Enabling Net Zero Data Centers: A Techno-economic Analysis of Bloom Energy's SOFC Systems

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Summary

The rising energy demands of Data Centers—driven by accelerating digitization and AI adoption—combined with increasing grid constraints and growing concerns around power availability, time-to-power, security, and cost, are pushing the sector toward on-site generation solutions.

In response to this evolving landscape, *Bloom Energy* partnered with Felipe Perez, a Master's student at *PoliTo*, and Prof. Massimo Santarelli, to investigate this topic. The present study examines the European Data Center landscape, develops a techno-economic analysis of *Bloom Energy*'s SOFC system for a 100 MW Data Center application under different configurations, and benchmarks their performance against alternative power solutions across technical, economic, and environmental dimensions.

The results indicate that Bloom's SOFCs deliver strong technical performance, low environmental impact, and—depending on deployment conditions—competitive economics. Their modular design and short deployment timeline (typically under one year) offer a key advantage in markets where traditional grid or on-site solutions may take 3 to 10 years. Without considering deployment delays, Bloom's Natural Gas systems show higher LCOEs than Gas Turbines and Combined Cycle Gas Turbines (CCGTs), with only CHP configurations approaching cost parity with Reciprocating Engines. However, when opportunity costs related to time-to-power are included, Bloom's systems become more cost-competitive than Gas Turbines, CCGTs, and even grid power in markets like Germany, the UK, and Ireland.

From an environmental perspective, baseline Natural Gas SOFC configurations achieve up to 36% lower carbon emissions than common alternatives, with further improvements seen through CHP integration, carbon capture, or hydrogen as fuel. Non-carbon emissions (e.g., NOx, SOx), land use, and water intensity are also significantly lower than for other technologies, which is especially relevant given growing constraints on land availability and the sector's increasing attention to water impacts. Hydrogen-fueled SOFC systems, while offering strong sustainability potential, remain economically unfeasible under current green hydrogen prices.

To account for future uncertainty, the study incorporates scenario and sensitivity analyses that evaluate how system performance and cost-effectiveness vary under different market and policy conditions. The analysis developed shows that Bloom's systems are more capital-intensive and thus more sensitive to interest rates than alternatives. However, they are less exposed to carbon pricing and fuel price volatility. These attributes could improve their competitiveness and resilience in future policy and market contexts, especially as carbon costs increase and fuels such as hydrogen become more accessible.

Overall, the analysis suggests that *Bloom Energy*'s SOFC systems offer a technically sound and environmentally advantageous solution for Data Center operators, particularly in regions facing grid access constraints and growing decarbonization pressures. When accounting for deployment speed, emissions performance, and long-term operating conditions, Bloom's systems appear as a strong alternative to conventional grid and on-site power solutions, especially in markets where sustainability, and time-to-power are critical.

A mi familia y a Euge, por todo su constante amor, apoyo y paciencia.

A mis amigos, a Uga y al río Paraná, que siempre me esperan en casa.

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Nomenclature

Acronyms and Abbreviations

Acronym	Definition
AEP	American Electric Power
AI	Artificial Intelligence
AFC	Alkaline Fuel Cell
AFOC	Annual Fixed Operating Costs
AVOC	Total Variable Operating Costs
CAKE	Centre for Climate and Energy Analyses
CAPEX	Capital Expenditure
CC	Combined Cycle
CCGT	Combined Cycle Gas Turbine
CEPCI	Chemical Engineering Plant Cost Index
CHP	Combined Heat and Power
CISPE	Cloud Infrastructure Services Providers in Europe
CSO	Central Statistics Office of Ireland
DC	Data Center
DETE	Department of Enterprise, Trade and Employment of Ireland
DOE	Department of Energy of the US
ECO	Association of the Internet Industry in Europe
EEA	European Environment Agency
EIA	Energy Information Administration of the US
EMC	Electromagnetic Compatibility
EMEA	Europe-Middle East-Africa
EPA	US Environmental Protection Agency
ES	Energy Server
EU	European Union
EU-ETS	European Union Emissions Trading System
FCHEA	Fuel Cell and Hydrogen Energy Association
FLAPD	Frankfurt, London, Amsterdam, Paris and Dublin
GDA	German Data Centers Association
HHV	High Heating Value
HX	Heat Exchanger
ICAP	International Carbon Action Partnership

