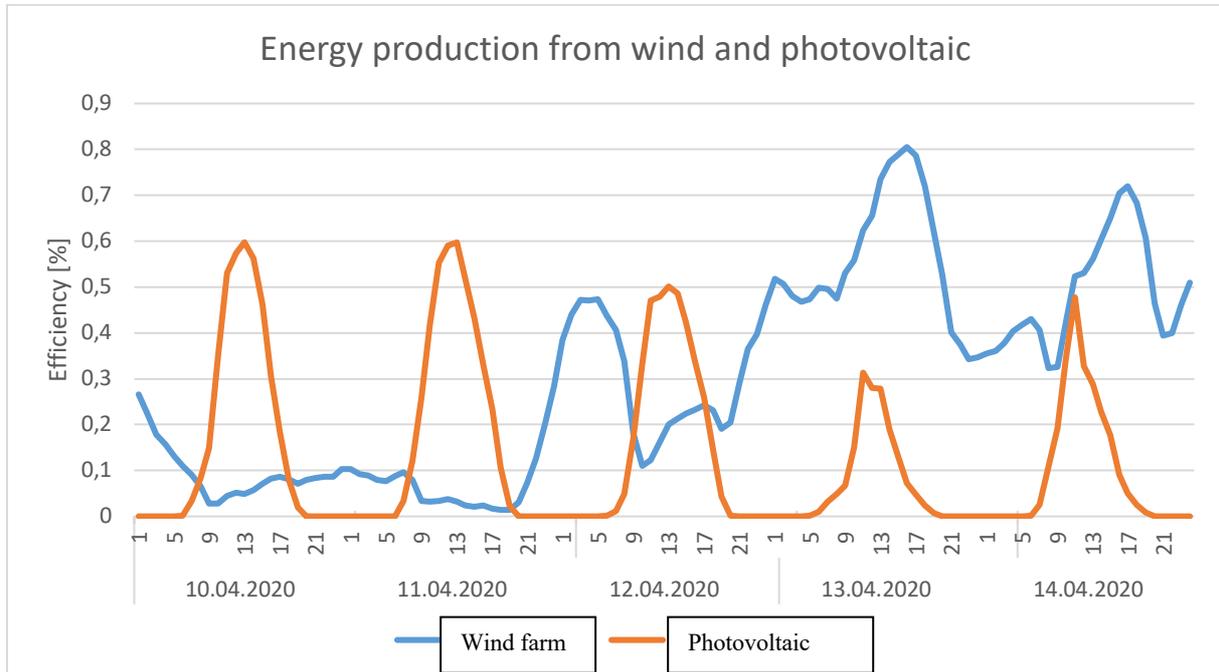
It should be noted that both distribution and transmission system operators, when evaluating an application for connection, assume that the generating unit may operate at its maximum contracted grid connection capacity at any moment. This assumption is rooted in system security requirements — since producers cannot be restricted in how they use their connection point, the network must always be capable of accepting the full output of the generating unit.

While this is a reasonable operational assumption from the operator’s perspective, it does not reflect the actual operating characteristics of various generation technologies, particularly weather-dependent sources such as wind and photovoltaic power plants.

In Poland, the typical annual yield of a modern onshore wind turbine is approximately 2,566 MWh/year/MW for a 3 MW turbine, corresponding to a capacity factor of 29%. For photovoltaic installations, the average annual yield is approximately 1,015 MWh/year/MW, corresponding to a capacity factor of 11.6%. It should be emphasised that this value refers to the energy yield of PV modules. Electrically, modules are coupled to inverters whose rated AC power is intentionally lower than the total DC module capacity. In practice, this relationship is expressed through the DC/AC ratio, typically ranging from 1.15 to 1.35. As a result, the effective capacity factor of the AC-side system is closer to 9.6%.

These values illustrate that weather-dependent sources rarely operate near their peak power. Figure 2 shows an example of wind and PV generation over a selected five-day period. As can be seen, PV generation occurs only during daylight hours, whereas wind generation depends on the passage of atmospheric fronts.

**Figure 2.** Wind and photovoltaic power generation in the period 10–14 April 2020



Source: Own elaboration based on data from PSE S.A.

## Literature review

Oversizing strategies for weather-dependent renewable generation units are widely discussed in the literature as an economically justified means of increasing annual energy output using existing grid connection capacity. This applies particularly to PV installations with high DC/AC ratios and hybrid PV+wind systems. Modelling studies indicate that the optimal oversizing factor depends directly on the hourly distribution of generation as well as on electricity price structures and profile-related costs.

In the case of PV, typical DC/AC values above 1.2 are shown to increase annual production with acceptable peak-hour losses, whereas for wind power the lower variance of extreme peaks favours smaller but still positive optimal oversizing values ( $k^*$ ). Oversizing is often analysed in the context of surplus energy management, tariff design impacts, and the economic fundamentals of curtailment. The topic is also widely discussed from the perspective of forecasting the output of oversized installations.

International studies consistently confirm that oversizing renewable generation capacity, combined with controlled limitation of instantaneous power, is a cost-effective strategy for increasing the share of RES in power systems with constrained grid capacity.

### **Economic rationale for oversizing**

Oversizing the installed capacity of a generating unit beyond the contracted grid connection capacity can be considered as a decision-making problem of the “oversizing under curtailment risk” type. In this framework, an investor maximises project value through two mechanisms:

- increasing production during periods when the installation would otherwise operate below its maximum potential, and
- accepting controlled curtailment during peak-generation hours.

The literature typically frames this challenge as a trade-off triangle: higher CAPEX vs. increased annual energy yield vs. curtailment losses. The decision to oversize follows from the statistical shape of instantaneous generation distributions, electricity price patterns, and the technical constraints agreed with the network operator.

### **Objective, methodology, and results**

The aim of this study was to verify whether oversizing the installed capacity of a generating unit beyond the contracted grid capacity can improve the efficiency of utilising that connection.

The underlying research hypothesis was formulated as follows:

**Oversizing the installed capacity of a wind or photovoltaic installation beyond its grid connection capacity improves the economic performance of the project despite the occurrence of curtailment.**

Under current technological conditions, implementing control systems that limit instantaneous power output to a desired setpoint presents no difficulty. Such solutions are already used in shared-capacity configurations, commonly known as *cable pooling*, in which two different generation technologies jointly utilise a single grid connection point up to a combined installed capacity of approximately twice the contracted grid capacity.

To analyse the impact of oversizing on generation limitations, hourly generation histograms for wind and photovoltaic sources published by Polskie Sieci Elektroenergetyczne S.A. (PSE) were used. The analysis covered the period from 1 January to 31 December 2020 with hourly resolution. As the data represent aggregated national generation, additional information on installed capacity provided by Agencja Rynku Energii S.A. (ARE) was used to construct standardised reference generation profiles.

A 30 MWp photovoltaic installation and a 30 MW wind farm were adopted as reference units. These capacities reflect typical sizes of commercial renewable projects requiring grid connection at the 110 kV level.

### **Data sources and selection**

Hourly national generation profiles for PV and wind (PSE, 01.01–31.12.2020) were used. The dataset was pre-processed to remove gaps: short interruptions (<3 h) were filled using linear interpolation, while longer missing intervals were replaced with the median of corresponding hours by weekday and month. The data were scaled to match reference installations of 30 MW (wind) and 30 MWp (PV), following the methodology presented earlier in the paper and results in Tables 2–3 and 5–6.

The following assumptions were applied:

- The wind farm and PV plant are subject to a constant power export limit equal to the contracted grid capacity (30 MW).
- Curtailment occurs instantaneously whenever gross generation exceeds the limit.
- The baseline scenario assumes a constant electricity price of 85 EUR/MWh.
- No storage, hybridisation or market optimisation is included in the base model.
- Historical PSE generation profiles are considered statistically representative of the operation of hypothetical 30 MW / 30 MWp installations.

### **Calculation procedure and evaluation criteria**

For a given oversizing factor  $k$ , the following steps were applied:

1. **Gross generation profile:**

Compute the gross generation profile  $G_t(k)$ .

2. **Grid export limitation:**

Apply the grid connection constraint  $P^{\text{grid}}$  (here: 30 MW):

$$E_t(k) = \min \{G_t(k), P^{\text{grid}}\}.$$

3. **Curtailment losses:**

Determine curtailment:

$$L_t(k) = G_t(k) - E_t(k),$$

and count all hours with curtailment, i.e. those for which  $L_t(k) > 0$ .

**4. Aggregation:**

Aggregate hourly results into annual production volumes and annual curtailment losses, as reported in Tables 2–3 (wind/PV).

**5. PV-specific DC/AC relationship:**

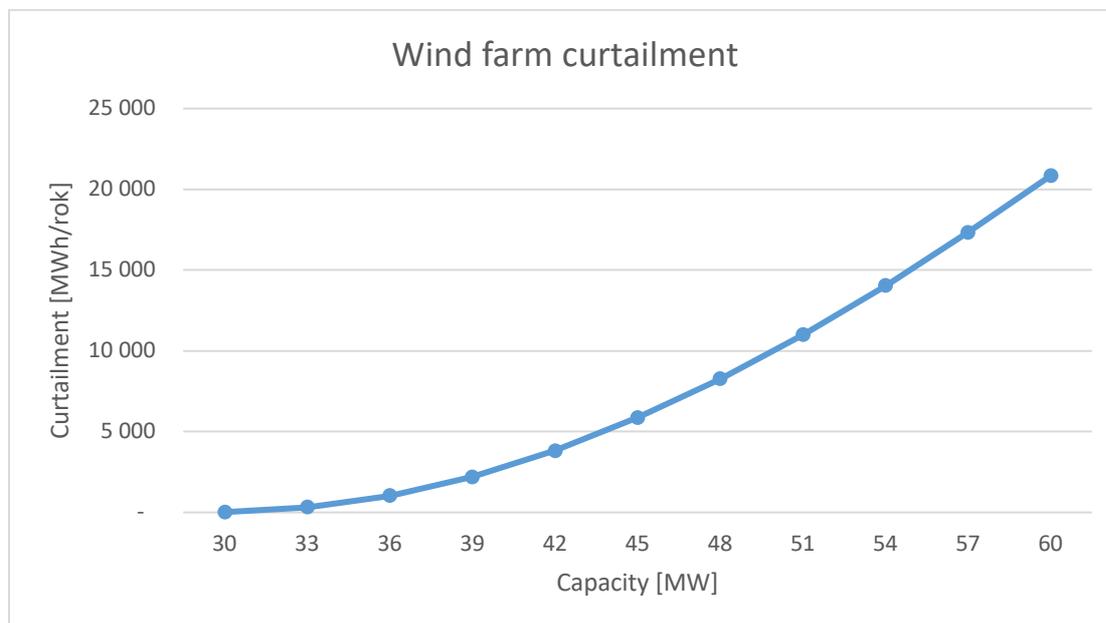
For photovoltaic systems, the DC/AC relationship was explicitly considered: the PV module profile is scaled to  $k \cdot P_{DC}^{grid}$ , while inverters limit AC output to  $P^{grid}$ .

**Table 2.** Curtailment levels for a wind farm with an assumed grid connection capacity of 30 MW.

Capacity [MW]	Production with no curtailment	Reduced production	No. of reduction hours	Reduction scale
30	78 837 MWh	78818 MWh	24	- 18 MWh
33	86720 MWh	86408 MWh	185	- 311 MWh
36	94604 MWh	93564 MWh	332	- 1 039 MWh
39	102487 MWh	100288 MWh	547	- 2 199 MWh
42	110371 MWh	106545 MWh	735	- 3 826 MWh
45	118255 MWh	112392 MWh	915	- 5 863 MWh
48	126138 MWh	117865 MWh	1 094	- 8 273 MWh
51	134022 MWh	123024 MWh	1 264	- 10 997 MWh
54	141906 MWh	127876 MWh	1 438	- 14 029 MWh
57	149789 MWh	132463 MWh	1 581	- 17 326 MWh
60	157673 MWh	136835 MWh	1 728	- 20 837 MWh

Source: authors' own elaboration.

**Figure 3.** Wind farm generation curtailment as a function of oversizing beyond the agreed grid connection capacity.



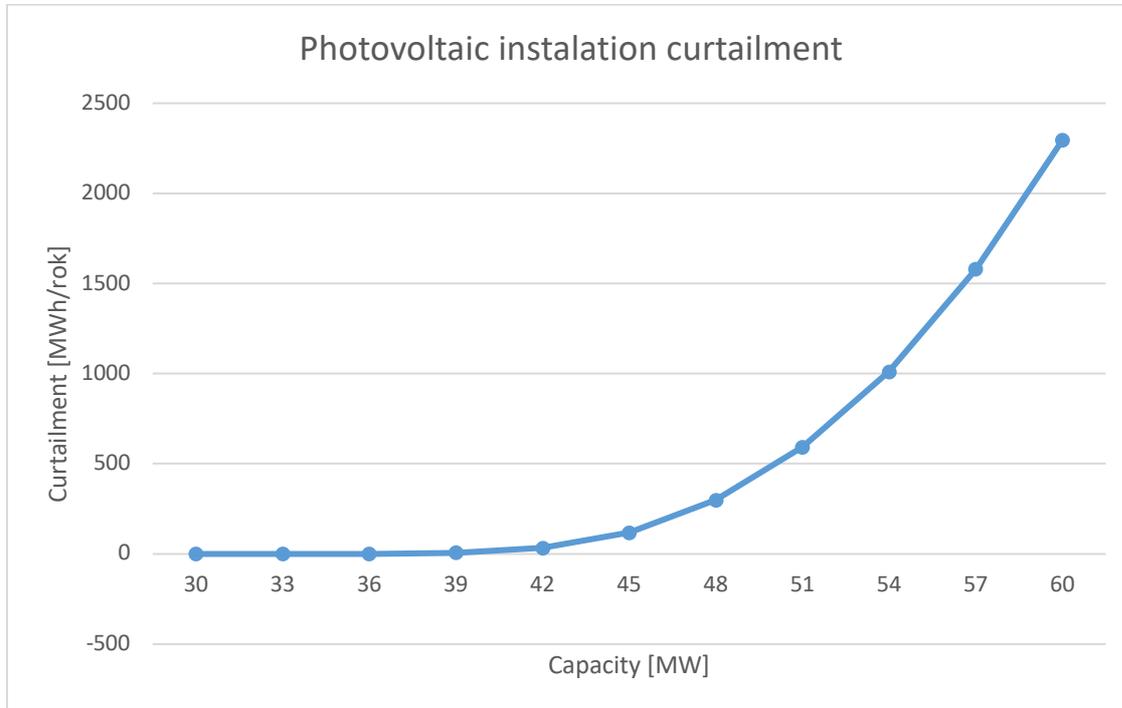
Source: authors' own elaboration.

**Table 3.** Generation curtailment of the photovoltaic farm for the assumed grid connection capacity of 30 MW.

Capacity [MW]	Production with no curtailment	Reduced production	No. of reduction hours	Reduction scale
30	30 450 MWh	30450 MWh	0 h	0 MWh
33	33 495 MWh	33495 MWh	0 h	0 MWh
36	36 540 MWh	36540 MWh	0 h	0 MWh
39	39 585 MWh	39578 MWh	7 h	6 MWh
42	42 630 MWh	42596 MWh	19 h	33 MWh
45	45 675 MWh	45557 MWh	59 h	117 MWh
48	48 720 MWh	48421 MWh	115 h	298 MWh
51	51 765 MWh	51172 MWh	186 h	592 MWh
54	54 810 MWh	53798 MWh	264 h	1 011 MWh
57	57 855 MWh	56275 MWh	353 h	1 579 MWh
60	60 900 MWh	58605 MWh	449 h	2 294 MWh

Source: Authors' own elaboration.

**Figure 4.** Photovoltaic plant generation curtailment as a function of oversizing beyond the agreed grid connection capacity.



Source: authors' own elaboration.

**Table 4.** Economic assumptions for the profitability analysis of different oversizing scenarios for generating installations.

	Wind Farm	Photovoltaics
CAPEX/MW	-€ 1 500 000	-€ 850 000
OPEX/MW	-€ 50 000	-€ 10 000
Energy price/MWh	€ 85	
Lifetime	25 years	
Inflation	2,50%	
Discount rate	9%	

Source: authors' own elaboration.

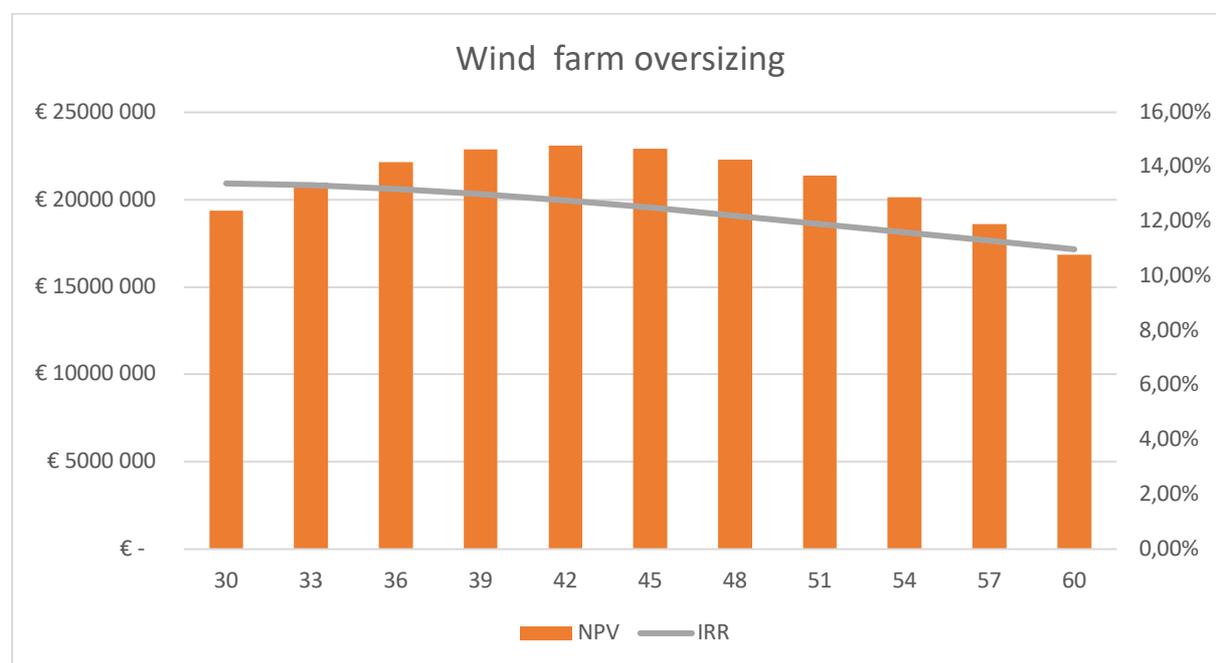
To evaluate the oversizing strategy, an indicator-based analysis was applied, using the Net Present Value (NPV) and Internal Rate of Return (IRR). Additionally, the Full Load Equivalent (FLE) metric was calculated, which expresses the utilisation level of the grid connection capacity over the operating period.

**Table 5.** Results of the indicator analysis for a wind farm under different levels of oversizing beyond the agreed grid connection capacity.

<b>Moc</b>	<b>CAPEX</b>	<b>NPV</b>	<b>IRR</b>	<b>FLE</b>
30	-€ 45 000 000	€ 19 364 717	13,40%	29,99%
33	-€ 49 500 000	€ 20 994 013	13,34%	32,88%
36	-€ 54 000 000	€ 22 166 651	13,20%	35,60%
39	-€ 58 500 000	€ 22 884 816	13,02%	38,16%
42	-€ 63 000 000	€ 23 111 233	12,78%	40,54%
45	-€ 67 500 000	€ 22 906 466	12,51%	42,77%
48	-€ 72 000 000	€ 22 308 561	12,22%	44,85%
51	-€ 76 500 000	€ 21 380 735	11,92%	46,81%
54	-€ 81 000 000	€ 20 128 722	11,61%	48,66%
57	-€ 85 500 000	€ 18 598 661	11,29%	50,40%
60	-€ 90 000 000	€ 16 841 838	10,98%	52,07%

Source: authors' own elaboration.