Acronym	Definition
ICIS	Independent Commodity Intelligence Services
IDA	Italian Data Center Association
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LCOE	Levelized Cost of Energy ($/MWh)
LHV	Low Heating Value
MCFC	Molten Carbonate Fuel Cell
NAEI	National Atmospheric Emissions Inventory
NESO	National Energy System Operator of the UK
NETL	National Energy Technology Laboratory of the US
NG	Natural Gas
NPV	Net Present Value
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
PoliTo	Politecnico di Torino
PPA	Power Purchase Agreement
PUE	Power Usage Effectiveness
PV	Photovoltaic
RICE	Reciprocating Internal Combustion Engine
ROI	Return on Investment
SOFC	Solid Oxide Fuel Cell
SEAI	Sustainable Energy Authority of Ireland
TPC	Total Plant Costs
UAV	Unmanned Aerial Vehicle
UCSS	United States Chamber of Commerce
VOCs	Volatile Organic Compounds
W2G	Well-To-Gate
XFMR	Transformer
ZB	Zettabyte

Symbols and Variables

Symbol	Definition	Unit
A	Active surface area of the cell	m^2
ASR	Area Specific Resistance	$\Omega\ cm^2$
C_{SC}	Capacitance of the supercapacitor	F (Farad)
F	Faraday's Constant	C/mol

Symbol	**Definition**	**Unit**
i	Current density	A/m^2
i_0	Exchange current density	A/m^2
I	Total current	A
$\bar{h}$	Enthalpy	kJ/(mol K)
K_p	Equilibrium constant	–
m	Electrical ramp rate	W/s
M	Maximum ramp rate of the fuel cell	W/s
n	Number of electrons transferred in the reaction	–
$\dot{n}$	Molar flow rate	mol/s
n_{cells}	Number of fuel cells in the stack	–
P	Power	W
Q_{SC}	Charge stored in the supercapacitor	C
R	Universal Gas Constant	J/(mol K)
SOC_{SC}	State of charge of the supercapacitor	–
T	Temperature	K
Uf	Fuel utilization factor	–
V_{c}	Cell voltage	V
V_{op}	Operating voltage of fuel cell	V
V_{SC}	Voltage of the supercapacitor	V
VOC_{SOFC}	Open Circuit Voltage of SOFC	V
y_i	Molar fraction of species i	–
W	Annual energy consumption	–
α	Charge transfer coefficient	–
η_{act}	Activation overpotential	V
η_{ohm}	Ohmic overpotential	V
η_{dif}	Diffusion overpotential	V
η_{total}	Total overpotential	V
ΔG	Gibbs free energy change	J/mol
ΔG^0	Standard Gibbs free energy change	J/mol
ϕ	Heat	W

Chapter 1

Introduction and Project Definition

Chapter Description

This chapter provides an overview of the project, including its definition, collaboration framework, goals, methodology, and the overall structure.

Contents

1.1 Introduction

Investment in new Data Centers has surged over the past years, fueled by accelerating digitization and the growing adoption of AI. This rapid growth is placing significant pressure on local grids, a challenge further intensified by the considerable mismatch between the pace of Data Center construction and the slower process of expanding and reinforcing grids and generation capacity (Spencer & Singh, 2024).

The sector's impact on electricity systems is already significant and continues to grow. According to Ramachandran et al. (2025), global Data Center electricity consumption is projected to reach 536 TWh in 2025, with estimates suggesting this could nearly double to 1.065 TWh by 2030. Europe follows a similar trajectory: demand from Data Centers is expected to rise from 10 GW in 2022 to approximately 35 GW by 2030 (Milanesi et al., 2025), with forecasts by the IEA predicting that electricity use by the sector in the EU alone will reach nearly 150 TWh by 2026 (IEA, 2024a). This trajectory suggests that Data Centers could account for 15–25% of all new net electricity demand added in Europe through 2030 (Milanesi et al., 2025).

Even with the expected growth forecast, Data Center industry development is being challenged, and new power generation solutions are emerging. Local grid constraints and lengthy interconnection times, which stem from underdeveloped transmission and distribution infrastructure that cannot keep pace with the rapid growth in Data Center electricity consumption, imply very large time-to-power periods. This, combined with concerns over energy availability, security, and costs, has led Data Center operators to increasingly favor on-site generation solutions: according to recent studies published by Bloom Energy (2025a), leaders expect approximately 30% of all Data Centers to use some onsite power by 2030 (Bloom Energy, 2025a; Ramachandran et al., 2025; Savills, 2022; Spencer and Singh, 2024).

Bloom's findings highlight a changing landscape: historically, on-site power at Data Centers has been used primarily for backup, but recent trends indicate a shift toward on-site power generation as a primary supply source (Bloom Energy, 2025a). Currently, most on-site power solutions consist on Simple Cycle Gas Turbines, but this landscape is changing with the uptake of new technologies for the application, something partially driven by the unprecedented large delivery times and backlogs Gas Turbine companies are having (Bloom Energy, 2025a; Gas Turbine Hub, 2025). New announcements to 2030 put Fuel Cells as one of the main players in the field, competing hand by hand with Gas Turbines (Bloom Energy, 2025a).

This global landscape in general, and the European one in particular, signifies a big opportunity for *Bloom Energy*. The company is a world leader in SOFC power systems which are able to work on natural gas, biogas and hydrogen, having the capacity to operate as a highly reliable off-grid load-following system with a high degree of efficiency and minimized environmental impact (Bloom Energy, 2024c).

In light of this, the present study focuses on the European market and provides a techno-economic analysis of *Bloom Energy*'s SOFC systems under various configurations. It compares them with alternative power solutions based on technical, economic, and environmental criteria. Additionally, the study evaluates the potential impact of these systems on the sector under different scenarios.

1.2 Project Definition

1.2.1 Collaboration Framework

This thesis is a collaborative project between Politecnico di Torino (*PoliTo*) and *Bloom Energy*, combining academic research with industry expertise.

PoliTo, a leading European technical university, is recognized for its work in engineering, energy systems, and sustainability. The academic supervisor is Professor Massimo Santarelli, an expert in energy systems and Fuel Cell technologies.

Bloom Energy is a global leader in SOFC technology, providing efficient and reliable on-site power solutions. The company contributes technical expertise, operational data, and industry insight through Patrizio Prunecchi, an expert in commercial SOFC deployment and Data Center applications.

The thesis is conducted by Felipe Perez, a Master's student in the *InnoEnergy SELECT* program at *PoliTo*, under the supervision of Professor Santarelli and industry mentorship of Patrizio Prunecchi.

1.2.2 Problem Statement

The growing electricity demand of Data Centers in Europe is putting an increasing pressure on electricity grids, compromising reliability and increasing time-to-power periods for new installations. Moreover, climate change is a pressing issue that forces the world in general, and the Data Center sector in particular, to adopt more sustainable practices. Given this landscape, sustainable on-site generation solutions for Data Centers represent a very promising solution, with SOFCs as one of the best performing alternatives.

Bloom Energy's SOFC systems are at the forefront of this shift. However, the technical, economic, and environmental study of the performance of these systems in the specific context of the Data Center sector in Europe could be further enhanced.

This thesis aims to fill that gap by developing a detailed assessment of the sector and conducting a comprehensive techno-economic, environmental, and comparative analysis of *Bloom Energy*'s SOFC systems for on-site power generation in European Data Centers, analyzing the overall impact these systems could have in the sector under different scenarios.