**Figure 5.** Results of the indicator analysis for the oversizing of a wind farm installation.



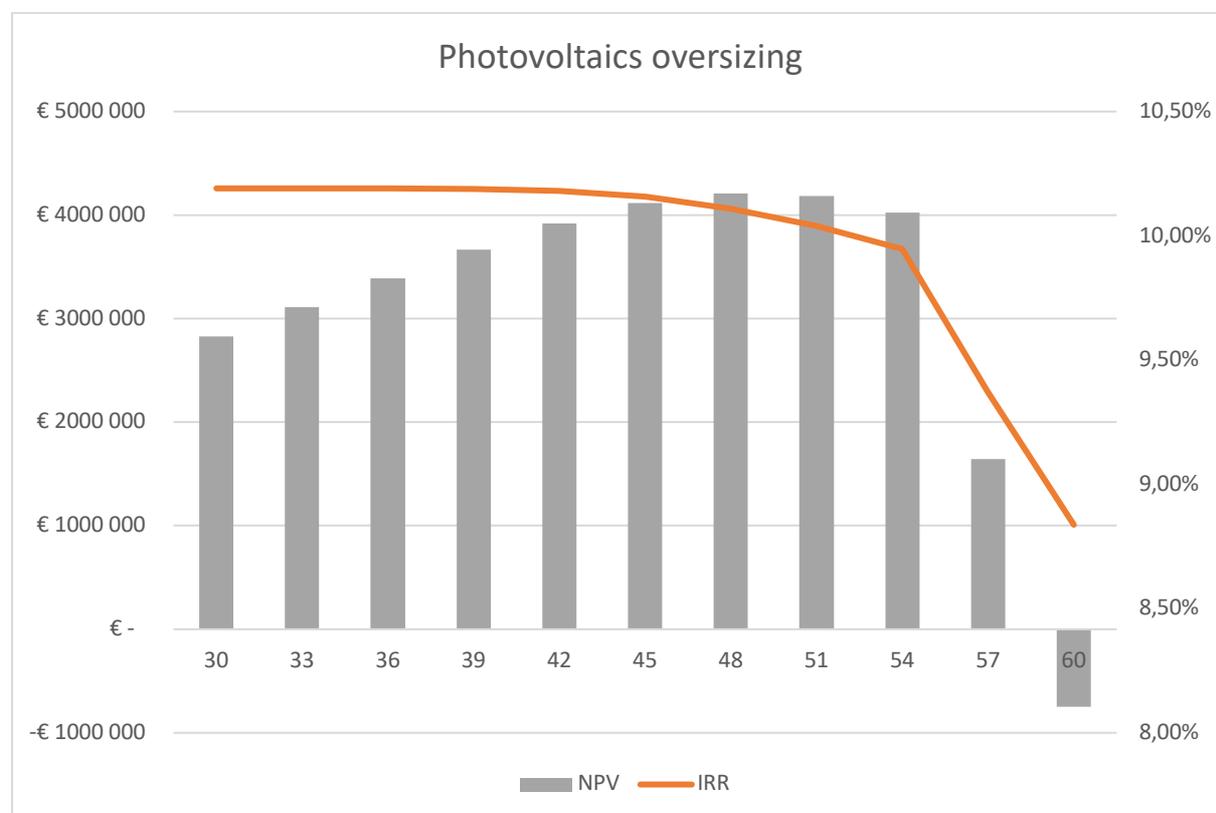
Source: authors' own elaboration.

**Table 6.** Results of the indicator analysis for a photovoltaic farm under different levels of oversizing beyond the agreed grid connection capacity.

Moc	CAPEX	NPV	IRR	FLE
30	-€ 25 500 000	€ 2 825 971	10,19%	11,59%
33	-€ 28 050 000	€ 3 108 568	10,19%	12,75%
36	-€ 30 600 000	€ 3 391 165	10,19%	13,90%
39	-€ 33 150 000	€ 3 667 193	10,19%	15,06%
42	-€ 35 700 000	€ 3 921 389	10,18%	16,22%
45	-€ 38 250 000	€ 4 115 301	10,16%	17,38%
48	-€ 40 800 000	€ 4 207 425	10,11%	18,54%
51	-€ 43 350 000	€ 4 181 126	10,04%	19,70%
54	-€ 45 900 000	€ 4 022 944	9,95%	20,86%
57	-€ 48 450 000	€ 1 642 673	9,37%	22,01%
60	-€ 51 000 000	-€ 749 297	8,84%	23,17%

Source: authors' own elaboration.

**Figure 6.** Results of the indicator analysis for the oversizing of a photovoltaic farm installation.



Source: authors' own elaboration.

## Sensitivity analysis

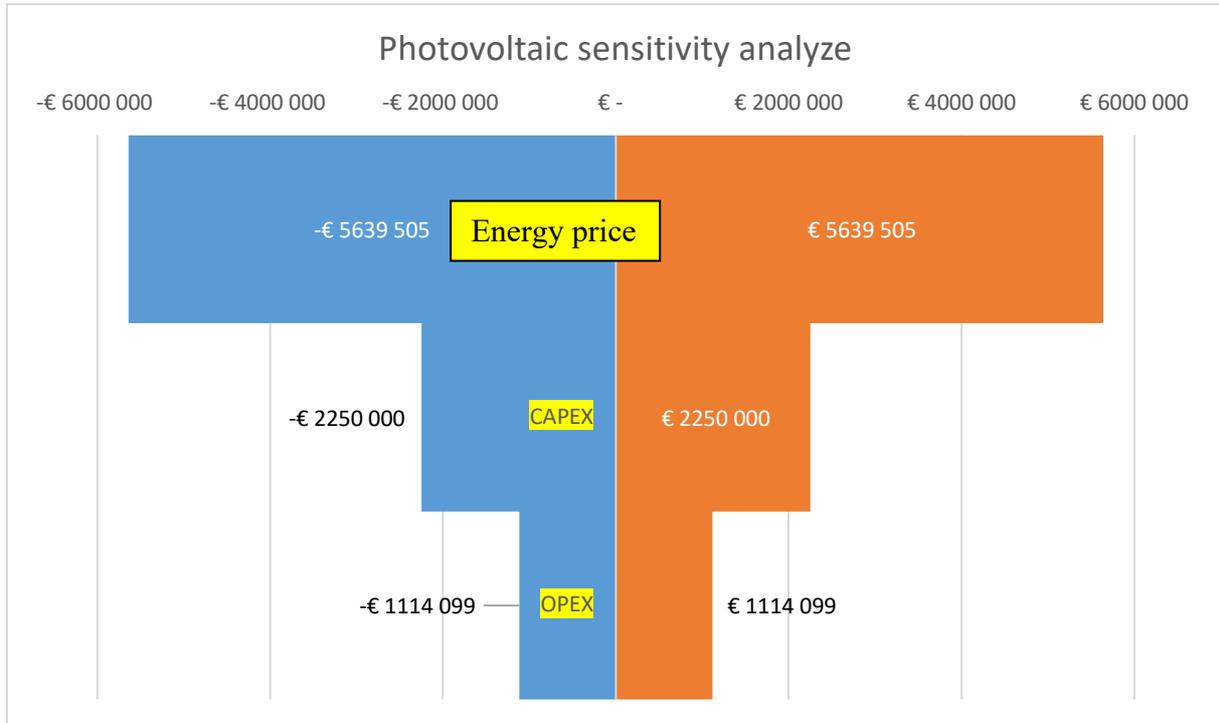
The sensitivity analysis was conducted based on variations in the project’s key economic parameters—capital expenditures (CAPEX), operational expenditures (OPEX), and the electricity sale price. For each factor, the Net Present Value (NPV) was calculated under the baseline scenario and under assumed increases and decreases of the respective parameter by a specified percentage. The results were then presented graphically in the form of a tornado chart, which enables comparison of the relative impact of each variable on the financial performance of the investment. For the baseline scenario, the installed capacity was assumed to be 45 MWp for the photovoltaic installation and 45 MW for the wind farm. Table 7 presents the assumptions adopted for the sensitivity analysis for both generation technologies.

**Table 7.** Assumptions adopted for the sensitivity analysis.

Photovoltaic facility						
CAPEX	-€	800 000	-€	850 000	-€	900 000
OPEX	-€	8 000	-€	10 000	-€	12 000
Energy price	€	85	€	75	€	95
Wind farm						
CAPEX	-€	1 500 000	-€	1 250 000	-€	1 750 000
OPEX	-€	50 000	-€	65 000	-€	35 000
Energy price	€	85	€	75	€	95

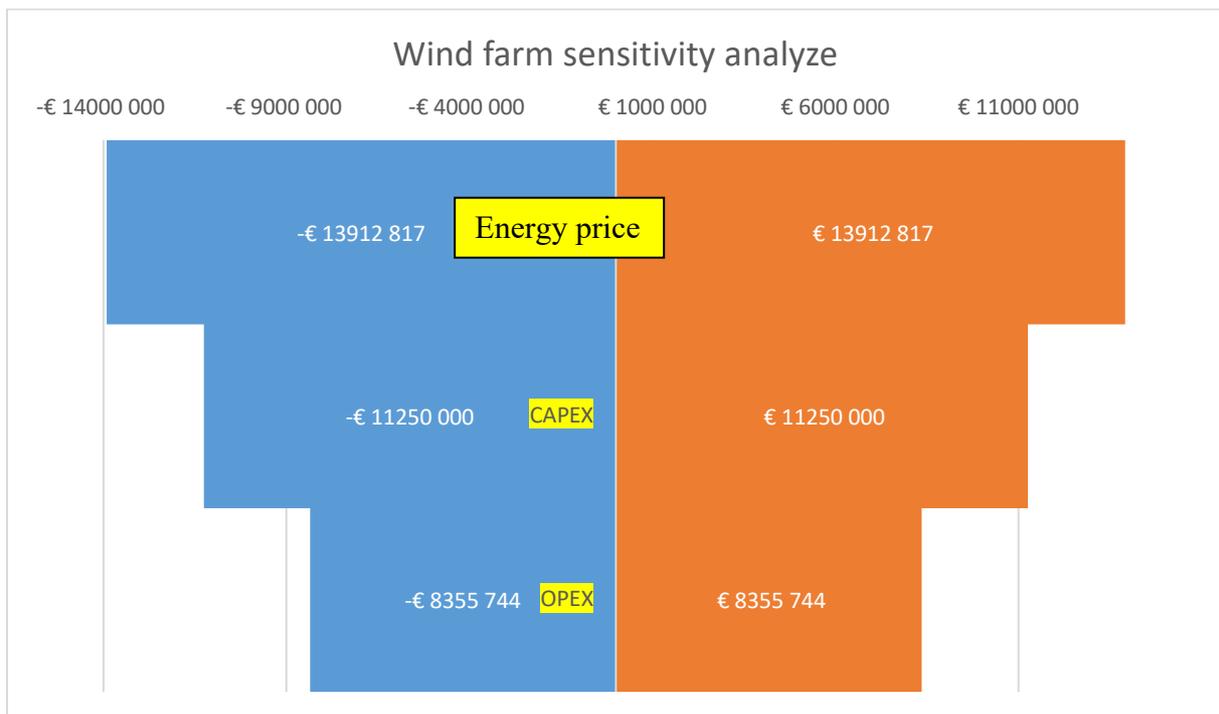
Source: authors’ own elaboration.

**Figure 7.** Results of the indicator-based analysis for oversizing a photovoltaic farm installation.



Source: Authors' own elaboration.

**Figure 8.** Results of the indicator-based analysis for oversizing a photovoltaic farm installation.



Source: Authors' own elaboration.

## **Sensitivity analysis**

The sensitivity analysis conducted for both the photovoltaic and wind farms indicates that the strongest factor affecting the net present value (NPV) of both investments is the change in the electricity price. Even small deviations in this parameter lead to significant differences in the financial outcomes of the projects, confirming their high exposure to fluctuations in market energy prices. Variations in capital expenditures (CAPEX) and operating expenditures (OPEX) have a noticeable but considerably smaller impact on project profitability.

In the case of the wind farm, a greater amplitude of NPV variation is observed in response to the same parameter changes compared with the photovoltaic installation. This results from the higher capital intensity of wind investments and the greater variability of their revenues. These findings highlight the importance of market risk and the need to incorporate it into investment assessments, particularly with regard to energy contracting strategies and revenue management in renewable energy projects.

## **Discussion**

Based on the analyses performed, it can be concluded that oversizing both wind and photovoltaic installations beyond the agreed grid connection capacity improves the efficiency of connection utilization and is justified by enhanced project profitability.

For the wind farm, under the assumed parameters, the optimal oversizing level is 40%. Although oversizing leads to a reduction in the internal rate of return (IRR), it increases the net present value from EUR 19.3 million to EUR 23.1 million, while raising the connection efficiency from 30% to 40.5%.

For the photovoltaic installation, oversizing also proved to be a rational strategy. Curtailment occurred only above 40% oversizing, while the maximum NPV was achieved at 60% oversizing (48 MWp). The difference relative to the wind farm results from PV's lower propensity to reach peak generation, leading to inverter clipping—commonly expressed through the DC/AC ratio, typically ranging from 1.15 to 1.35 depending on the investor. Oversizing increased the NPV from EUR 2.8 million to EUR 4.2 million and improved connection efficiency from 11.6% to 18.5%. It may therefore be concluded that PV's weaker capability to reach full installed capacity justifies a higher oversizing level than in the case of wind farms.

## **Conclusions**

The ongoing energy transition faces significant challenges. One of the most critical barriers is the limited capacity of the power grid to connect new generation sources. It is therefore essential to search for opportunities to increase installed capacity through alternative mechanisms within the existing structure of the National Power System.

Given the methodology used by grid operators for assessing connection capacities—based on the assumption that a generating unit may operate at its full agreed capacity at any time—the question arises whether different types of generation, particularly weather-dependent units, actually utilize their grid connection to its full extent. According to data published by the Polish Transmission System Operator, Poland currently has a combined 28 GW of installed wind and photovoltaic capacity.

In this context, the study examined the feasibility of oversizing wind and PV installations beyond their agreed connection capacity. The results clearly demonstrate that such a strategy is both technically viable and economically justified. Moreover, the analyses show that substantial oversizing is possible (40% for wind, 60% for PV), leading to improved connection efficiency and enhanced investment economics.

Based on the results, it can be estimated that through oversizing alone, installed capacity could be increased—within the existing agreed grid connection capacities—to approximately 14 GW of wind and 28.8 GW of photovoltaic capacity. This perspective also suggests a new investment strategy: acquiring existing assets for the purpose of expanding them beyond their current configuration.

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# Maritime decarbonization and its strategies in the European Union: a bibliometric perspective with global implications

*Emir Gürlevük, Pervin Ersoy*

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**Abstract:** Although maritime transport is a fundamental component of global trade, it remains a significant source of greenhouse gas emissions due to its heavy reliance on fossil fuels. In recent years, maritime decarbonization has gained increasing academic attention, particularly within the context of the European Union's green transition policies. This study aims to map and analyze the scientific literature on maritime decarbonization with a specific focus on the European Union, employing a bibliometric approach. The analysis is based on peer-reviewed journal articles indexed in the Scopus database between 2020 and 2025. Bibliometric techniques were applied to examine publication trends, keyword co-occurrence patterns, and country-level collaboration networks, with visualizations generated using VOSviewer. The results indicate a rapid growth in research output, with dominant themes centered on alternative fuels, hydrogen, ammonia, renewable energy, and sustainability. European Union member states emerge as central actors in international research collaboration, reflecting the significant influence of EU climate and maritime policies. Overall, this study provides a structured overview of research trends and thematic priorities in the field of maritime decarbonization.

**Key words:** Maritime Decarbonization, European Union, Bibliometric Analysis, Sustainable Maritime Transport, Climate Policy

## Introduction

Global climate change driven by human-related greenhouse gas emissions has intensified the need for decarbonization across all economic sectors. Among these sectors, maritime transport plays a critical role in the global economy, carrying more than 80% of international trade volume while remaining heavily dependent on fossil fuels. As a result, maritime activities contribute a non-negligible share of global greenhouse gas emissions, prompting increasing regulatory and academic attention. In recent years, the European Union has emerged as a key regulatory actor in maritime decarbonization through its Green Transition agenda, including the European Green Deal, the integration of maritime transport into the EU Emissions Trading System, and the introduction of sector-specific regulations such as FuelEU Maritime. These initiatives not only influence shipping activities within the EU but also shape global research agendas and policy discussions related to maritime sustainability. Parallel to these regulatory developments, academic research on maritime decarbonization has expanded rapidly, addressing a wide range of topics such as alternative fuels, technological innovation, and regulatory frameworks. However, the growing body of literature remains fragmented across different

disciplines and thematic areas, making it difficult to obtain a structured overview of research trends, dominant themes, and geographic contributions.

In this context, bibliometric analysis offers a suitable methodological approach for systematically mapping the evolution and structure of maritime decarbonization research. By quantitatively analyzing publication patterns, keyword relationships, and country-level contributions, bibliometric methods enable a comprehensive assessment of how scholarly attention to maritime decarbonization particularly within the European Union context has developed over time. The article seeks to answer the following research questions:

1. How has academic research on maritime decarbonization evolved between 2020 and 2025?
2. How is scholarly research on maritime decarbonization distributed across countries?
3. Which dominant themes and keywords characterize the literature on maritime decarbonization in context of European Union?

## **1. Conceptual and literature background**

### **1.1. Maritime decarbonization as a research field**

#### **1.1.1. Conceptual definitions of decarbonization in the literature**

In the academic literature, decarbonization is generally defined as the process through which carbon emissions are reduced or entirely eliminated, with the ultimate aim of achieving net-zero emissions. Early scholarly discussions conceptualize decarbonization as the systematic reduction of carbon dioxide (CO<sub>2</sub>) and other greenhouse gas emissions resulting from human activities. One of the earliest academic discussions of the concept is attributed to Jesse H. Ausubel, who introduced decarbonization in 1995 within the context of climate change as the process of reducing the carbon intensity of primary energy, as cited in Wimbadi and Djalante (2020). Similarly, the IPCC's Fourth Assessment Report (2007) defines decarbonization as a long-term reduction in the average carbon intensity of primary energy, emphasizing gradual shifts in fuel composition and improvements in energy efficiency within the energy sector. Subsequent scholarly contributions have expanded this conceptualization by framing decarbonization as a broader climate change mitigation strategy. Williams and Bell (2022) define decarbonization as the substantial reduction of human-induced carbon and greenhouse gas emissions, highlighting the need for sector-specific strategies and clearly defined implementation

timelines. In the academic literature, decarbonization is defined through different but closely related conceptual frameworks depending on the sectoral and thematic focus of the studies. Within the context of global energy systems, decarbonization has been defined by Grubler and Nakicenovic (1996) as a reduction in the specific amount of carbon (or CO<sub>2</sub>) emitted per unit of primary energy consumed, emphasizing long-term structural changes in energy production and consumption patterns.

From a climate change perspective, the concept of “deep decarbonization” has been introduced to describe pathways aimed at reducing emissions to zero or near-zero levels in order to limit global warming (Johnson et al., 2023). This definition reflects the ultimate mitigation objective of decarbonization and highlights the scale of emissions reductions required to meet climate targets. Complementing these approaches, decarbonization has also been conceptualized as an integral strategy for climate change mitigation. In this regard, Tabor and Rafferty (2024) characterize decarbonization as a comprehensive process focused on systematically reducing carbon dioxide and other greenhouse gas emissions across economic activities, reinforcing its role as a central concept within contemporary climate and sustainability research.

### **1.1.2. Decarbonization as a multidimensional transformation**

Within the academic literature, decarbonization is increasingly framed as a systematic transformation that extends across multiple economic sectors rather than as a narrowly defined technical intervention. Decarbonization is increasingly conceptualized in the academic literature as a system-wide transformation that extends across multiple economic sectors rather than as a narrowly defined technical intervention. In this context, Sachs et al. (2019) frame decarbonization as a comprehensive transition requiring deep structural changes across key sectors such as energy systems, industry, transportation, and urban infrastructure, with the objective of achieving net-zero greenhouse gas emissions in line with long-term climate targets. Building on this perspective, the literature emphasizes that decarbonization constitutes a multidimensional process encompassing not only technological solutions but also broader economic, social, and political transformations. Studies underline that effective decarbonization pathways require fundamental changes in production and consumption patterns, institutional arrangements, and governance frameworks, reflecting the complexity of transitioning toward low-carbon systems.

Accordingly, decarbonization research commonly addresses a wide range of sectors, such as energy, industry, buildings, agriculture and land use, carbon capture and storage (CCS), as well as transportation and policy-related dimensions. This sectoral breadth illustrates that decarbonization cannot be confined to a single domain, but instead represents an integrated transformation process involving diverse actors, sectors, and policy arenas. One of the primary drivers of global climate change is the increase in greenhouse gas emissions resulting from human activities. Among these emissions, carbon dioxide accounts for the largest share, being released into the atmosphere through fossil fuel combustion, industrial processes, and deforestation (Türkeş, 2008). The volume and sectoral distribution of these emissions are considered critical for the development of effective climate policies and decarbonization strategies.

In this context, data on the sectoral distribution of greenhouse gas emissions clearly demonstrate why decarbonization efforts tend to concentrate on specific sectors. According to observed data from 2021, greenhouse gas emissions are monitored across sectors such as energy, agriculture, industrial processes, waste, and land use. Among these, the energy sector stands out as the dominant source of global greenhouse gas emissions. This situation highlights why improvements in the energy sector occupy a central role in decarbonization policies. The expansion and promotion of renewable energy are therefore regarded as effective instruments for limiting emission growth and supporting a more sustainable energy transition (Ge et al., 2024).

### **1.1.3. Fragmentation and scope of the decarbonization literature**

The academic literature on decarbonization is characterized by a high degree of conceptual and thematic diversity. References to decarbonization can be found across different sectors and disciplinary perspectives, indicating that the concept is not confined to a single analytical framework. As a result, defining decarbonization within one specific scientific discipline is increasingly regarded as insufficient to capture its full scope. This diversity is further reinforced by the expansion of decarbonization research across multiple thematic domains, including energy systems, climate change mitigation, economic transformation, and sector-specific transition pathways. While this broad coverage reflects the growing relevance of decarbonization, it also contributes to a fragmented body of literature in which studies are dispersed across different research traditions and policy contexts. Such fragmentation complicates efforts to develop a comprehensive overview of how decarbonization research has evolved over time and how its key themes are interconnected. Consequently, systematic approaches such as bibliometric analysis

become particularly relevant for mapping the structure, thematic patterns, and development trajectories of the decarbonization literature.

## **1.2. Decarbonization in maritime transport and its strategies**

Maritime transport is identified as one of the fundamental pillars of the global economy, with over 80% of the volume of goods traded worldwide being carried by this sector (UNCTAD, 2024). Despite its critical role, maritime transport contributes significantly to global greenhouse gas emissions due to its heavy reliance on fossil fuels. Emissions from maritime transport are primarily generated through the combustion of fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO) in ship engines, resulting in the release of carbon dioxide as well as other air pollutants, including sulfur oxides, nitrogen oxides, and particulate matter (Mueller et al., 2022). Although the maritime sector accounted for 2.76% of global greenhouse gas emissions in 2012, this share increased to 2.89% in 2018 (IMO, 2020). Considering the scale of the sector and the expected growth in global trade volumes, these trends underline the necessity of implementing effective decarbonization strategies in maritime transport. Beyond climate impacts, studies have shown that emissions from maritime transport also pose significant public health risks, particularly in port regions and along major shipping routes (Mueller et al., 2022; Viana et al., 2020). In response to these environmental and health-related challenges, both industry practitioners and the academic literature increasingly emphasize the need for comprehensive decarbonization pathways in the maritime transport sector. Within this context, the literature identifies alternative fuels as one of the central strategies for reducing greenhouse gas emissions from maritime transport, forming the first major pathway toward decarbonization in the sector.

### **1.2.1. Alternative fuels in maritime transport**

Alternative fuels are widely recognized in the literature as a key strategy for maritime decarbonization, aiming to reduce the sector's dependence on conventional fossil fuels. Cleaner alternative marine fuels and energy sources discussed in the literature include liquefied natural gas (LNG), liquefied biogas (LBG), hydrogen, ammonia, methanol, ethanol, hydrotreated vegetable oil (HVO), fuel cells, nuclear energy, wind energy, solar energy, and electricity (Wang et al., 2022). Among these options, LNG has attracted significant attention as a marine fuel, particularly in the context of compliance with sulfur and nitrogen oxide (NOx) regulations (Anderson et al., 2015). Due to its relatively high efficiency and lower emissions compared to

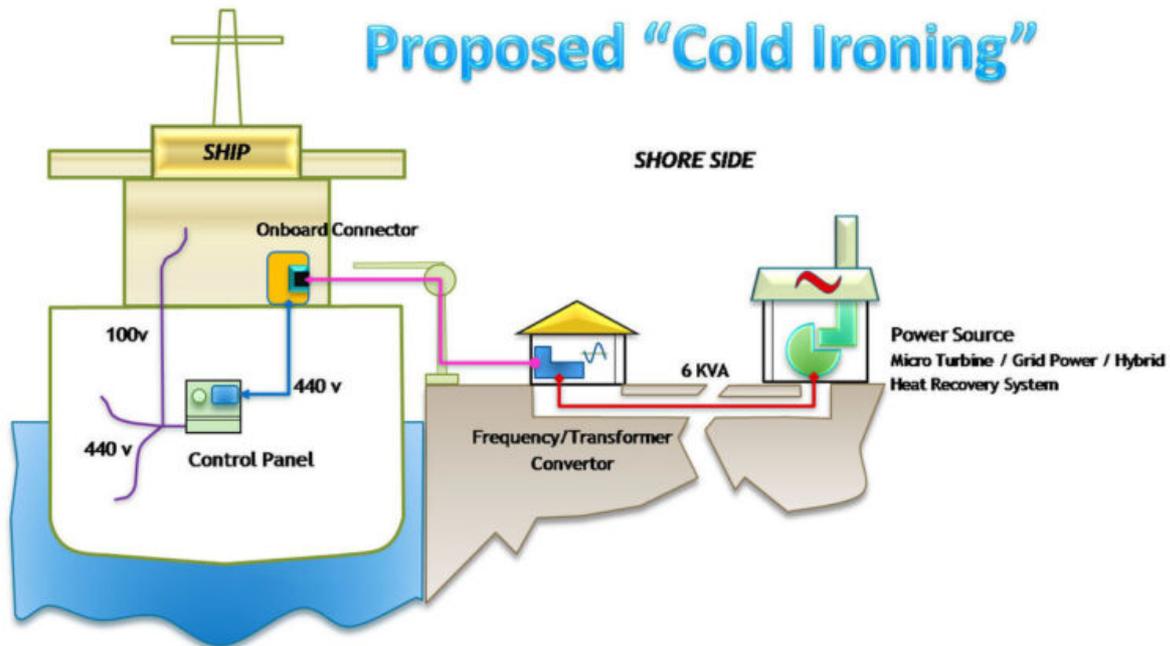
traditional marine fuels, LNG has historically been identified as the most extensively studied alternative fuel in maritime research (Wang et al., 2022; Zhu et al., 2022).

However, recent literature indicates a gradual shift in research focus toward fuels such as methanol, ammonia, and hydrogen, which are increasingly discussed as potential long-term solutions for achieving deeper decarbonization in maritime transport (Ampah et al., 2021). Methanol, in particular, is highlighted as a promising alternative fuel for the future of the sector, with studies emphasizing its potential to improve engine efficiency while reducing carbon dioxide and nitrogen oxide emissions compared to conventional marine fuels (Zincir & Deniz, 2021). Similarly, hydrogen is frequently characterized as a promising option due to its carbon-free structure and the absence of carbon dioxide, particulate matter, and sulfur oxide emissions during combustion, although nitrogen oxide emissions may still occur under certain conditions (Ciniviz & Köse, 2012; Ampah et al., 2021). Within the literature, hydrogen is often presented as a long-term, renewable, and comparatively low-polluting fuel option for maritime applications.

Despite the growing consensus on the necessity of alternative fuels for reducing emissions from maritime transport, the literature also emphasizes the importance of addressing safety, storage, and operational challenges associated with their use. In particular, the toxic and corrosive properties of ammonia, the fire and explosion risks related to LNG, and the wide flammability range of hydrogen are identified as significant barriers that must be carefully managed to enable large-scale adoption (Wang et al., 2022; SGMF, 2023). These considerations suggest that alternative fuels constitute a central yet complex component of maritime decarbonization strategies rather than a standalone solution.

### **1.2.2. Shore power and electrification**

One of the methods used to reduce emissions from ships is known as “shore power” or “cold ironing.” This technique involves supplying electricity from shore while a vessel is docked, allowing ships to meet their energy needs without relying on onboard auxiliary generators and thereby reducing emissions (Innes & Monios, 2018).

**Figure 1.** Proposed Cold-Ironing (Shore Power).

Source: Photo by: Pawanexh Kohli.

As illustrated in Figure 1., during the cold ironing process, the vessel shuts down its engines upon berthing and connects to shore-based electricity, allowing essential onboard services to continue without interruption (SAFETY4SEA, 2019).

According to the study conducted by Innes and Monios (2018), shore power technology installed at medium-sized ports is projected to reduce approximately 4,767 tons of CO<sub>2</sub> and other harmful emissions. In a related study by Nur et al. (2025), shore power connections (SPC) were found to reduce sulfur dioxide (SO<sub>2</sub>) and nitrogen oxide (NO<sub>x</sub>) emissions by an average of 55%, and operational costs by approximately 60%, compared to the use of auxiliary engines while ships are docked. When implemented correctly, shore power not only contributes to improved air quality but also provides additional benefits emphasized in the literature, including enhanced onboard comfort during port stays, the development of an environmentally friendly image for shipowners and clients, and a reduction in total life-cycle costs due to lower fuel consumption and maintenance requirements (Arduino et al., 2011).

With the advancement of the modern era, such emerging technologies have enhanced the effectiveness of decarbonization strategies. Growing global concerns regarding sustainability and environmentally friendly development, together with technological progress, have encouraged the maritime logistics sector to turn toward digitalization in order to reduce its

environmental impact. In this context, developments discussed in the following section include concepts such as smart ports, smart ships, digital twins, and Internet of Things (IoT) integrations.

### **1.2.3. Digitalization**

Digitalization is regarded as both a strategy and a responsibility aimed at reducing carbon emissions on a global scale (Blažina et al., 2022). One of the developments brought to the sector by digitalization is smart ports, which represent a level of digital transformation that utilizes advanced digital technologies such as the Internet of Things (IoT), artificial intelligence, cloud computing, and digital twins. The primary objective of smart ports is to reduce the need for human labor through automation, accelerate operations, and enable more profitable use of resources through online applications that enhance efficiency for all stakeholders (Yorulmaz & Deric, 2023). The transformation of traditional ports into smart ports can be achieved by reaching the required level of digitalization through the establishment of high-speed internet infrastructure and effective internal data networks within the port (Öztemiz, 2023).

Smart ships, on the other hand, constitute a critical component of decarbonization efforts within the maritime sector's digitalization process. Artificial intelligence (AI) algorithms analyze variables such as weather conditions, ocean currents, and fuel consumption to determine the most optimal routes. These systems can reduce fuel consumption by up to 10% and shorten voyage durations, thereby increasing operational efficiency (Raviv, 2025). Beyond fuel efficiency, smart ships also offer additional benefits such as increased profitability, reduced personnel costs, and improved navigational safety (Yorulmaz & Karabulut, 2021). Digital technologies play a key role in enhancing fuel efficiency, reducing emissions, and mitigating the environmental impacts of maritime transportation. Furthermore, the integration of digitalization and automation significantly contributes to energy-efficient operations in the maritime sector (Zeng et al., 2025).

### **1.3. European union's green transition strategy and global impacts**

#### **1.3.1. European green deal's strategic framework on maritime transport**

The Green Deal is a strategy adopted by the European Union (EU) in 2019, aiming to achieve its core goals in combating climate change and promoting sustainability. As part of this strategy, the EU targets becoming carbon neutral by 2050, increasing energy efficiency, expanding the use of clean energy sources, supporting environmentally friendly transportation systems, and strengthening the green economy (Ersöz, 2023).

For instance, under the EU Green Deal, it is planned that all new cars and light commercial vehicles will be zero-emission by 2035. In line with this, a significant reduction in vehicle emissions is projected by 2030, and road transport is expected to become entirely zero-emission by 2050 (European Commission, 2021). Moreover, these regulations are not limited to road transport; they also include measures for the aviation and maritime sectors. For example, targets have been set to gradually reduce the average annual greenhouse gas intensity of the energy used in ships, and the use of renewable and low-carbon fuels is being promoted. (Gürlevük, 2024)

The European Green Deal is implementing a series of policies and regulations to reduce emissions and enhance sustainability in the maritime sector. The European Climate Law has made it a legal obligation for the EU to reduce its emissions by at least 55% by 2030. To meet this target and achieve climate neutrality across the EU by 2050, member states have adopted new legislation (European Council, n.d.). One of the most significant steps taken in this context is the inclusion of maritime transport in the European Union Emissions Trading System (EU ETS). Through this regulation, emissions generated by large ships calling at EU ports have been brought under a market-based carbon pricing mechanism, with the aim of internalizing the environmental costs associated with maritime transport and supporting investments that promote emission reductions within the sector (European Commission, n.d.a).

In addition to the EU ETS, the FuelEU Maritime Regulation has emerged as another important policy initiative targeting emissions from maritime transport. FuelEU Maritime introduces limits on the greenhouse gas intensity of the energy used by ships operating in European ports and encourages the gradual adoption of renewable and low-carbon fuels. By adopting a technology-neutral and target-oriented approach, this regulation provides ship operators with flexibility in fuel and technology choices, while supporting innovative solutions and facilitating the adaptation of existing fleets (European Commission, n.d.c) (European Commission, n.d.b).

At the international level, the European Union aims to ensure regulatory coordination with the International Maritime Organization (IMO) in order to achieve coherence between regional and global decarbonization efforts. In this context, the EU supports IMO initiatives aimed at reducing greenhouse gas emissions from maritime transport, including technical and operational measures adopted under MARPOL Annex VI, such as the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). These measures contribute to aligning the EU's maritime decarbonization strategies with global regulatory frameworks and reinforce collective efforts toward achieving climate neutrality in the maritime sector (Avrupa Birliği Bakanlığı, 2025; ClassNK, 2022).

In line with international decarbonization efforts, the International Maritime Organization (IMO) has also introduced region-specific regulatory measures. A recent example is the designation of the Mediterranean Sea as an Emission Control Area (ECA), effective from May 1, 2025. This decision aims to reduce greenhouse gas emissions and air pollution from ships, while protecting human health and marine ecosystems by imposing stricter fuel sulfur limits on vessels operating in the region (Esenyel Partners, 2025). Such measures illustrate how regional environmental controls complement broader global and EU-level maritime decarbonization strategies (Sustainable Ships, n.d.).

### **1.3.2. EU's financial support and mechanisms**

In addition to regulatory measures, the European Union supports the green transition through a range of financial instruments designed to mobilize investment and facilitate the implementation of climate policies. The European Green Deal Investment Plan (also referred to as the Sustainable Europe Investment Plan) constitutes the financial backbone of the Green Deal by aiming to mobilize large-scale public and private investments for sustainable development. A substantial share of the EU's long-term budget for the 2021–2027 period is allocated to climate and environmental objectives, providing significant financial support for green transition initiatives (European Commission, 2020).

Complementing this approach, the Recovery and Resilience Facility (RRF), established under the NextGenerationEU framework, supports reforms and investments aimed at strengthening economic resilience while advancing climate and digital objectives. Member States are required to allocate a considerable portion of their national recovery plans to climate-related investments, thereby reinforcing the EU's commitment to sustainability-oriented growth (European Commission, n.d.d).

The InvestEU programme further enhances access to long-term financing by leveraging public guarantees to mobilize private investment in line with EU priorities, including the green and digital transition. By consolidating previous EU financial instruments, InvestEU reduces investment risks and improves funding accessibility for sustainable projects, including those related to clean energy and transport infrastructure (European Commission, n.d.e). In order to ensure a fair and inclusive transition, the Just Transition Mechanism (JTM) provides targeted support to regions and communities most affected by the shift toward a climate-neutral economy. This mechanism aims to mitigate socio-economic impacts by supporting regions with high carbon intensity and workforces dependent on fossil fuel industries (European Commission, n.d.f).

### **1.3.3. Global impacts of EU's green policies**

The European Green Deal encompasses policies that extend beyond the borders of the European Union and directly affect international trade and global competition. By explicitly considering the environmental impact of products consumed within the EU, regardless of their country of origin, the Green Deal introduces new compliance requirements for trading partners. As a result, goods exported to the EU may face additional costs based on their associated carbon emissions (Tunahan et al., 2023).

One of the most prominent instruments in this context is the introduction of carbon-related trade measures aimed at preventing carbon leakage. Such mechanisms are designed to address competitive imbalances by imposing additional costs on imports from countries with less stringent climate regulations or lower carbon pricing (Larch & Wanner, 2017). These measures signal a shift in global trade practices, encouraging firms and exporting countries to adopt cleaner production processes in order to maintain access to the EU market.

While the EU's environmental policies aim to promote global decarbonization, they also raise concerns regarding international competitiveness. If trading partners do not adopt similar climate commitments or if EU industries fail to maintain leadership in clean technologies, stricter environmental regulations may place European firms at a competitive disadvantage (Ecer et al., 2021). At the same time, the Green Deal incentivizes innovation and strategic repositioning, prompting companies worldwide to integrate sustainability into their production processes as a means of enhancing competitiveness in an increasingly carbon-conscious global market (Yüce, 2021).

The European Green Deal has significant implications for supply chain structures, particularly in sectors closely linked to maritime transport and logistics. As sustainability becomes

a core element of corporate strategy, companies are increasingly required to integrate environmental criteria into supplier selection, logistics operations, and procurement processes (Achillas et al., 2019). In the maritime context, this transformation affects fuel suppliers, port services, shipbuilders, and logistics providers, reshaping traditional supply chain relationships. The logistics sector plays a central role in enabling sustainable supply chains through transportation, storage, and distribution activities. The Green Deal emphasizes the monitoring of environmental performance across logistics networks, encouraging collaboration with suppliers that comply with environmental standards and decarbonization targets (Yolcu, 2023). Product-related regulations introduced under the EU's sustainability framework aim to promote circularity by increasing durability, recyclability, and the use of secondary raw materials, thereby influencing supply chain decisions from production to end-of-life stages (Fernandez-Stark & Bamber, 2024).

While these regulatory developments support the EU's climate objectives, they also introduce challenges for supply chain actors. Compliance costs, reporting requirements, and access to green technologies may place additional pressure on smaller firms, potentially leading to increased concentration within maritime-related supply chains. As a result, the Green Deal not only drives decarbonization but also reshapes competitive dynamics and supplier selection criteria within global maritime logistics networks (Fernandez-Stark & Bamber, 2024).

Based on the conceptual framework and policy-oriented literature discussed in the previous sections, it becomes evident that maritime decarbonization constitutes a rapidly expanding and highly fragmented research field shaped by technological developments, regulatory frameworks, and global sustainability objectives. Given the diversity of approaches, themes, and disciplinary perspectives observed in the literature, a systematic and quantitative method is required to comprehensively map the structure and evolution of research on maritime decarbonization. Therefore, this study adopts a bibliometric methodology to analyze the scientific literature in a structured and objective manner, enabling the identification of dominant research trends, thematic clusters, and emerging areas within the field.