1.2.3 Goals

The central goals of the study are to assess the Data Center sector in Europe, analyze *Bloom Energy*'s SOFC system from techno-economic and environmental perspectives for a Data Center application, benchmark the results obtained with alternative power solutions, and analyze the net zero achievement of the Data Center sector along with the role that *Bloom Energy* systems could have in it (Figure 1.1).

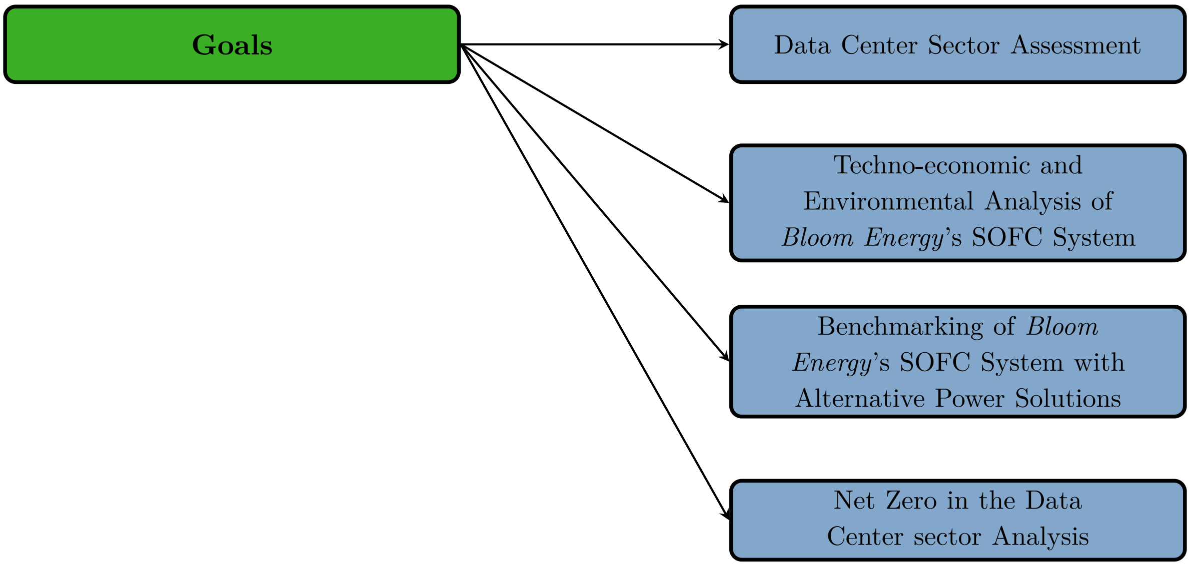

Figure 1.1: Core goals of the project.

Particularly, the project aims to fulfill the following objectives:

- **Assessment of Current Data Center Growth Trends and Sector Constraints in Europe:**
  - **Data Center Landscape:** Comprehensively analyze the current state of Data Centers in Europe, including energy consumption patterns, geographic distribution, capacity, and growth trends.
  - **Sector Constraints:** Analyze existing limitations constraining the development of the sector.
  - **Impact Assessment:** Evaluate how these constraints and the evolving Data Center landscape impact the deployment of *Bloom Energy*'s SOFC systems.
  - **Opportunities and Challenges:** Identify opportunities for SOFC integration in addressing Data Center power needs.
- **Techno-economic Evaluation of *Bloom Energy*'s SOFC Systems:**
  - **Technical Evaluation:** Analyze the technical performance of *Bloom Energy*'s SOFC systems when implemented to power a 100 MW Data Center, including but not limiting to efficiency, reliability, dynamic load response, fuel flexibility, system integration, and operational considerations, working on different fuels under varying system architectures depending on heat usage and carbon capture presence (Table 1.1).