## **2. Methodology**

Bibliometrics is a field of science that measures research activity and impact through quantitative data derived from scientific literature. While Pritchard (1969) defines this field as 'the application of mathematical and statistical methods to publications,' Broadus (1987) describes it as the quantitative study of published bibliographic units. This approach provides a quantitative description of publications through performance analysis and science mapping techniques (Zheng et al., 2023). According to De Bellis (2009), the primary objective of bibliometrics is to systematically identify patterns in the literature, such as production trends, institutional or country-based productivity, and academic collaboration structures. This method is particularly utilized to systematically identify the intellectual structure and evolutionary trends of a research topic in cases where the scope of the literature is too broad for manual review (Donthu et al., 2021). In recent years, comprehensive data access and visualization capabilities provided by academic databases such as Scopus and analysis software like VOSviewer have significantly increased scholarly interest in bibliometric analysis (Donthu et al., 2021)

### **2.1. Research design**

In line with the directions outlined in the previous section, this study employs a bibliometric analysis method to examine research trends in the literature on maritime decarbonization within the context of the European Union. The research design focuses on identifying publication trends, thematic structures, and collaboration patterns, rather than evaluating policy outcomes or technological effectiveness. The bibliometric findings are subsequently interpreted in connection with the conceptual and policy-oriented discussions presented in Sections 2.2 and 2.3, thereby linking the empirical mapping of the literature with maritime decarbonization strategies and EU-level regulatory developments. The methodological framework of the study is informed by Öztürk et al. (2024), titled "How to design bibliometric research: an overview and a framework proposal," and has been developed in accordance with established principles and stages of bibliometric research design.

### **2.2. Data source**

The Scopus database was used as the sole data source due to its broad coverage of peer-reviewed journals across maritime transport, energy, and environmental studies, as well as its standardized bibliographic metadata suitable for bibliometric analysis. All bibliographic data

were retrieved from the Scopus database on December 22, 2025. Conducting the search on a single date ensures consistency and reproducibility, as the database content is continuously updated.

### **2.3. Search strategy**

The literature search was conducted using the advanced search function of the Scopus database in order to systematically identify publications related to maritime decarbonization. The search query was constructed by combining the concept of decarbonization with key terms associated with maritime transport, using Boolean operators to ensure conceptual consistency and comprehensive coverage. Specifically, the search included the terms decarbonization AND (shipping OR “maritime transport” OR “maritime transportation”). To ensure temporal relevance and alignment with recent regulatory and policy developments, the search was limited to publications published between 2020 and 2025.

To maintain academic quality and consistency, only peer-reviewed journal articles and review papers written in English were included in the dataset, while conference papers, book chapters, editorials, and other non-peer-reviewed publications were excluded. The final dataset used for the bibliometric analysis consisted of 4,004 publications, which constitute the empirical basis of the study and are further described in the Results section.

### **2.4. Data processing**

Prior to analysis, the dataset was screened to remove duplicate records and to ensure basic relevance through title and abstract checks. This step aimed to improve data consistency without altering the original bibliographic information.

### **2.5. Bibliometric analysis techniques**

The bibliometric analysis employed techniques such as annual publication trend analysis, keyword co-occurrence analysis, and country-level publication assessment. These techniques enable the identification of dominant research themes and geographic research patterns within the literature.

### **2.6. Software and visualization tools**

All bibliometric analyses and network visualizations were conducted using VOSviewer, which facilitates the construction of bibliographic networks based on co-occurrence and collaboration relationships.

## **2.7. Methodological limitations**

Despite the systematic approach of this study, several methodological limitations should be acknowledged. First, the analysis relies exclusively on the Scopus database. While Scopus provides extensive coverage of high-impact maritime and environmental literature, the exclusion of other databases such as Web of Science or Google Scholar may result in the omission of some relevant studies. Second, the search was restricted to English-language publications, which may lead to a linguistic bias and the exclusion of significant regional research published in other languages. Finally, the study is limited to peer-reviewed journal articles and reviews, excluding gray literature, conference proceedings, and book chapters to ensure a high level of academic quality. While these limitations define the boundaries of the dataset, they do not compromise the overall reliability of the identified research trends and thematic patterns

## **3. Results**

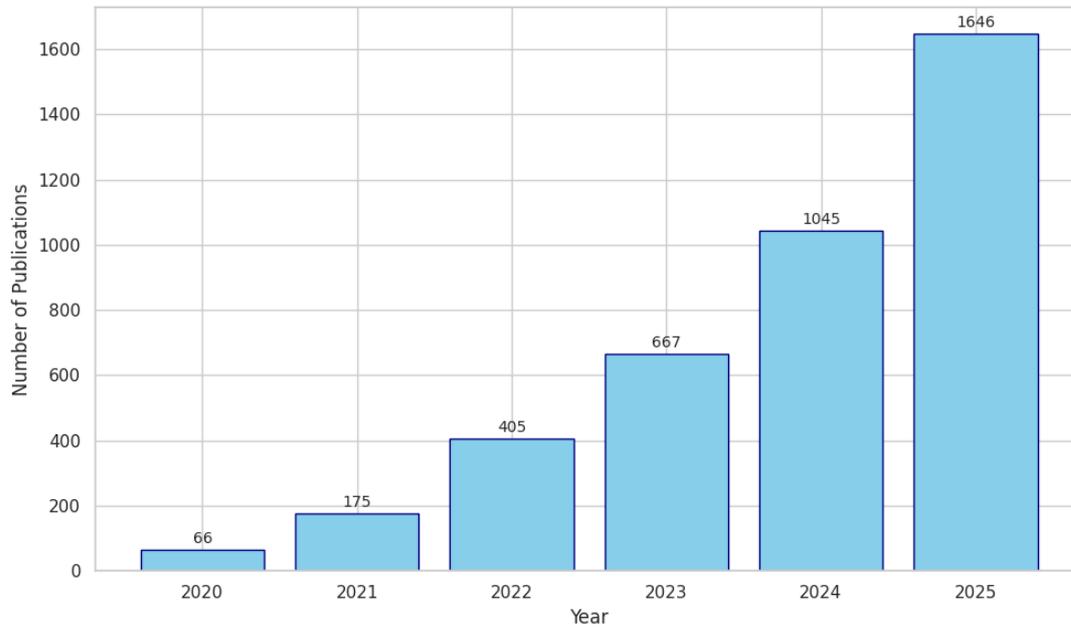
### **3.1. Descriptive overview of the dataset**

Following the data collection and screening process, a total of 4,004 publications published between 2020 and 2025 were included in the bibliometric analysis. These publications constitute the empirical basis of the study and reflect the recent evolution of academic research on maritime decarbonization.

### **3.2. Annual publication trends**

Figure 2 presents the annual distribution of publications on maritime decarbonization between 2020 and 2025 based on the Scopus dataset. The results indicate a strong upward trend in academic output over the analyzed period. While only 66 publications were recorded in 2020, the number increased steadily to 175 in 2021 and 405 in 2022. A more pronounced growth is observed from 2023 onwards, with 667 publications in 2023, rising sharply to 1,045 in 2024 and reaching 1,646 publications in 2025. This pattern demonstrates a rapidly growing academic interest in maritime decarbonization in recent years.

Maritime decarbonization and its strategies in the European Union: a bibliometric perspective with global implications



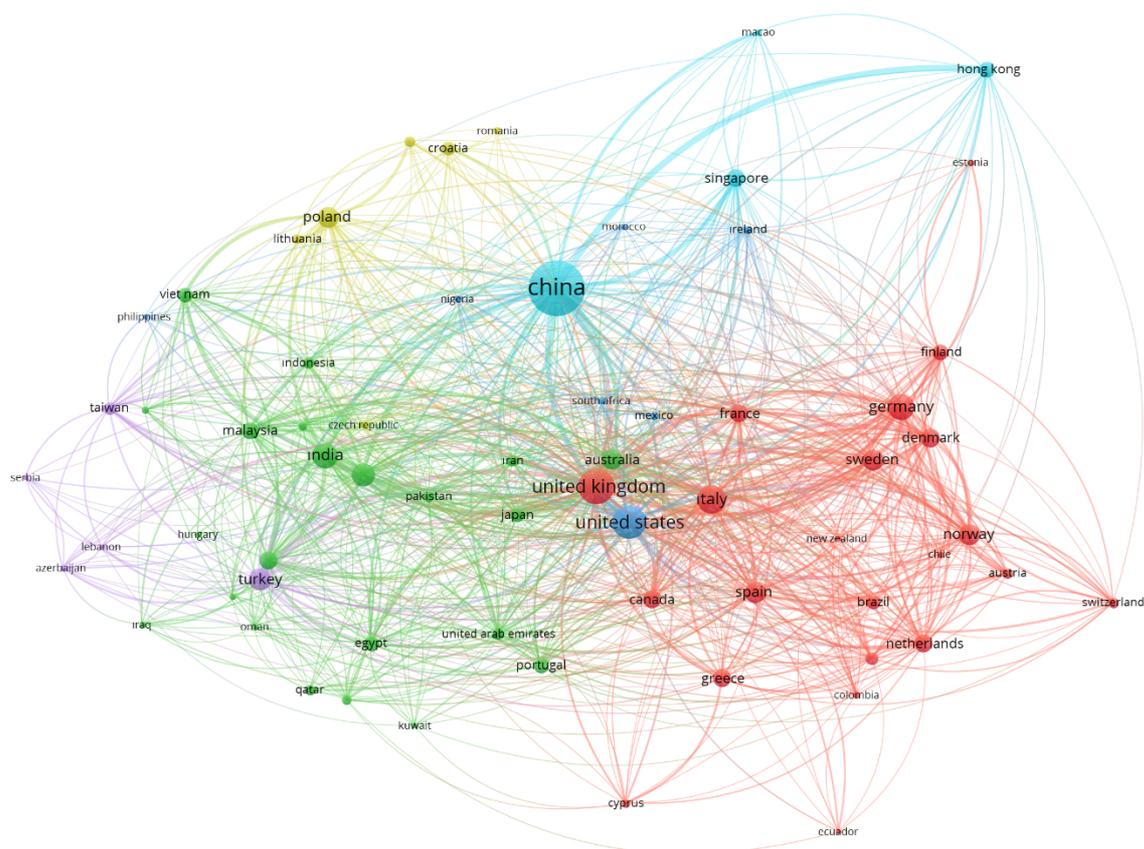
**Figure 2.** Annual number of publications on maritime decarbonization (2020–2025). Source: author’s own elaboration.



The clustering structure suggests that maritime decarbonization research is characterized by a multidisciplinary orientation, integrating technological solutions, energy-related topics, and sustainability considerations. The proximity and linkages between keywords reflect the interconnected nature of research themes within the field.

### 3.4. Country-level publication analysis

Figure 4. Country Collaboration Network in Maritime Decarbonization Research



Source: author's own elaboration

A country-level co-authorship analysis was conducted to examine the geographical distribution of research output and international collaboration patterns in maritime decarbonization studies (Figure 4). The analysis was based on Scopus data and visualized using VOSviewer, with a minimum threshold of 10 publications per country.

The results indicate that research activity is highly concentrated in a limited number of countries. China emerges as the most prominent contributor, occupying a central position in the collaboration network. Several European Union member states, including Germany, the Netherlands, Sweden, and Italy, also demonstrate strong research output and dense collaborative links, reflecting the influence of EU-level climate and maritime policies.

In addition, the United Kingdom and the United States appear as key international hubs connecting different regional clusters. The presence of cross-regional collaboration links suggests that maritime decarbonization research is characterized by an increasingly global research network, although the intensity of collaboration varies across regions.

Although the analysis reflects a global collaboration network, the strong presence of European Union member states and their dense interconnections indicate the influence of EU-level regulatory and policy frameworks on research activity. Moreover, the central positioning of non-EU countries such as China and the United States suggests that EU maritime decarbonization policies have implications beyond regional boundaries, shaping research agendas at the global level.

#### **4. Discussion**

This study provides a comprehensive bibliometric overview of the academic literature on maritime decarbonization within the context of the European Union. By systematically mapping publication trends, keyword structures, and international collaboration patterns, the findings offer insights into how research priorities have evolved alongside regulatory and policy developments in the maritime sector.

The results reveal a sharp and sustained increase in academic output after 2020, which coincides with the intensification of global and EU-level climate policies, particularly the European Green Deal. While this policy framework provided the initial regulatory momentum, the particularly pronounced surge in publications during the 2023–2024 period can be further interpreted in connection with the geopolitical shifts triggered by the Russia–Ukraine war. This conflict acted as a critical external driver by escalating energy security concerns across Europe and accelerating the transition toward alternative fuels to reduce fossil fuel dependency. Consequently, the war-induced urgency for energy independence has not only reshaped EU strategic priorities as seen in the REPowerEU plan but also intensified scholarly focus on maritime decarbonization as a vital component of both environmental and strategic resilience. This temporal alignment suggests that both long-term policy initiatives and sudden geopolitical crises play a catalytic role in stimulating academic interest.

The keyword co-occurrence analysis highlights that the literature is strongly oriented toward technological and energy-related solutions, with dominant themes such as alternative fuels, hydrogen, ammonia, renewable energy, and sustainability. This finding is consistent with the conceptual discussion in Section 2, which emphasized decarbonization as a

multidimensional transformation encompassing technological, economic, and policy dimensions. The prominence of fuel-related keywords indicates that research efforts are largely focused on supply-side solutions aimed at reducing carbon intensity, rather than demand-side measures or behavioral aspects. This thematic concentration also reflects the priorities embedded in EU maritime policies, such as FuelEU Maritime and the inclusion of shipping in the EU Emissions Trading System, which explicitly promote low-carbon and renewable fuel alternatives.

The country-level collaboration analysis demonstrates that maritime decarbonization research is globally distributed but geographically concentrated. China emerges as the most central contributor, reflecting its significant maritime industry and growing research capacity. At the same time, several European Union member states such as Germany, the Netherlands, Sweden, and Italy occupy prominent positions within the collaboration network. This pattern underscores the influence of EU-level regulatory frameworks on shaping national research agendas and fostering cross-border academic collaboration within Europe. The strong interconnections among EU countries suggest that regional climate and maritime policies not only guide industrial practices but also stimulate coordinated scientific research.

Furthermore, the presence of major non-EU countries such as the United States and the United Kingdom as central collaboration hubs indicates that EU maritime decarbonization policies have implications beyond regional boundaries. These findings support the argument that EU climate regulations function as global reference points, indirectly influencing research priorities and collaborations worldwide. This observation aligns with the broader discussion in Section 2.3 regarding the global impacts of EU green policies on international trade, competition, and regulatory convergence.

## **Conclusion**

This study provides a bibliometric evaluation of academic research on maritime decarbonization within the context of the European Union's green transition between 2020 and 2025. The findings indicate a clear and accelerating growth in scholarly output, particularly after 2022, reflecting the increasing policy relevance of maritime decarbonization. This rise in academic interest appears to be closely linked not only to long-term EU climate strategies such as the European Green Deal, the EU Emissions Trading System, and FuelEU Maritime, but also to external geopolitical developments, notably the Russia–Ukraine war, which intensified

energy security concerns and accelerated the search for alternative fuels. In addressing the research questions, the analysis demonstrates that academic research on maritime decarbonization has evolved rapidly in recent years, that scholarly output is geographically concentrated yet internationally connected with strong participation from EU member states alongside major global actors, and that the literature is thematically dominated by alternative fuels, energy efficiency, sustainability assessment, and emission reduction technologies. These thematic patterns mirror the strategic priorities embedded in EU maritime decarbonization policies, indicating a close interaction between regulatory developments and academic knowledge production. Future research could strengthen this line of inquiry by combining bibliometric analysis with qualitative policy evaluation, extending the temporal scope beyond 2025, and conducting comparative studies across different maritime regions. Overall, the findings confirm that academic research both responds to and reinforces EU-driven decarbonization strategies, contributing to the shaping of pathways toward climate-neutral maritime transport

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# Strategy of adaptation to climate change in France: between economic resilience and climate justice in the third decade of the 21st century

*Barbara Gregorczyk*

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**Abstract:** Global trends in greenhouse gas emissions indicate that by the end of the century, the climate could warm nearly twice as much as predicted by the 2015 Paris Agreement. In this context, France has positioned climate change adaptation as central pillar of its climate policy, aiming to prepare its economy, infrastructure and society for the impacts of a warming climate. The aim of this article is to analyse French climate change adaptation policy from an economic and climate justice perspective. The study is based on an analysis of government strategies and legal frameworks, sectoral policy documents, and selected local-level case studies in key sectors, including energy, agriculture, water management and the health system. As a result it is difficult to assess the effectiveness both of already incorporated and planned measures. The analysis shows that that French climate change adaptation policy in the third decade of the 21st century is characterised by growing strategic ambition, which is not, however, balanced by adequate implementation instruments and coordination mechanisms, leading to a gap between adaptation planning and the actual strengthening of social and economic resilience. The article argues that for adaptation policy to become genuinely effective, it requires a shift towards greater social inclusiveness, stronger institutional coordination, comprehensive monitoring frameworks, and the integration of economic and ethical considerations into decision-making processes.

**Key words:** Nuclear Energy Renaissance, SMRs, Energy Sovereignty, Industrial Alliance, Green Deal, Green Taxonomy.

## Introduction

This article addresses the interdependence of climate, society and ecosystems. The above-mentioned systems are strongly interconnected, which means that changes in one of them affect the others (IPCC 2022: 6). Therefore, the natural phenomenon of climate change, which is driven by anthropogenic greenhouse gas emissions, poses a risk of damage to society and ecosystems. It is projected that according to the trends resulting from the implemented policies of countries by the end of 2020 extended by comparable levels of ambition after 2030, the level of global warming relative to the pre-industrial era could reach between 2.1 and 3.5°C (IPCC 2023: 57). Societies are counteracting climate change through mitigation measures aimed at reducing greenhouse gas emissions into the atmosphere, such as energy transitions to a clean energy economy or the transformation of the transport sector. Although such measures are being taken in individual countries, they are most effective when implemented at the international level (Raman, Iniyani and Goik 2012: 882). This is because greenhouse gases emitted into the atmosphere in one country have an impact on the climate felt across the globe. Adaptation to climate change, on the other hand, is a task that is mainly implemented at the local and national levels.

The effects of climate change are already having serious economic and financial consequences for the European Union, including France (Delahais and Robinet 2023: 63). This is linked to more frequent natural disasters and a new reality to which societies must adapt in order to protect the population and ensure the stability of our economies. These measures are not only dictated by ethical considerations, but also by economic ones. Preparing the economy for disasters such as droughts, hurricanes, floods, coastal erosion and heat waves reduces the cost of damages they cause (Ministère de la Transition écologique 2025: 7). This article focuses on politics whose main goal is not to reduce emissions, but to prepare the state and its society for the risks of climate change. Adaptation is not a substitute for mitigation efforts, but is complementary to them, as the adaptive capacity of societies decreases with the increase in global average temperature.

This article combines two theoretical approaches: economic and justice-based (so-called just adaptation). In his 2007 report “The Economics of Climate Change”, Nicholas Stern argues that a lack of adaptation measures will lead to cumulative economic losses far exceeding the costs of adaptation measures. This theory focuses on the profitability of investments aimed at protecting against disasters and thus adapting to climate change, which frames adaptation as an opportunity to stabilise a country's economic resilience. Delays and misguided adaptation measures increase the losses that a given country suffers because of climate change.

Parallel to this approach, the concept of climate justice is gaining popularity, drawing attention to social inequalities exacerbated by the effects of climate change, as vulnerable groups such as the elderly, people with disabilities, and communities with limited economic resources have fewer resources to protect themselves from the effects of climate change (Schlossberg and Collins, 2014). In the context of climate change adaptation in France, territorial inequalities are evident, as risk forecasting systems often cover only metropolitan France, leaving France's overseas territories more vulnerable to sudden events such as floods. Integrating these two approaches could reduce economic losses, strengthen the socio-economic resilience of society and reduce territorial and social inequalities. In view of the above considerations, the article formulates the hypothesis that French climate change adaptation policy in the third decade of the 21st century is characterised by growing strategic ambition, which is not, however, balanced by adequate implementation instruments and coordination mechanisms, leading to a gap between adaptation planning and the actual strengthening of social and economic resilience. This hypothesis is examined through a qualitative analysis of national adaptation strategies, funding mechanisms and selected sectoral case studies. To examine this hypothesis, the following research questions are addressed: are current adaptation strategies economically viable in

the long term? What financing mechanisms have been adopted and who are the actual beneficiaries of adaptation funding? Are there territorial inequalities in access to adaptation measures? The aim of this article is to analyse French climate change adaptation policy from an economic and climate justice perspective. The article uses triangulation of research methods to capture both the institutional assumptions of adaptation policy and its practical consequences. A qualitative analysis of public policies was conducted, covering national adaptation strategies, ministerial documents and reports from public institutions responsible for shaping climate policy. The analysis was supplemented by case studies of selected sectors particularly vulnerable to the effects of climate change, including agriculture, energy and healthcare. Additionally, it focuses on assessing the coherence between strategic objectives and implementation instruments, as well as the extent to which adaptation measures address social and economic resilience. The evaluation is guided by two analytical criteria: how ambitious the policy is, understood as whether it prepares for the most severe climate change scenarios and the extent to which this preparedness is supported by specific implementation tools. Due to the heavy dependence of this analysis on publicly accessible documents and the lack of evaluations of adaptation policy outcomes, the assessment is oriented toward the declared strategies rather than their actual implementation or effectiveness.

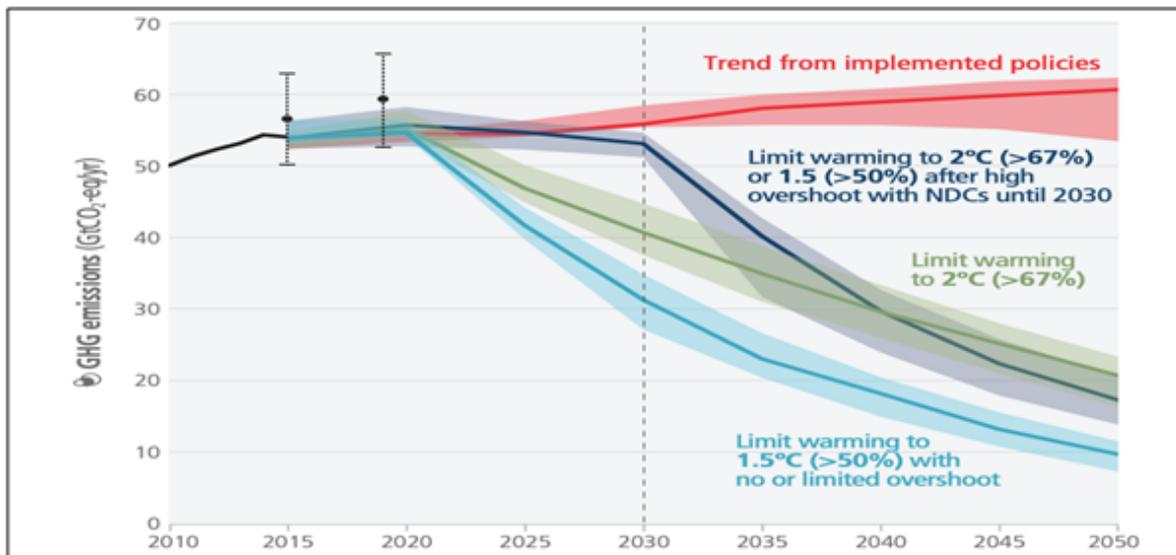
Previous studies on adaptation to the effects of climate change in France have mostly focused on specific consequences. In 2021, Samuel Robert and Alexandra Schleyer-Lindemann conducted a study entitled "How ready are we to cope with climate change? Extent of adaptation to sea level rise and coastal risks in local planning documents of southern France", which points out the need for greater cooperation between local and central authorities in this area. In the 2025 monograph „Agriculture et changement climatique”, Philippe Debaeke et al. (2025) describe the relationship between agriculture and the climate crisis in France. However, there is a lack of research in the literature on climate change in France from an economic perspective combined with a climate justice approach.

## **1. Global warming trends and the imperative for national adaptation**

The Paris Agreement signed on 12 December 2015 by 196 countries, including France, is an international treaty that commits signatories to combating climate change (UNFCCC 2015: 1-16). One of its long-term goals is to limit the increase in global average temperature to 2° C and to make efforts to keep this value at 1.5 degrees Celsius compared to the pre-industrial era (ibid.: 4). This limit is determined based on measurements of the global average temperature

over a period of 20 years. In 2024, for the first time, the average temperature on Earth was at least 1.5 degrees higher than that of the reference period 1850-1900. The year 2024 was also the warmest in recorded history and the period 2015-2024 represents the warmest decade on record (Copernicus Climate Change Service 2025). However, this does not mean that the limits set in 2015 in the Paris Agreement have already been exceeded, as a single year's measurement is not synonymous with permanent change. Nevertheless, this result marks a dangerous and noticeable trend in which the limits set in the treaty may be exceeded much faster than previously thought. In order to meet the long-term goal of limiting global warming to 1.5°C by the end of the century, all countries that were parties to the Paris Agreement would have to obtain energy only from clean resources by 2040 (IPCC, 2023: 93). Additionally, predictions of greenhouse gas emissions based on currently applied policies for 2030 are insufficient and will not result in maintaining global warming on 1.5 degree Celsius. (Ibid.)

**Chart 1: Projected global GHG emissions from NDCs announced prior to COP26 would make it likely that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C**



Source: IPCC, 2023: Sections. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647 [https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC\\_AR6\\_SYR\\_LongerReport.pdf](https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf) (access: 04.06.2025)

Climate change leads to changes in the frequency, intensity, spatial extent and duration of extreme weather events such as droughts, floods and hurricanes, which increases the risk of damage to society (IPCC 2023: 46). Over the past 50 years, the number of extreme weather events has increased fivefold (World Meteorological Organization 2025). The long-term goal of limiting global warming to 1.5 degrees Celsius by the end of this century seems unrealistic,

thus increasing the importance of not only climate protection, understood as limiting greenhouse gas emissions into the atmosphere, but also adaptation to the new changing reality. Adaptation to climate change involves taking measures, including implementing strategies and initiatives to minimise the vulnerability of the population, economy, infrastructure and environment to the risk of disasters whose intensity, frequency or extent are driven by a warming climate (IPCC 2023: 46).

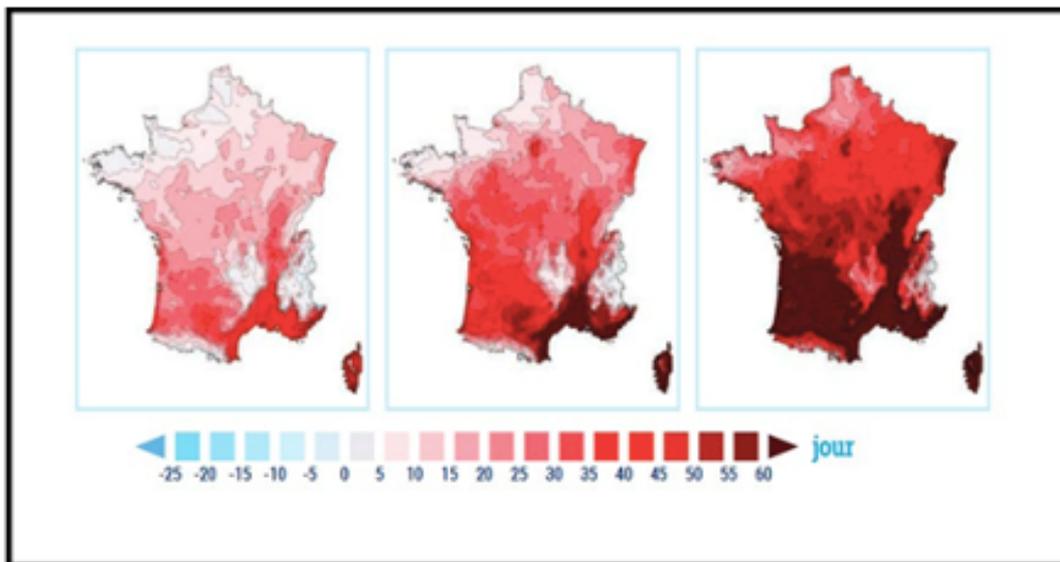
The Intergovernmental Panel on Climate Change (IPCC) defines adaptation to climate change as *'the process of adjusting to current or expected climate and its effects in order to mitigate damage or take advantage of opportunities arising from favourable conditions.'* (Ibid.: 52). As the global average temperature rises, the costs of adapting to climate change increase and the possibilities for implementation decrease (IPCC 2022: 22). Adaptation to climate change has its limits as actors' needs cannot be fully protected from intolerable risks through adaptation (Ibid.: 2898). The IPCC points to the existence of adaptation constraints, among which it distinguishes soft constraints, such as financing and coordination of adaptation projects, which can be managed, and hard constraints, such as physical obstacles, e.g. relocating an entire village located in flood-prone areas to a place with a lower risk of flooding. Adaptation does not prevent damage and losses entirely but is only an action aimed at minimizing the effects of climate change.

## **2. Scenario of global warming that France is preparing for**

France, which played a leading role in securing the adoption of the Paris Agreement in 2015 (Stothard and Chassany 2015: 2), now appears to be tacitly acknowledging the potential failure of its long-term objective to limit the global temperature increase to 2°C above pre-industrial levels. The national climate change adaptation strategy submitted by France in March 2025 (PNACC-3) is based on the Reference Warming Trajectory for Climate Change Adaptation - TRACC (Ministère de la Transition écologique 2025: 16). The trajectory implements two scenarios based on the projections of the sixth report produced by the IPCC (ibid.). The first TRACC scenario, referred to as the optimistic scenario, assumes a 2°C increase in global warming by the end of the century, and the second, called pessimistic, assumes a 4°C increase for mainland France relative to the pre-industrial era. The first scenario assumes that the Paris Agreement target is met, while the second, so called pessimistic, is based on current global greenhouse gas emissions data and greenhouse gas emissions trends. Any adaptation measures taken in France, by local governments or central authorities, should be

implemented considering the 4°C warming trajectory for mainland France (Ministère de la Transition écologique 2023). The choice to consider a worst-case warming scenario reflects adherence to risk management principles and the precautionary approach. Basing adaptation policy solely on an optimistic scenario could lead to an underestimation of the scale of the risks and therefore, have a negative impact on the country's resilience to the negative effects of climate change if the actual rate and extent of warming turn out to be greater than previously assumed. On the other hand, adopting a pessimistic scenario increases the ability of public systems and infrastructure to function in conditions of high climate uncertainty.

**Chart 2 .** Number of tropical nights in pessimistic scenario by 2030 (left) 20250 (centre), 2100 (right)

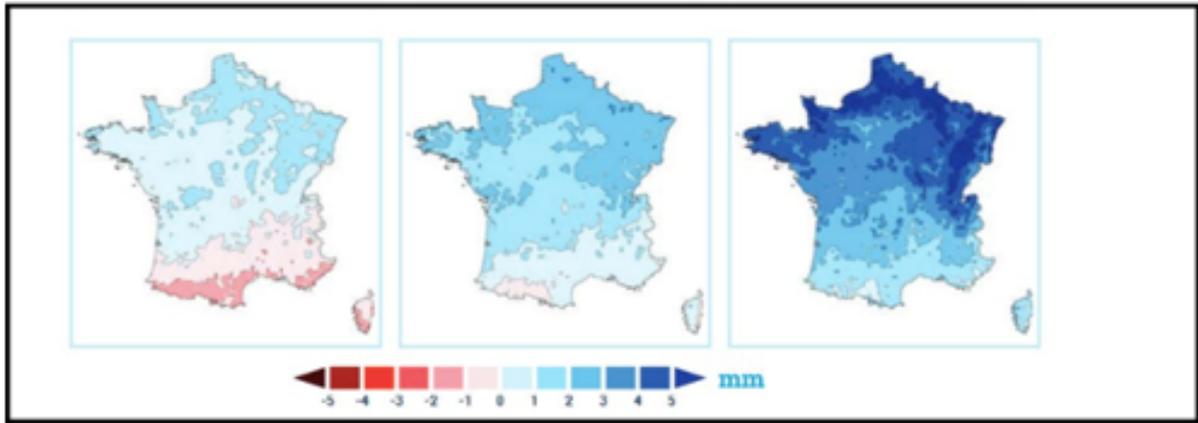


Source: Ministère de la Transition écologique 2023, <https://www.ecologie.gouv.fr/> [Accessed 4.01.2025].

This trajectory assumes global warming relative to the pre-industrial era of 1.5 °C in 2030, 2°C in 2050 and 3°C in 2100. However, this is the average for the entire globe, and Europe is the fastest warming continent (Copernicus Climate Change Service 2025). Therefore, this scenario assumes that in continental France alone the warming of the climate relative to the pre-industrial era will be: 2 °C in 2030, 2.7 °C in 2050 and 4 °C in 2100. The warming predicted in this scenario will result in a twofold increase in the number of tropical nights, that is, those with temperatures that remain at 20°C or higher. This is a particularly dangerous phenomenon for the elderly or those with cardiopulmonary insufficiency, as the body does not have a chance to regenerate at night after a hot day (Ballester et al., 2023). In the northern part of the country, it is estimated that there will be 40 to 50 of tropical nights per year. Most vulnerable is the south

of France, where there could be up to 90 such nights, which is twice as high as the current number (Ministère de la Transition écologique 2023: 12).

Higher global temperatures can lead to increased evaporation from oceans and land, and warmer air can hold more water, leading to changes in the intensity and frequency of rainfall, raising the risk of flooding (IPCC 2021: 1518). A relevant example here seems to be 2024, when a heatwave hit the Mediterranean region in July 2024 warming up the sea that contributed to low-pressure systems to transporting moist air masses, contributing to more severe flooding in Europe (Merz et al. 2024). At the same time, continental France will also be exposed to more severe droughts. Meteorological droughts are expected to become much longer. The southern part of the country and the west coast are most vulnerable, where hydrological droughts of more than a month may occur in the summer (Ministère de la Transition écologique 2023: 13). Flooding and hydrological drought are paradoxically dependent on each other, since dry soil does not absorb and retain water as well as soil that has been exposed to systematic, less intense rains (Tang et al. 2024 : 255). According to the TRACC document, in mainland France, droughts that previously occurred on average once a decade will occur approximately 5.1 times more frequently (Ibid. : 9). In the northern part of the country, rainfall intensity is expected to increase. It is more difficult to predict what rains will occur in the southern part of the country, as the climate model does not include forecasts for so-called Mediterranean episodes, i.e. very intense rainfall exceeding 150 mm per day (ibid.). However, outside of these episodes, annual precipitation in the south of the country, especially in the Pyrenees and the Alps, is expected to be lower. It is predicted that the snow resources will decrease dramatically in these regions in the spring, and river water levels will be very low in the summer (ibid : 13).

**Chart 3.** Intensity of heavy daily rainfall in pessimistic scenario by 2030 (left) 20250 (centre), 2100 (right)

Source: Ministère de la Transition écologique 2023, <https://www.ecologie.gouv.fr/> [Accessed 4.01.2025]

Pessimistic scenario also assumes that by the time the regional climate warms by 4 °C, all French glaciers will disappear (ibid.). The precipitation, frequency and intensity of droughts and floods may also determine the migration of people who may have to leave their current place of residence. The consequences may be felt in many areas of social and economic life. Buildings, whether residential or office, schools or health care facilities, will have to be adapted to operate under prolonged and intense heat waves (ibid.). Similarly, transportation infrastructure, power, water and telecommunications networks will have to be secured to maintain continuity of operations despite the increased risk of cataclysmic events.

All of the above figures apply only to mainland France (ibid : 14). France's overseas territories have received much less attention in the TRACC scenario. These regions also, due to a population with lower economic resources and a higher cost of living than in mainland France, have less capacity to protect themselves from the effects of climate change. In the Indian Ocean islands (Réunion and Mayotte), precipitation is expected to decrease during the peak dry season and delay and shorten the rainy season (ibid.). In the Antilles, rainfall is expected to decrease along with a delayed and shortened rainy season. The higher the level of warming, the more intense these changes will be (ibid.). In addition, the frequency of intense tropical cyclones will increase by about 50% from +1.5°C. Despite the disparity in attention to overseas regions in the adopted strategy, Météo-France plans to conduct high-resolution climate simulations to detail two warming scenarios over an extended time horizon (about 2 years) and to develop climate services tailored to the challenges and vulnerabilities of each territory (ibid.). If no French climate change adaptation measures are taken, it is estimated that France's GDP could decrease by 10 percentage points in 2100. In this scenario, agriculture-related costs will amount to approximately one billion euros per year by 2050. On the other hand, the cost

of renovating road infrastructure necessitated by the effects of climate change will increase by about 5%, or about 22 billion euros, by 2050 (Ministère de la Transition écologique 2025: 7). Adaptation to a different climate thus touches not only on ethical issues, to protect the welfare of the population, but also on economic ones. France, wishing to remain a leader or even strengthen its position in the European Union and the world, needs a stable economic situation that is resilient to the effects of climate change.

### **3. Adaptation instruments and programmes in France**

The Fund for the Prevention of Major Natural Hazards (FPRNM), established in 1995 and colloquially known as the Barnier Fund, in honor of then-Minister of Climate and Environment Michele Barnier, was originally created as a disaster risk prevention instrument (Direction Générale de la Prévention des Risques 2021: 3). Although it predates the formal emergence of climate change adaptation as a policy field, it is now widely regarded as an early mechanism that was later integrated into France's climate adaptation framework. According to the IPCC (2014: 1758) definition of climate change adaptation "The process of adjustment to actual or expected climate and its effects. " establishing the Barnier's Fund can be considered an early manifestation of adaptation policy, even though adaptation to climate change had not yet been formally established as a policy area at that time. The purpose of the fund is to protect human life and property and to subsidise measures to prevent major natural hazards. Initially, it was intended to finance only compensation for the expropriation of properties exposed to the negative effects of natural phenomena and expenses related to the eventual demolition of these properties. Over time, its scope was expanded to include preventive measures. Local authorities, small businesses, private individuals, public land management companies and government services can apply for these funds (ibid.). Resources related to the costs of expropriation were used, among other things, after storm Xynthia hit the Vendée department in 2010 and after the floods in the Aude department in 2018 (Ministère de la Transition écologique 2025: 52). This fund may be used to cover the costs of implementing risk prevention plans and conducting information campaigns. In fact, it is a type of social insurance program that allows for a rapid response and payment of compensation to those affected by extreme weather events, which are occurring with increasing frequency. Since 2021, the Fund has been an integral part of the state budget. Resources from this program are divided into authorisations for commitment (AE) and payment appropriations (CP) (La Commission des Finances, de l'Économie générale et du Contrôle budgétaire, 2025 ). AE define the maximum value of financial obligations that the

fund can undertake in a given fiscal year (planned resources), whereas CP correspond to the funds actually available for disbursement to beneficiaries during the same period (funds actually paid out). In 2020, AE amounted to €205 million per year, while CP reached €200 million. By 2025, AE had increased to €300 million, with CP at approximately €287 million (ibid.). The difference between AE and CP reflects that the fund can commit to a larger number of projects, but some obligations will be executed in subsequent years or may not be fully utilized. At the end of 2024, the Fonds Barnier had outstanding commitments of €622.9 million (ibid.). This situation illustrates a structural budgetary tension, arising from the fact that the fund's obligations exceed the funds available for disbursement, which delays the implementation of some adaptation projects. In addition, in its opinion on PNACC3, the Haute Conseil pour le Climat stated that funding should be increased for, among other things, the Barnier Fund, as one of the main tools for adaptation to climate change in France (Haut Conseil pour le Climat, 2025: 6). The proposed 2026 budget law indicates that the Barnier Fund will be maintained at last year's level, while simultaneously reducing the payment credits (CP) – the actual amount available for preventive actions in a given year – to €228 million (La Commission des Finances, de l'Économie générale et du Contrôle budgétaire 2025). This scenario suggests a further tightening of financial resources for climate change adaptation measures that could lead to the reduction of effectiveness of adaptation policies (ibid.).

The National Plan for Adaptation to Climate Change (PNACC1) was adopted in 2011 (Ministère de l'Écologie, du développement durable, des transports et de la mer 2011), which has since been updated twice in 2018 and in 2025 (Ministère de la Transition écologique 2023) (Ministère de la Transition écologique 2025). The plan had to be updated twice to maintain the effectiveness of the adaptation policy. The 2011 version preceded the 2015 Paris Agreement, which aims to increase the capacity to adapt to the negative effects of climate change. At that time, France, which had taken significant steps to take the global lead in ambitious climate policies, may have been keen to demonstrate its dynamic activity in this area. The 2018 version, on the other hand, preceded the establishment of TRACC, i.e. the climate warming trajectory, making it necessary to revise the adaptation programmes. Such frequent updates to adaptation policy may indicate France's desire to demonstrate its climate policy activities to maintain its pioneering role on the international stage in this area. The latest PNACC3 is based on five main tenets, which are: protecting the population, ensuring resilience to the effects of climate change on territories, infrastructure and basic services, adapting human activity, protecting natural and cultural heritage and mobilizing the nation (ibid.). It contains a program of 52 actions, the first point of which involves strengthening and expanding the Barnier Fund, the backbone of

France's prevention policy. PNACC3 calls for a 30% increase in this fund, which will equate to an increase of up to 300 million euros annually. Although the plan provides for an increase in the above-mentioned amount, it should be noted that, with the adoption of PNACC3 in March 2025, the projected budgetary allocation for the Barnier Fund had already been set at a higher level, amounting to €330 million. The fund will be used to pay for, among other things, the relocation of the village of Miquelon, currently at high risk of being submerged by sea (Ministère de la Transition écologique 2025: 420).

The analysis highlights the essential role that the Barnier Fund plays within the climate adaptation framework, while also revealing significant limitations in its utilization. There is a lack of a multi-year financing plan, which may result in insufficient funding for adaptation measures in future years. The Fund's importance is expected to grow as the impacts of climate change intensify. Furthermore, there are no tangible indicators or reports to assess the effectiveness of the funds allocated from the Barnier Fund in achieving policy objectives. Documentation is prepared in terms of expenditures and the number of projects, but there is no system in place to monitor actual reductions in climate risk. The Fund's financing system does not ensure a balance between commitments and the actual allocation of resources. This leads, among other issues, to the accumulation of obligations and a limited capacity to respond to and prevent the adverse effects of climate change. There is no monitoring system to demonstrate whether increased funding translates into improved adaptive capacity. The current system does not include a long-term, multi-year adaptation plan.

In contrast, PNACC3 is neither a law nor incorporated into the environmental code, and its implementation depends on regulations, which means that the strategy itself is not legally binding. The plan also does not identify which actions are most urgent, and therefore does not demonstrate a risk-assessment approach. Adaptation limits i.e., the maximum capacity to adapt to climate change in specific areas have not been identified. Likewise, vulnerable groups have not been singled out, nor have targeted adaptation measures been proposed for them. The analysis points to potential territorial inequalities in access to adaptation resources. Access to the Barnier Fund depends on administrative capacities, the ability to prepare projects, and the prior existence of preventive plans, which favors territorially better-equipped institutions. Consequently, areas with weaker administrative resources may have limited access to adaptation financing, further exacerbating disparities in adaptive capacity at the local level.

## 4. Overview of selected climate-related disasters and adaptation measures in France

### 4.1. Floods

Floods according to IPCC's definition are „the overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged”. (IPCC 2012 : 559) Floods can be distinguished by where and why they occur. Marine submersion is the temporary inundation of a coastal area by the sea during severe weather conditions (Ministère de la Transition écologique et de la Cohésion des territoires 2025: 14). This type of flooding is directly related to rising sea levels, storm surges, tides and meteorological conditions. Currently, the average cost associated with this type of flooding in France is about €0.2 billion, and it is estimated that this cost will increase to €2 billion by 2050 and to €20 billion in 2100 in the absence of adaptation measures (Vousdoukas et al. 2018). The projected increase in costs indicates that coastal regions such as Normandy and Brittany will face mounting financial pressures, underscoring the urgency of implementing targeted adaptation strategies. These pressures may constrain the economic development of areas particularly exposed to this type of flooding, through mechanisms such as increased migration driven by deteriorating living conditions, declining tourist attractiveness, and a reduction in planned investments in the region. In the PNACC-3 plan, significant attention is devoted to this type of flooding, as sea levels are projected to continue rising even beyond the year 2100. Moreover, according to the TRACC scenario, a substantial increase in the frequency and intensity of heavy and sudden rainfall events is expected. Although marine submersion is closely linked to sea-level rise, flood risk management in France also places strong emphasis on monitoring inland water bodies, as river flooding accounts for a significant share of flood-related damages.

A well-functioning monitoring system for rivers and other bodies of water, as well as a warning system, is needed to prevent damage from floods. To this end, the Vigicrues system has been set up, which monitors the level of water bodies and warns when there is a risk of flooding (Ministère de la Transition écologique 2025: 48). The system currently monitors 23,000 km of rivers, covering most rivers over 50 km in length. It alerts the population 24 hours before the risk of flooding occurs. So far, the system operates not only in mainland France, but in 2020 it was also launched in Corsica and French Guiana. Plans are in place to extend it to all overseas territories, but this has not yet been implemented. The Vigicrues system is an important climate adaptation tool, as strengthening the early warning system allows for earlier preparation of emergency services, protection of the population and infrastructure, and

preventive closure of critical infrastructure. Risk assessment is crucial in the climate adaptation process, as it enables anticipation of negative impacts and preparation for them.

A measure foreseen in the latest adaptation strategy is to support local authorities in selecting appropriate actions. However, no specific steps have been outlined, nor has a budget been defined for this purpose. This creates a risk of inappropriate measures being chosen by local authorities and the possibility of uneven development of adaptation actions depending on the location of the territorial unit. The adaptation plan also highlights the need to pay particular attention to regions located in close proximity to water bodies as well as areas situated below sea level. However, it does not specify concrete actions or implementation mechanisms in this regard, which in practice implies a shift of responsibility for adaptation to the negative impacts of climate change towards territorial units. The plan further outlines a general direction for the development of instruments aimed at increasing the resilience of these regions to flood risks, with an emphasis on nature-based solutions. Nevertheless, no specific measures are defined, and the document merely states that by 2030 the length of natural flood protection barriers is expected to increase by 50 km. This objective remains broad and does not clarify which actions will be undertaken or how this target is to be achieved.

## **4.2. Droughts**

As a result of climate change, droughts that previously occurred once a decade in mainland France if the global climate warmed by 3°C would occur between 2 and 8.2 times more often (Ministère de la Transition écologique 2023: 3). One of them was the 2022 drought in France, which cost more than 5.6 billion euros and is probably underestimated (Ministère de la Transition écologique 2025). In this calculation, the Ministry of Climate and Environment did not take into account some of the impacts related to industry or tourism, as well as long-term effects on biodiversity. In 2022, as much as 61% of the costs caused by drought corresponded to damage to buildings linked to the swelling and subsequent shrinkage of building materials, a process predominantly affecting structures built on clay-rich soils. It is estimated that the costs incurred from this will increase by 44% by 2050 (*ibid.*). The 2022 drought also caused a decline in electricity production from hydroelectric and nuclear power plants, and the resulting deficits had to be compensated for by energy production from alternative, carbon-intensive sources, which corresponded to 16% of the costs associated with the effects of the disaster that year. An important part of France's adaptation to the drought is therefore the renovation of buildings so that they are less prone to breakage. The PNACC-3 program includes assessing the

effectiveness of options to protect against this effect of the drought. The main costs of installing waterproofing membranes, for example, remain with individual stakeholders, suggesting that at least part of the financial burden of drought adaptation is borne by individuals. France's climate change adaptation plan also calls for the creation of the Water Plan (fr. Plan Eau), which primarily involves the ministry's cooperation with local governments, businesses that use large amounts of water, the creation of a legal framework for the construction and renovation of new residential buildings to use as little water as possible, the creation of special reservoirs at critical facilities such as hospitals, and support for farmers in managing water resources. The goal of the plan is to ensure a continuous supply of good-quality water by 2050. The plan calls for a shift from reactive water management, which is implemented when a crisis occurs, to management based on prevention and forecasting.

In France, the doubling of the frequency of extreme agricultural droughts and the projected significant crop losses by 2050 will lead to increased water demand for both irrigation and livestock farming. Although the Water Plan is technically feasible, its effectiveness depends largely on coordinated political efforts, including control of excessive water use in agriculture and the anticipation and management of local distribution conflicts related to water availability, which may intensify because of more frequent droughts. At the same time, an increase in the number of droughts may exacerbate existing frustration among farmers, highlighting the need to take social aspects into account in adaptation, in line with PNACC-3 recommendations on support for the agricultural sector and water risk management.

## **5. Sector analysis**

### **5.1. Power system adaptation**

France, which is the world's seventh biggest economy in terms of its nominal gross domestic product (IMF 2025), is also resource-poor (Bernard 2019). Coal mining stopped there in 2004 (Bezzina 2004), and France is forced to import oil and gas from third countries. In response to the oil shocks and lack of its own raw material resources, France adopted a development model based on nuclear power. Nuclear power plants were responsible for producing 73% of France's total primary energy production and 39% of its consumption in 2023 (Ministères Aménagement du territoire Transition écologique 2024). Energy today is at the center of geopolitical tensions, and a country's independence from gas or oil supplies means greater resilience to intentionally or unintentionally triggered crises (Bouvier 2003, 71; Młynarski 2013, 56). In this aspect, securing energy infrastructure against the negative effects of climate change

is also key to maintaining economic and social security, as well as a country's stature in the international arena. Climate change has a direct impact on energy production levels. (Ministère de la Transition écologique 2025: 88). Lower efficiency of nuclear and hydroelectric power plants can be observed with the occurrence of higher temperatures and hydrological drought. There is also a risk associated with flooding of coastal nuclear facilities because of rising sea levels. The climate change adaptation plan calls for a study of nuclear power plants, both those already in existence and those under construction, considering current knowledge of water resource management, and in regions at particular risk of drought to examine the viability of installing water pumps. The operation of nuclear power plants strongly depends on access to water, and it is currently impossible to completely protect them from the impact of higher air temperatures and drought (ibid.). As a result, France has announced further stress tests to study the consequences of shortages in nuclear power production. As for hydropower, on the other hand, the plan is to deepen the analysis of the impact of climate change on the hydrological situation, update the risk assessment and, where it proves necessary, also install water pumps. Also based on the analysis of the risk assessment of the negative effects of climate change is the adaptation strategy for wind and solar power, particularly in France's overseas territories (ibid.). In addition to adapting the energy generation system, the system of networks that distribute it must also be secured. On the one hand, these networks need to be physically protected from higher temperatures, floods, or hurricanes, while on the other hand, climate change may affect changes in energy production and consumption patterns, which should also be considered when renovating and building networks. The plan calls for the renovation of 80% of existing networks by 2040, allocating 20 billion EUR. Renovation is aimed at increasing the temperature tolerance of conductors and locating systems outside zones with a high risk of flooding. However, these measures are limited to mainland France at this stage (ibid.).

While the PNACC3 and related planning documents provide detailed lists of adaptation measures for the energy sector, their feasibility and expected effectiveness remain uncertain. On the one hand, the renovation of 80% of electricity networks by 2040 and the installation of water pumps in droughtprone regions are technically feasible. On the other hand, the implementation of these measures depends on longterm political continuity, stable investment frameworks and social acceptance, particularly given the high upfront costs and the absence of a multiannual expenditure plan dedicated to these adaptations. As a result, the gap between planning documents and actually delivered infrastructure makes it difficult, at this stage, to robustly assess their effectiveness in reducing climaterelated energy security risks.

## **5.2. Health sector adaptation**

This is a sector that is doubly vulnerable to the burdens caused by the effects of climate change. On the one hand, it is fraught with risks such as deterioration of infrastructure, interruptions in the supply of medicines or medical equipment, lack of continuous access to water and electricity, among others. On the other hand, it is a sector that, due to more frequent disasters, will face the challenge of helping more patients and overburdening employees. Adaptation of the health sector can be carried out through “structural” and “non-structural” adaptation (Huges and Simonet-Umana 2024: 20) The former includes measures to secure the infrastructure of medical facilities, managing resources such as water or energy so as to keep their supply stable, while the latter includes measures to strengthen the development of knowledge and resources available to workers who will be able to take appropriate action more quickly and accurately. By 2100, 103 medical facilities in France would have to close due to damage to infrastructure if adaptation measures are not taken. The health care system may experience the impacts of climate change through an increased burden of patients. (XDI 2023).

The immediate physical risks to the population because of climate change are mainly cataclysmic injuries, an increase in cardiovascular and respiratory diseases, an increase in strokes and dehydration (Huges and Simonet-Umana 2024: 19). However, one should also consider the easier spread of insect-borne diseases, such as dengue fever which is reported in mainland France (Ministère de la Transition écologique 2025: 88). An often-overlooked health effect of climate change is an increase in mental illness due to post-traumatic disorders. Given the numerous hospitals, medical facilities, doctor's offices and extensive supply chains, and the increased risk of illness and injury among patients, adapting health care to the effects of climate change is not an easy undertaking. Adaptation measures are largely undertaken depending on risk assessments.

## **5.3. Agriculture adaptation**

The French Council for Food, Agriculture and Rural Affairs - CGAAER has estimated the cost of climate change to agriculture and the food industry at more than €4 billion a year by the middle of the 21st century (Tremblay and Ruiz 2022: 29). Agriculture is one of the sectors that will be most affected by climate change. Extreme climate events such as heat waves, droughts and heavy rainfall contribute to crop losses and drive changes in crop selection across latitudes. In 2024, soft wheat production is nearly 25% from the average of the previous five

years (Agreste 2024). At the same time, agriculture is a major contributor to driving climate change, accounting for about 20% of France's greenhouse gas emissions. Longer and more intense heat also increases the use of water to grow crops and raise animals. Increasing access to water resources for agriculture will intensify the sector's negative impact on climate, which will secondarily amplify the effects of climate change. At the same time, France is the European Union country with the largest number of farmers, which may increase the scope and complexity of adapting to the adverse impacts of climate change. The ministry is proposing the development of two studies. The first focuses on recommendations to enhance the resilience of agriculture and livestock to the effects of climate change and to transition them toward low-carbon practices, providing guidance for policymakers and farmers, and potentially improving the efficiency of adaptation measures. The second study examines the consequences of sea level rise for agriculture, supporting the design of risk maps and the development of adaptation strategies for vulnerable coastal areas. In addition to research, the Plan calls for investing 30 million euros a year in renovating existing irrigation infrastructure and developing new projects so that agricultural water use does not increase by 2030.

## **Conclusion**

The analysis of France's adaptation policy confirms that French climate change adaptation policy in the third decade of the twenty-first century is characterised by a growing level of strategic ambition, which is not matched by sufficiently robust implementation instruments or coordination mechanisms. France's clear preparations for a 4 °C warming scenario indicate its aspirations to mitigate the negative effects of climate change. At the same time, strategic goals seem to be guidelines rather than an actual multi-year plan, as the implementation of the PNACC depends on the successive adoption of laws or decrees, since the PNACC does not have the form of a law. Furthermore, it is difficult to unequivocally assess the effectiveness of both existing and planned policies due to the lack of comprehensive monitoring and evaluation systems. The primary motivation for adaptation measures is to limit economic losses and secure infrastructure, with climate justice issues being of secondary importance. The ability of individuals to adapt to climate change depends largely on their personal resources. France, although it includes not only its metropolitan part but also its overseas territories, marginalises them by not implementing the same adaptation measures there as in its continental part. Adaptation to climate change partially reduces the costs that could be incurred in the event of climate change impacts, but there is no monitoring system in place to accurately assess such costs.

There is also a lack of compensation or advisory mechanisms to support groups at risk of climate change impacts in applying for funds. Adaptation funding is therefore uneven in practice. However, government documents emphasise the need to build social resilience, which in many cases is limited to training for specific groups. While education in this area can be beneficial, it will not make stakeholders resilient to the effects of climate change. Programmes such as the Barnier Fund, which enables the relocation of people from flood-prone areas, or Plan Eau, which aims to prevent water shortages, are necessary, but the scale of these measures is still insufficient. For adaptation policy to be truly effective, it needs to be transformed towards greater social inclusiveness. This requires increased funding and the integration of economic and ethical considerations into decision-making at all levels. By pursuing a programme of adaptation to a 4°C warmer climate, France is suggesting that it is possible to protect oneself from the effects of climate change that go so far, although adaptation also has its limits.

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# Legal framework for investing in energy storage in Poland

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**Abstract:** The aim of this article is to define the general legal framework and reconstruct the course of the investment process in energy storage in Poland, taking into account EU regulations. The research area outlined above comprises the following issues: the EU and Polish regulatory frameworks for energy storage, development of the investment process in projects of this type, regulatory costs, and possible sources of revenue. Considering this, the author attempted to assess the regulatory framework and identify potential future objectives of the Polish legislator in the field of energy storage development and promotion on the basis of the analyses carried out. As conclusions, it can be indicated that investing in energy storage is a complicated economic process in legal terms. It requires prior planning, ensuring financing at an appropriate level and understanding the currently applicable legal regulations. Moreover, in order to achieve the goals of EU and Polish legislators in the field of supporting the development of energy storage, it is necessary to focus on ensuring appropriate forms of financing for this type of technology. It is important to strive to ensure that energy storage facilities become a necessary element of every renewable energy source installation.

**Key words:** Poland, EU, energy transition, energy storage, investment process, polish law, EU law.

## Introduction

An integrated and harmonised European Union's ("EU") energy market has a crucial role to fulfil in achieving a cost-effective, secure and sustainable energy supply. In September 2023 the European Parliament supported a new target of 42.5% of energy from renewable sources by 2030 (Staff working document on the energy storage, 2023 : 1). However, EU countries are encouraged to aim for a 45% target, which was also supported by the European Commission as part of its REPowerEU plan (Communication from the Commission of the European Parliament, COM/2022/230 : 6/20). Presented in May 2022, above mentioned the REPowerEU plan emphasises the need to accelerate the transition to clean energy and phase out energy imports from Russia by increasing the share of renewables in power generation, industry, construction and transport to 45% by 2030 (European Parliament News, 2017 : 4). This raises the challenge of maintaining a steady supply of energy even at times when wind or solar resources are limited. The solution to this may be energy storage, which will be an essential part of the energy transition.

With the increasing share of renewable energy sources, the EU legislator is recognising the growing potential of energy storage. It identifies storage technologies as one of the key-ways to ensure the necessary flexibility, stability and reliability of the energy system. In order to effectively integrate renewable energy sources into the energy grid and to develop investments in flexible fossil-free technologies, additional resources are needed. The European

Commission (“EU Commission”) indicates that one of these measures is the deployment and use of energy storage technologies (Staff working document on the energy storage, SWD(2023) 57 : 2/35). To effectively apply the technology within the state's economy, the role of the legislator is to shape an appropriate legal framework for its implementation in the legal system. In this context, it is important - from the point of view of a researcher and a lawyer at the same time - to make legal analyses and assess the implementation of this particular type of technology, i.e. energy storage, into the legal systems of the EU member states - including the Polish legal system.

The aim of this article is to define the general legal framework and reconstruct the course of the investment process in energy storage in Poland, taking into account the EU regulations covering this specific energy sector. It includes three parts - introduction, substantive content and conclusion. The substantive content includes a presentation of the EU and Polish regulatory framework for energy storage, the identification of the phases of the investment process in energy storage, regulatory costs and possible income sources. Conclusions include an assessment of the regulatory framework and identification of potential future objective of Polish legislator for the development and promotion of energy storage.

This publication is a work in the legal sciences (social sciences) research field. The author employed the dogmatic-legal method. It was used to carry out a comprehensive analysis of the currently binding and relevant, from the point of view of the subject of the publication, legal regulations, including the interpretation of Polish and EU legal acts. The subject of the article is Polish energy law and administrative law, as well as legal acts and guidelines of the European Union and Polish bodies and institutions. The article also utilized the method of content analysis of official information from EU bodies and Polish regulators’ (President of the Energy Regulatory Office).

## 1. Energy storage in EU regulations

The legal framework for investing in energy storage facilities in Poland is still evolving, creating an environment full of opportunities for investors, but also significant regulatory barriers related to legal uncertainty and the practices of transmission and distribution systems operators. The basic regulations are undergoing numerous amendments, forcing investors to constantly monitor changing regulations and take legislative risk into account in their business and project models. The rules for connecting to the grid are particularly problematic, as they are a key constraint for many projects: in many regions, there is a lack of free connection capacity, operators are prolonging the technical analysis process, and the lack of full transparency regarding available grid capacity makes it difficult to make investment decisions. Finally, the market for system services, where storage facilities could generate revenue, is still in its infancy. All these factors mean that investing in energy storage today requires not only knowledge of technology and market conditions, but also a very good understanding of changing regulations and close cooperation with operators and administrators at every stage of the investment process.

Thus, moving on to the fundamental aspects of this article, it is necessary to address the issue of the legal definition. The definition of “energy storage” and “energy storage facilities” was first introduced into the EU legal act – in the Directive 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market in electricity and amending Directive 2012/27/EU (“Directive 2019/944” - OJ EU. L. 158 : 18/75) as part of the Clean Energy Package. It is difficult to find an answer to the question of whether the directive in question has been fully implemented into Polish law. This issue can be reduced to the question of whether the applicable national legislation and the legal mechanisms provided for therein achieve the objectives of the analysed and aforementioned European Union legal act, which must be transposed into the legal system of a given Member State. It should be added that the directive in question was amended by Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 amending Directives (EU) 2018/2001 and (EU) 2019/944 with regard to improving the structure of the European Union electricity market (OJ EU L. 1711)<sup>1</sup>.

Further on, according to Article 2 point 59) of the aforementioned directive “energy storage” means, in the energy system, deferring the final use of energy to a moment later than when it was generated, or the conversion of energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into energy or use

as another energy carrier. In turn, Article 2 point 60) indicates that "energy storage facility" means, in the energy system, a facility where energy storage occurs. In the presented definition, the legislator committed an *idem per idem* error (or circular reasoning error), which is a logical error consisting in explaining a given word (*definiendum*) using the same word or its derivatives in the definition (*definiens*). As a result, the legislator has not provided any new information that could be considered relevant to the process of interpreting the law.

Directive 2019/944 also regulated access to storage facilities and the establishment of common rules for energy storage operation and market participation. As part of the Clean Energy Package, the following were also adopted Regulation 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market in energy ("Regulation 2019/943" - OJ EU. L. 2019 No. 158 : 2/71), which contains, among other things, provisions for storage in terms of non-discriminatory access to the grid and the maintenance of transparent market rules. The shape of the EU energy market to date encourages the greater use of energy storage in the market and the provision of flexibility services on equal terms with other energy sources. The EU legislator focuses on the need to ensure the competitiveness of the energy market and at the same time indicates that the development of energy storage should be market-driven.

On 14 March 2023 EU Commission published a series of recommendations on energy storage (C/2023/1729 : 1/5), identifying actions that EU countries can take to increase the use of storage technologies. In this regard, we can distinguish between state and EU activities in the following areas:

- EU energy market legal design (Commission Recommendation, C/2023/1729 : 3/5);
- public financing and support in the EU (Commission Recommendation, C/2023/1729 : 4/5);
- research and innovation for a strong energy-storage value chain (Commission Recommendation, C/2023/1729 : 4/5).

These recommendations were matched by a Commission staff working paper (Commission Recommendation, C/2023/1729 : 1/5). The context of these documents emphasise that energy storage can have an important role to play in complementing the variable nature of renewable energy production. By effectively bringing energy storage solutions to the market, the EU in total and EU members can increase the integration of renewables, optimise grid management and attract investment in sustainable technologies, including flexibility technologies. However, the integration of renewable energy sources, in order to effectively integrate variable

energy production and encourage investments in demand response and energy storage, requires adaptation to market conditions.

## **2. Energy storage in Polish regulations**

Thus, continuing the topic of legal regulation of energy storage, it is necessary to present Polish regulations governing this subject. The main regulation dedicated to energy storage can be found in the Polish Act of 10 April 1997 - Energy Law (“the Energy Law”, J. of L. of 2024, i. 266 : 447). This Act is the basic legal act regulating the principles of shaping Poland's energy policy. It defines the standards, conditions for the supply and use of fuels and energy, as well as the basis for the activities of energy enterprises. According to Article 3 point 10k) of the aforementioned Act, an energy storage facility means an installation enabling the storage of energy and its introduction to the power grid. In turn, the storage of energy itself (Article 3 point 59) of the Energy Law) means the deferral, in the power system, of the final consumption of energy or the conversion of energy taken from the power grid or generated by a generating unit connected to the power grid and cooperating with the grid into another form of energy, the storage of this energy and its subsequent conversion back into energy.

Notwithstanding the above, an energy storage facility may be part of a renewable energy source installation (Grzywacz *et al.*, 2023/el : 44). This is indicated by Article 2 point 13) of the Act of 20 February 2015 on Renewable Energy Sources (“Act on Renewable Energy Sources” - J. of L. of 2024 i. 1361 : 6/378) defining the term “renewable energy source installation”<sup>2</sup>. The above means that energy storage can either be an integral part of a renewable energy source (part of a larger installation) or function as a separate installation.

### **3. Investment process**

Considering the practice, as well as the legal regulations in force, the investment process for the construction of an energy storage facility in Poland can be divided into the following stages:

1. obtaining an environmental decision;
2. spatial planning (local spatial development plan or decision on land development conditions);
3. obtaining legal title to the property;
4. building permit;
5. occupancy permit;

In order to comprehensively cover the issue at hand, a brief description of each of the five points listed above should be made in the article.

Thus, beginning with point 1) on the requirement to obtain an environmental decision, it should be emphasised that under the current state of then Polish law, it is not unequivocally determined that energy storage facilities require an environmental decision in every case. This will depend on the individual facts of the case of a particular investor. Each investment should therefore be analysed individually. If the energy storage facility is part of a renewable energy source installation (e.g. a wind farm or a photovoltaic installation), obtaining this decision will be mandatory due to the functional connection of the energy storage facility with the installation. An environmental decision will also be required if the energy storage covers a correspondingly larger area (0.5 hectares or 1 hectare) due to the regulation of the § 3 sec. 1) point 54) of the Regulation of the Council of Ministers of 10 September 2019 on projects likely to significantly affect the environment (J. of L. i. 1839 : 10/17)

In terms of spatial planning, there are currently no regulations that establish specific rules for the location of energy storage facilities. The relevant property on which the development is planned may be covered by a local spatial development plan, which are adopted through resolutions of the municipal councils. The plans are intended to describe in detail the spatial conditions for the development of a given area. The investor is obliged to plan future development in accordance with the provisions of the local spatial development plan. In the event that no plan has been adopted for the area in which the property is located (which is relatively frequent in Poland), the investor may apply to the relevant public administration authorities for the issuance of development conditions. The development conditions will, like the local zoning

plan, specify the basic conditions for the development of a given building site. In order to apply for development conditions, the investor does not need to hold any legal title to the property.

In this regard, it is important to be aware of the Act of 7 July 2023 amending the Act on spatial planning and development and certain other acts (J. of L. i. 1688 : 14/69) which introduced the obligation to locate new energy renewable sources' installations on the basis of specific rules set out in the local spatial development plan. Until now, photovoltaic installations could be located on the basis of development conditions, regardless of their total power. According to the amendment, it is now prohibited to locate renewable energy installations with a capacity of more than 1 MW on the basis of development conditions.

Aforementioned act introduces different spatial planning rules in relation to renewable energy installations - photovoltaic installations and wind farms. This means that in a situation where an energy storage facility is connected to one of the installations defined above, passing through this point, may cause problems for the investor. There are detailed regulations in this respect and each investment must be considered individually.

Another point in the energy storage investment process is obtaining the legal title to the land. The market standard is that the developer does not own the property on which the project is to be built, but obtains the right to use the property from its owners. It is extremely important that the title to the property is secured before the application for a building permit is submitted. Having legal title to the property for construction purposes is one of the conditions for issuing a building permit. A building permit issued despite the addressee of the decision not having proper title to the property may be challenged. There are many different forms of securing title to land (e.g. lease, perpetual usufruct). The choice of form depends on the type of land to be secured and also on the purpose (the type of infrastructure to be placed or the activity to be carried out on the land).

After obtaining the title to the property and before starting construction work, the investor is required to obtain a building permit. The current provisions of the Polish construction law (J. of L. 2024 i. 725 : 167) do not prescribe any special rules for the construction of energy storage facilities. This means that energy storage facilities can only be built on the basis of a valid building permit - similar to a renewable energy source installation with supporting energy storage.

The beginning of the use of an investment, as a rule, takes place after the appropriate use permit has been obtained. In the case of smaller investments (which did not require the issuance of a construction permit), it is sufficient for the investor to notify the relevant

authorities of the completion of the construction work (provided that the authorities do not raise objections within an appropriate period of time).

Moreover, to successfully start an energy storage business, an energy storage licence must be obtained by the investor. Pursuant to Article 32 sec. 1, point 2) section a) of the Energy Law, it is required to obtain a licence in order to carry out the business of storing energy in energy storage facilities with a total installed energy capacity of more than 10 MW. For energy storages with a total installed capacity of more than 50 kW, an entry in the register of energy storages is required (Article 43g of the Energy Law). Energy storages below the ceiling of 50 kW of total installed capacity do not need to have either a licence or appear in the register.

#### **4. Procedure for obtaining a license**

The owner of an energy storage facility applies to the President of the Energy Regulatory Office to obtain a licence for energy storage. Obtaining a licence is a necessary and indispensable condition for undertaking and carrying out the business of energy storage. Pursuing such activity without a license is subject to administrative sanctions - in particular monetary penalties set out in the Energy Law.

It is possible to divide the documents which should be attached to the licence application into three groups: documents confirming formal, legal and organisational conditions (such as confirming that the entity applying for a licence exists - an excerpt from the National Court Register, a certificate of no criminal convictions for both the applicant and the persons authorised to represent the entity, a list of entities with significant influence on the applicant or exercising control or joint control over the entity); technical documentation (such as: documents confirming the legal title to the property on which the energy storage facility is located, technical description of the storage facility, documents confirming the location of the energy storage facility, permit for use, documents confirming installed capacity, documents obtained from grid operators); documents confirming the financial resources available (such as: statement of annual, planned revenues and costs for a period of at least 3 full years, financial statements for the last 3 years, documents confirming the possession or possibility of acquiring sufficient financial resources to properly conduct the licensed activity, a certificate of no arrears in the payment of social security contributions, and a certificate from the appropriate tax office stating that there are no arrears with liabilities to the state budget).

Also, the granting of a license is subject to a fee of PLN 616. In accordance with the general principles of administrative proceedings, the granting of a license should take place within one to two months. In practice, the approximate duration of license proceedings is 5-

8 months. However, in certain cases, during the course of the proceedings, due to the factual state and legal situation of the applicant, the President of the Energy Regulatory Office may call for additional explanations and the presentation of relevant documents stating that the applicant meets the conditions set out by the Act to carry out business activity in the scope covered by the application - which may prolong the proceedings. In practice, the length of the proceedings is also affected by the number of cases to be handled in a given time by the individual departments of the office of the President of the Energy Regulatory Office (President of the Energy Regulatory Office: 1/15). When the licence is granted, the investor can start the licensed activity.

## **5. Procedure for connection to the grid**

Connection to the distribution or transmission grid is necessary for the commencement of energy storage activity. Pursuant to Article 7 sec. 1 of the Energy Law, distribution system operators and transmission system operators are obliged to conclude a grid connection agreement with entities applying for grid connection on an equal treatment basis if technical and economic conditions for grid connection and supply of that energy exist and the entity applying for the agreement meets the conditions for grid connection and off-take.

Commented process can be divided into the following stages:

1. Submission of an application for the issue of grid connection conditions;
2. Payment of an advance for the fee for connection of energy storage facilities connected to the grid with a rated voltage higher than 1 Kv. The advance payment amounts to PLN 30 for each kilowatt of connection capacity specified in the application for the issue of connection conditions. At the same time, the amount of the advance payment may not be higher than the expected grid connection fee and may not exceed PLN 3,000,000;
3. Obtaining the connection conditions. When the distribution system operator or the transmission system operator deems that the technical and economic conditions for connection to the grid exist and the prepayment has been made, depending on the voltage of the grid to which the connection shall take place) from the date of filing the application, they issue the connection conditions which are valid for 2 years. During this time, the entity wishing to be connected must conclude a grid connection agreement with the relevant distribution system operator (or transmission system operator);
4. Conclusion of the connection agreement;

5. Execution of the connection agreement, which may take from several to a twelve months, depending on the scope of the work to be carried out.

Moreover, it should be underlined that detailed criteria for the grid connection procedure are set out in the Regulation of the Minister of Climate and the Environment of 22 March 2023 on detailed conditions for the operation of the energy system (J. of L. i. 819 : 7/73).

## **6. Costs regulated in Polish law**

The final point in the article that needs to be developed is the question of the costs incurred in an energy storage investment (not counting the costs associated with the creation of the storage facility and connection costs). Thus, legally regulated costs for energy storage activities are:

1. the license fee;
2. distribution costs;
3. taxes.

Pursuant to Article 34 sec. 1 of the Energy Law, an energy company to which a license has been granted pays an annual fee to the state budget charged to its operating costs. The amount of the license fee is the product of the revenue of the energy enterprise, obtained from the sale of goods or services within the scope of its activity covered by the license, achieved in the year in which the obligation to pay the fee arose and the relevant coefficient, indicated in a separate provision (Article 34 sec. 2 of the Energy Law). The license fee may not be less than PLN 1,000 and more than PLN 2,500,000 (Article 34 sec. 3 of the Energy Law). The deadline for calculating and paying the license fee is 15 April of the year following the year for which the fee is due.

Article 45 of the Energy Law contains special rules for settlements for energy drawn from the grid, which apply in particular to energy storage installations that are part of renewable energy source installations, as well as energy storage installations operating as a separate unit. In the case where the energy storage is part of a generating unit, as well as in the case of a separate energy storage, in settlements for the provided energy transmission or distribution services in the scope of fees for energy drawn from the energy grid by the energy storage, the subject of settlement is the difference between the energy drawn from the grid by the energy storage and the energy introduced into the grid by this storage in a given settlement period.

Depending on the technical design of energy storage facilities and their functional connection with the generating installation, they may be treated differently under the provisions of

the property tax under the Polish law. Due to the fact that the issue of taxation of energy storage facilities with property tax in Poland is relatively new, a detailed analysis is required each time depending on the specific factual circumstances and the specific design of such storage facilities. Depending on the classification of the storage facility as a building or construction equipment or an installation constituting an element of a structure, the tax base may be different. Furthermore, if the energy storage facility fails to meet the requirements regarding its classification as a building or construction equipment or an installation constituting an element of a structure, the scope of taxation of a specific type of generating installation (for example: photovoltaic) should be analyzed.

Moreover, it should be indicated that energy storage is exempt from the obligation to prepare a tariff, which allows for the free setting of prices for services provided by energy storage.

## **7. Possible sources of income from energy storage activities**

It is possible for energy storage to participate in support systems for renewable energy sources organized under the Renewable Energy Sources Act. Energy storage facilities can be part of the auction system in a primary or secondary manner. This means that either the RES installation takes part in the auction already with the energy storage facility or the energy storage facility is added to an existing installation that has already won the auction.

In principle, energy storage facilities can also participate in the capacity market as a unit of the demand reduction capacity market. The technical parameters of energy storage facilities are specified in the Capacity Market Regulations published by the transmission system operator (Capacity Market Regulations, Polskie Sieci Elektroenergetyczne S.A.).

In addition to the performance of the capacity obligation by the energy storage facility based on the capacity agreement concluded on the capacity market, demand side response's services also operate. This is an active participation in system balancing. This service assumes a temporary and voluntary limitation or shift in time of energy consumption by recipients in favor of the transmission system operator. For the provision of this service, recipients are entitled to remuneration.

Energy storage facilities may also constitute an element of system balancing. In accordance with the Regulation of the Minister of Climate and Environment of 22 March 2023 on detailed conditions for the operation of the energy system (J. of L. i. 819 : 18/73), an energy storage facility may constitute a component of a schedule unit, which will be subject to transmission system operator orders in the scope of dispatch, including load changes within the

scope of the offered available capacity. The provider of balancing services, i.e. the entity managing the resources of system users, receives remuneration for the balancing capacity sold to the transmission system operator resulting from the settlement price of the given balancing capacity determined in a given process, both in the case of delivery and non-delivery of this balancing capacity.

## **Conclusions**

The article was intended to show the legal framework of investing in energy storage. It revealed the multi-dimensionality and level of complexity of this procedure. Investing in this type of technology is a complex process that requires the cooperation of many specialists from different fields of science. There is a place here for both lawyers and engineers. Moreover, it requires advance planning, ensuring financing at an appropriate level and understanding the current legal regulations, which are often subject to change. Presented legal regulations are contained in various legal acts from different branches of law - both EU and Polish.

In this context - energy storage facilities should be made a necessary element of every renewable energy installation. In order to support the development of this technology, Polish legislator should focus on developing support mechanisms for investments in this area or introducing specific and lower taxation or tax exemption. This would be a real incentive for potential investors. Thanks to energy storage, the energy market will maintain its flexibility and - at the end - it can work both ways. On the one hand, increasing consumption when there is a surplus and prices are low and - on the other hand - reducing it when there is a shortage.

The key legislative proposals for both – Polish and UE legislators mainly concern the simplification and standardization of grid connection procedures so that investors have transparent access to information about available grid capacity and a guarantee that connection conditions will be issued on time. At the same time, tax and regulatory stability is needed, including transparent rules for settling energy consumed and returned by storage facilities and the elimination of the risk of double charging and taxation. Such predictability of regulations is crucial for project financing, especially as energy storage facilities operate in markets with constantly changing revenue models. A consistent and stable regulatory system would allow investors to assess risk more effectively, shorten the investment preparation process, and accelerate the development of modern energy infrastructure in Poland.

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# Green dreams or dirty realities? Lithium mining, electric vehicles, and the illusion of sustainability

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**Abstract:** As the worldwide push for greener technology intensifies, electric vehicles (EVs) have become a symbol of that movement. The lithium-ion battery lies at the center of the EV boom. But behind this green façade, a darker truth unfolds – lithium mining, concentrated in the Global South, comes at a heavy cost of environmental and social fallout of local communities. This article examines a skyrocketing demand for lithium and impact of mineral’s extraction on local communities. More importantly, the article looks into a paradox ecological imperialism, drawing lines between traditional and green colonialism, or better say extractivism, by examining the ownership of mines. Additionally, the article raises important questions: Who truly benefits from a global lithium boom? Are we shifting from one harmful resource to another equally destructive? Does the end justify means?

**Key words:** Lithium mining, electric vehicles, extractivism, imperialism, colonialism

## Introduction

One of the many strategic resources of the twenty first century is Lithium - commonly used for the production of multiple sorts of batteries. As a part of a green transition, a lot of emphasis has been put on abandoning Internal Combustion Engine cars, which use fossil fuel and thus contribute to climate change. At face value, Electric Vehicles (EV) are a perfect replacement, as their usage emits no greenhouse nor toxic gases to the atmosphere. However, the question of getting to the stage of an EV’s beginning of life is often overlooked. Lithium needs to be mined somewhere and by someone, and the process of extracting it is not necessarily as green as using an EV, nor is there a guarantee of respect for the workers who mine it. Policy makers and manufacturers push for a more widespread transition to EVs; as such, this article will examine whether emissions reduction arising from the global transition to EVs outweigh the costs associated with lithium mining in the Global South. To address this, the analysis will answer the following questions: what are the environmental and social consequences of lithium mining? What is the economic and political result of this practice? The article argues that the global transition to EVs emerges as a limited and uneven climate solution due to an unsustainable lifespan of EVs, resulting directly from harmful and exploitative practices surrounding lithium mining in the countries of Global South.

## **1. Lithium – the ‘white gold’**

As the world sets the trajectory towards a greener and more sustainable future, lithium has emerged as its cornerstone. Lithium, known as ‘white gold’, has emerged as a master key to the door of the green energy revolution, with demand increasing as nations compete for a share of this precious metal in the global quest for sustainability. In the lithium-rich ‘Golden Triangle’ of South America, where Argentina, Chile, and Bolivia merge, is believed to be hidden what is estimated to be more than a half of the world’s lithium reserves (Guyon, Ordoñez 2024: 42). These seemingly unaffected by modern society areas have become the forefront of a high-stakes global game in which companies and governments compete for the supremacy over sustainability. As a result of a struggle for lithium, the disparity between resource-rich nations, such as Chile, which was labelled as the ‘Saudi Arabia of Lithium’ (Forbes 2012), struggling to fully capitalize on the resource, and foreign countries like China, which have swiftly seized control over crucial supply chains, embracing the benefits while local economies lag behind, has widened. As the demand for EVs rises, the strain on lithium deposits intensifies, unleashing a novel type of resource struggle. To substantiate, the demand for lithium is predicted to increase from 101kt to 1326kt, in a span from 2021 to 2040, which is an increase by 1213% ushering a ‘white gold’ frenzy in the energy landscape (International Energy Agency 2024). Even though the supply is expected to rise, it remains a drop in the bucket compared to a growing demand (Jaganmohan 2024). As the race heats up, people may eventually find themselves at a turning point in the energy landscape - where swelling demand collides with dwindling supply, which can potentially impede the green revolution before it even kicks off.

## **2. Social and environmental consequences**

As commonly observed, everything we want or desire comes with a cost and lithium mining is no exception. Behind the promise of electric cars and green energy there is environmental degradation, economic inequality, and societal exploitation.

On the one hand, lithium is portrayed as the cornerstone of the green energy revolution, its manufacturing process is a far cry from a green story. In reality, while the world is celebrating a march toward a sustainability, the impacts left behind are inadequately addressed, namely, air and water pollution, as well as soil degradation. Presently, a great deal of lithium is obtained from underground brine reserves or hard rock mines, with CO<sub>2</sub>-emitting fossil fuels providing much of the energy needed for the extraction and processing. Overall, any kind of extractions

of resources is damaging to the planet as it is frequently associated with fossil fuels and lithium is not an exception. Specifically in hard rock mining, for every tone of lithium extracted there is a respective 15 tons of carbon dioxide emitted into the atmosphere (Crawford 2022). Needless to mention frequent leaks of harmful contaminants and underground fires releasing toxic chemicals that, even in small amounts, are harmful to the environment and human health. With regards to brine mining, the extraction process inevitably poses a threat the local waters of the region. According to the report made by Zacune (n.d.: 2), the salt flats where lithium is found are commonly situated in arid areas, where water accessibility is critical for local residents and their livelihood, as well surrounding wildlife and flora. For example, in Chile's Atacama Desert, water has turned into a commodity held by mining firms, disrupting lifestyle of local people by making them rely on tankers for their simplest needs. While in Toconao in the North of Chile, water-related conflicts in the community are taking place. Similarly, in Salar de Hombre Muerto in Argentina, communities are voicing concerns about lithium mining as it is ruinous for their agriculture and livestock. Therefore, what once was a fertile ground is at risk of becoming impoverished, raising the question of whether such approach merely shifts the harm instead of eliminating it.

Although environmental implications are staggering, economic ramifications of lithium mining are equally severe. A vital element of sustainable development is ensuring that natural resources are employed in a way that fosters economic development. In this context, the role of the state in regulating resource exploitation is essential for driving national growth while simultaneously safeguarding human rights and the environment. However, lithium-rich countries usually encounter a paradox: although having enormous quantities of valuable resource, they lack financial means and technological infrastructure to utilize it, leading them to rely significantly on foreign investment and cede control over their own riches. The case in point is Bolivia, home for one of the world's largest reserves of lithium, that although nationalized production of lithium, was not able to proceed with lithium extraction alone. Currently, foreign firms must collaborate with the state-owned YLB to do business in the country. The latest tender for lithium projects launched by YLB had risen concerns about transparency and benefits for the country. Specifically, YLB has given preference to foreign companies over local firms, while shrouding its activities in secrecy and restricting access to important data (Radwin 2024). Another issue is the flourishing of tax avoidance, bribery, illegal export and illicit financial flows due to inadequate mechanisms to limit such activities. For instance, the lithium rush in a state-owned Sandawana mine in Zimbabwe has led to eviction of artisanal miners and further accusation of the government of preventing Zimbabweans from profiting from the lithium rush

in favor of their intermediaries and the Chinese, who would ordinarily pay them bribes (Mkodzongi 2024: 8). Consequently, the marginalization of locals in favour of multinational mining groups is likely to undermine resource-driven economic growth. Not to mention the trend of an increased involvement of criminal groups in mining activities, which not only poses a threat to local communities but also results in significant revenue loss, that otherwise could have been redirected towards social initiatives and advances in mining infrastructure itself (Hunter, Ofosu-Peasah 2022; Al Jazeera Investigative Unit 2023). Finally, to get a bigger picture of the impact of the lithium mining on the economies of the host countries, it is critical to look at the GDPs of these countries. Given the immense potential of lithium mining, host countries should have experienced a significant boost in GDP following the start of extraction of the resource and price changes. Upon examination of market dynamics, lithium prices have boomed from 2015 to 2017 peaking in 2018, followed by a decline from 2019 to 2021 because of oversupply, and then surging again in 2022 due to supply deficit (IMF in Soltani 2024). Building on this, such prices booms should be reflected in the GDP growth of lithium-rich countries, as higher export revenues and increased foreign investment typically lead to economic expansion. Taking Chile as an example, despite its abundant lithium reserves, its GDP growth exhibits little correlation with spikes in lithium prices. Particularly, in period from 2015 to 2018, Chile's GDP growth fluctuated insignificantly and even declined, then recovering in 2021 after pandemic, and dropping substantially again in 2022 compared to 2021 (World Bank 2023). Another example is Argentina, where GDP faced insignificant fluctuation over 2015-2018 and negative trends during the lithium prices boom in 2022 (Instituto Nacional de Estadística y Censos in Trading Economics 2024). It is, therefore, apparent, that the economic performance of lithium-rich countries is largely detached from the lithium market trends.

An increase in demand for lithium has far-reaching social consequences that go far beyond economic advantages and should be closely examined. Communities located in a close proximity to the mines often encounter such challenges as displacement, human rights abuses, and poor working conditions. Firstly, as demand for lithium rises, companies are expanding lithium mines, often at the expense of local population. Although there are regulations in place to safeguard the rights of indigenous communities, local residents complain about 'the absence of free, prior and informed consultation with the Government' (Giglio 2021: 50). The report released by the Oxfam America has demonstrated that only 29 of 43 corporations had public policies focused on human rights protection, but even fewer had pledges addressing FPIC (Free Prior Informed Consent), which enables indigenous people to negotiate the terms under which

the project is implemented (UN Economic and Social Council in Sellwood, Hodgkins, Hirschel-Burns 2023: 17). Almost all firms with FPIC policies tailored them so that they might still proceed with the project even if the consent of residents is not acquired. As a result, forced relocations of communities became commonplace. For instance, the research conducted by Joshua Matanzima has revealed that 41 families in Buhera were relocated to make a room for Zimbabwe's third-largest lithium mine. These families were offered new housing, but the ones they received were smaller and of lesser quality, developing structural issues shortly after moving in. Additionally, residents have lost access to vital resources, like water and grazing area, and the exhumation of cemeteries led to distress among relatives of the buried (Matanzima 2024). Secondly, the expansion of mining operations has been accompanied by degrading labor conditions, including low wages, human rights abuses, and child labor exploitation. According to the report published by Zimbabwe Environmental Law Associations, in Anjin Ptv Ltd., a Chinese controlled diamond mining company, the workforce is divided into 14 grades, with wages based on the precise grade to which each worker belongs. At some point, workers were forced to submit false pay slips with a salary of \$1,000 in order to escape media scrutiny after journalists' visit to Anjin in 2012 (Mtisi, Sunguro, Zano 2015: 20). Furthermore, companies do not provide medical aid cover as it should according to the company's policy document (Mtisi, Sunguro, Zano 2015: 21). Despite the strikes and protests of employees, the complaints regarding low wages were treated with disdain by senior officials (Mtisi, Sunguro, Zano 2015: 22). While it is a description of conditions in a diamond mine, the authors of the report acknowledge that 'Anjin is not the only place where workers are facing problems and working conditions are hard', and that this specific situation serves as an illustration of problems that all Zimbabwean workers face (Mtisi, Sunguro, Zano 2015: 5); as such, it is reasonable to assume that lithium mines workers face similar conditions, especially since a large portion of these are also Chinese owned, as will be demonstrated later. These oppressive practices are not just violation of labour rights, but also a reminder that business frequently takes precedence over human dignity.

### **3. Ownership of lithium mines and power dynamics**

To deepen the analysis, it is important to check who are the actual owners of lithium mines. The previously mentioned state-owned Bolivian YLB seems to be an exception when it comes to control of mines, even if foreign actors reap more benefits than local ones. Upon inspection, said control seems to be in the hands of private companies. The case of Argentina highlights this best; one million hectares of salt flats is owned by five private companies, namely: Litica Resources, subsidiary of Pluspetrol, an Argentine corporation headquartered in Netherlands (owning 320.000 ha); Arcadium Lithium, a company merged from the American Livent and Australian Allkem (232.637 ha); Integra Lithium, owned by an Argentine businessman and former politician (163.000 ha); Ganfeng Lithium, a Chinese mining company (122.432 ha); and Rio Tinto, British-Australian company (83.000 ha) (Delfino 2024). In Chile, only one company owns lithium mines - the Chilean *Sociedad Química y Minera de Chile* (SQM). The state owned Corporación Nacional del Cobre de Chile has formed a partnership deal with SQM in December 2025 as a part of President Gabriel Boric's plan to increase state control of lithium supply. However, Tianqi Lithium Corp, a Chinese company which owns 20% of SQM, tried to halt that deal by appealing Chile's Financial Market Commission's ruling that a shareholder vote is not necessary to proceed with the partnership (Cambero 2025). Whereas in Zimbabwe, where in the past, most mining projects were under private Australian ownership, China appears to be winning the resource race as of 2025 (Boafo, Spencer, Dotsey 2025); several of mining projects have been acquired by Chinese companies, with some investments reaching hundreds of millions of dollars, such as the Arcadia Lithium Mine owned by the Huayou Cobalt Co., Ltd. (Zimbabwe Environmental Law Association, Africa Institute of Environmental Law 2023: 8). This has prompted the Zimbabwean government to ban the export of lithium concentrate from 2027 onwards, aiming at extrapolating the benefits of its own natural resources. Even then, Chinese companies are planning to invest into processing plants at existing mines (Ecofin Agency 2025).

As such, while having a broad picture of the situation across several lithium mining countries in the Global South, one can observe the situation from a broader perspective. Clearly, lithium mining in its current shape and form is detrimental to local communities; poor working conditions, environmental damage, and virtual lack of financial benefits from lithium mining despite its status as a critical, strategic resource and high prices, among other things, harm social progress and welfare. Additionally, in most cases, land and capital is owned by private companies; while sometimes they are not foreign corporations, in most cases foreign

actors determine their actions. In other words, local actors have decreased agency. Having said that, one can look theories of imperialism; specifically, economic imperialism. While the former generally refers to broad domination of one nation over the other to achieve its own political, social or economic goals, the latter specifically refers to ‘foreign control of assets and decisions, including where such control exists in fact but not in law’ (Cope 2022: 15). To substantiate, Stathakis (2008: 113-114) explains:

*Accumulation was always taking place on the world scale. Surplus from the periphery was transferred to the centre through unequal exchange, the relocation of profits and incomes in the centre and financial dependency, producing polarization and increasing the gap between the industrial centre and the rural periphery.*

It could be argued that the situation lithium mining countries face are, in a way, a reincarnation of imperialism; as evidenced by the damage to the environment and local communities, as well as the fact that foreign capital is not only extensively involved in lithium mining, but also extracting wealth away from peripheral countries (i.e. the Global South) without leaving an opportunity for them to benefit from it. It is important to acknowledge that traditionally, states were the main actors when speaking of imperialism, while here, the main drivers behind mining are predominantly, all things considered, private actors and their influence. Some scholars have tried to expand; Foster & Clark (2004: 187), for instance, speak of ecological imperialism, defining it as a process in which resources of countries are ‘pillaged’ by others, transforming vital ecosystems in the process, accompanied by movements of labour and population. However, one could argue that the most precise way to describe the situation in the affected countries is to examine the concept of extractivism, which can be defined as ‘activities which remove large quantities of natural resources that are not processed (or processed only to a limited degree), especially for export’ (Acosta 2013: 62). More accurately, the term neoextractivism also applies; the difference between them being the increased involvement of financial capital in the process (Lang, Mokrani 2013: 192). These concepts, among other things, stress that transnational corporations take ‘advantage of their contribution to the balance of trade to influence the balance of power in the country.’ They benefit from favourable regulations and direct or indirect backing of various non-state actors, such as the International Monetary Fund (Acosta 2013: 67). In such a process, the state is ‘deterritorialized’ – it remains uninvolved in the activities of these companies as well as areas where they operate, leading to severe decreases in living conditions, including lawlessness (Acosta 2013: 68). It is also crucial to point out that evolving economies that were built on extractives is tied to external demand (Acosta 2013: 73); in other words, as long as there are buyers of lithium, they will be permitting or participating in

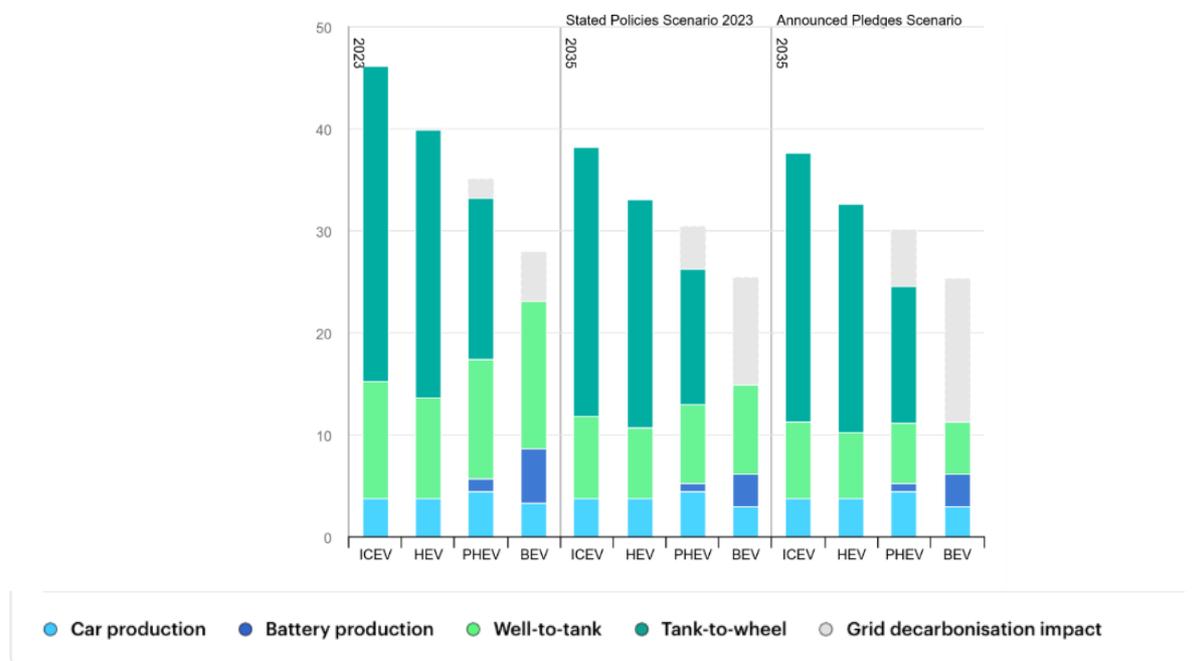
its extraction. Having said that, situations such as Tianqin's resistance to state partnership with SQM, lower participation of local workforce in Zimbabwe combined with increased criminal group activity, or YLB's favouritism towards foreign firms, provide evidence that aforementioned theories are relevant.

The role of private companies has been stressed; however, pinning fault on them solely does not reflect the picture fully. While there are varying opinions in the academia on what exactly a corporation's purpose is, it can be said with certainty that in the case of for-profit companies, their primary goal is to generate profit. As such, in the absence of strong regulations or incentives for sustainable practices, lithium mining is likely to continue inflicting environmental and social harm, indicating that external actors may need to play a more active role. The state could serve that purpose well, as it is best equipped to shift the balance of power away from the companies. But there have been cases in Argentina where corporations were forced to give concessions, or outright aborted projects, thanks to local, organised resistance (González, Snyder 2021: 212). It proves that even without state backing, sufficiently organised people can shift the balance of power in their favour, too. Nevertheless, such instances are still rare; otherwise, there would be less evidence of harm across other countries. Importers are not without fault, too. China along with countries of the Global North are the main drivers of the increasing demand; based on value of imports, China exports nearly five times as much as the second biggest importer, South Korea (Jaganmohan 2024). So long as world governments import lithium while neglecting social and environmental harm, the demand will keep rising.

#### 4. Justification and sustainability of EV use

Given the issues mentioned above, it is evident that lithium mining is damaging and unsustainable to ecosystems and local populations. To progress the analysis further, the reduction of emissions resulting from increased EV usage can be studied:

**Chart 1.** Comparison of global average lifecycle emissions by powertrain across policy scenarios, 2023-2035



Source: International Energy Agency 2024.

As illustrated in the graph, clearly Battery Electric Vehicles (BEVs) bring a substantial emission reduction as compared to Internal Combustion Engine Vehicles (ICEVs), which exhibit high tank-to-wheel emissions. However, BEV emit: an additional 5.3 tonnes from battery production; and 14.5 tonnes of CO<sub>2</sub> equivalents per vehicle, compared to ICEVs' 11.5 tonnes. It could be argued that the increased emissions from these sources diminish the gains from eliminating tank-to-wheel emissions, even if the latter are substantial. In addition, while the impact of the grid decarbonisation is apparent, it also highlights that BEVs' advantage is heavily dependent on the transformation of the energy system, which, in turn, means that that sustainability of BEVs' is not universal and not assured in countries with carbon-intensive energy mixes. As such, it is valid to question the validity of a complete switch to BEVs at the current stage. Moreover, considering the factors mentioned in previous paragraphs, such as labor rights abuse, economic inequality, and ecological degradation, such a sharp difference prompts a holistic examination of the trade-offs inherent in the transition to electric mobility that would include a full lifespan of these cars - from manufacturing to disposal. Therefore, this instance

clearly demonstrates that sustainability not only means green or carbon neutral, which is undeniably important, but also social responsibility. A broader definition of sustainability must address environmental impacts alongside ethical considerations, namely well-being of local communities and the maintenance of ecosystems. Given the unsustainable nature of lithium-ion batteries and scarcity of lithium, of which there is a shortage as of 2026 (Lv and Munroe 2026), alternative options should be explored. For example, sodium-ion batteries, that are more abundant, more environmentally friendly, have higher temperature operating range and lifecycle, make them a promising advancement in energy storage technologies (Climate Adaptation Platform 2023).

## **Conclusion**

In conclusion, lithium-ion batteries are often referred to as the cornerstone of a greener future, facilitating the transition to renewable energy sources and electrification. However, this narrative overlooks the deeper environmental, ethical and social implications of lithium extraction. Primarily due to a race for lithium - driven by the world powers such as the US, Europe, and China - which ironically resembles the rush for oil and gold (Penn, Lipton 2021). While these batteries result in a reduction of carbon emissions, these achievements are often offset by emissions and environmental contamination caused by extraction and manufacturing processes, that disproportionately harm residents. The EV transition risks becoming a replacement of one form of extractive harm with another, as lithium mining frequently results in soil and water contamination, and disruption of the livelihood of local communities, while the emissions generated by the battery production can negate climate benefits achieved through reduction of the emission during the usage phase. As a result, the overall sustainability of these technologies is undermined. Taking above-mentioned into account, it could be argued that the 'green' transition is simply transferring the burden elsewhere, and that lithium-ion batteries are only a transitional stage on the path to ultimate sustainability. The future of environmental sustainability will encompass far more than just technological innovations - it will cause fundamental shifts in paradigms and approaches. As environmental crises worsen, green future will not merely mean swift fixes and single solutions, rather it will be about reimagining how economies, communities and ecosystems coexist.

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