  - **Economic Evaluation:** Perform an economic assessment through life-cycle cost analysis, and obtain the resulting levelised cost of electricity (LCOE) for Bloom systems in the Data Center application.
- **Environmental Evaluation:** Evaluate the potential for reducing emissions, considering both direct and indirect contributions of CO_2 and other pollutants. Additionally, quantify, water and land intensities as well as noise pollution.
- **Comparative Analysis with Existing Power Systems:**
  - **Comparative Framework:** Develop a comparative framework that benchmarks *Bloom Energy*'s SOFC against these existing solutions on key performance, environmental and economic indicators.
  - **Benchmarking:** Benchmark the techno-economic and environmental analysis results obtained with alternative systems to power Data Centers, considering both the Grid and on-site generation: Simple Cycle Gas Turbines (GT), Combined-Cycle Gas Turbines (CCGT), and Reciprocating Engines (RICE).
- **Sensitivity Analysis:** Assess how changes in key parameters influence the overall performance, economic viability, and environmental impact of *Bloom Energy*'s SOFC systems compared to alternative power solutions.
- **Pathway to Net-Zero Emissions in Data Centers:**
  - **Potential Impact:** Identify the role of SOFC technology in reducing overall carbon emissions within Data Centers.
  - **Scenario Analysis:** Analyze scenarios where the integration of SOFC systems contributes to achieving or maintaining net-zero operational emissions.
  - **Barriers and Enablers:** Evaluate policy, market, and technological factors that could facilitate or hinder the transition to net-zero power solutions.

1.2.4 General Methodology

Next, the general methodology underpinning the work done is presented. While this section presents a high-level overview of the overall methodological approach, more detailed and specific methodologies are discussed within the individual chapters that follow, each tailored to the aims and scope of the respective components.

Data Collection and Sector Assessment

Assessment of the Current Data Center Landscape and Constraints in Europe:

- **Data Center Landscape:** Data on European Data Centers was compiled and analyzed using industry reports, academic publications, and market databases. Energy consumption patterns, geographic distribution, capacity, and growth trends were examined.
- **Sector Constraints:** Technical reports, governmental studies, and regulatory documents were reviewed to identify existing limitations, including grid capacity issues, power reliability concerns, renewable integration challenges, and regulatory barriers, as well as other sectoral constraints.
- **Impact and Opportunities Assessment:** Findings were synthesized to evaluate how the evolving Data Center landscape and sector limitations affect the opportunity for deploying on-site power solutions, with a particular focus on *Bloom Energy*'s SOFC systems.

Techno-Economic Evaluation of *Bloom Energy*'s SOFC Systems

System Configurations

Bloom Energy's SOFC systems were assessed under different configurations depending on the use of heat, the type of fuel, and carbon capture coupling, as presented in Table 1.1 for a 100 MW Data

Center[1].

Two different system configurations were analyzed based on the utilization of the energy contained in the exhaust gas: (1) wasted heat and (2) hot water production. Each configuration was evaluated with two fuel options (natural gas and hydrogen), and carbon capture was considered for the Natural Gas sub-cases. Therefore, six configurations were assessed in total.

Table 1.1: Analyzed system configurations with fuel types and carbon capture options.

N	Configuration	Case	Subcase	Carbon Capture	Fuel
1	Wasted Heat	a	i	No	Natural Gas
			ii	No	Hydrogen
		b	i	Yes	Natural Gas
2	CHP - Hot Water Production	a	i	No	Natural Gas
			ii	No	Hydrogen
		b	i	Yes	Natural Gas

Technical Evaluation:

- **Performance Metrics:** System specifications were gathered from *Bloom Energy* experts and analyzed to extract key performance indicators such as electrical efficiency, reliability, and dynamic load response. Operational parameters including needed redundancies and and system integration characteristics were also evaluated.
- **Operational Considerations:** Custom mixed *Excel/Matlab* models were developed to assess the system performance in a Data Center application.

Economic Evaluation:

- **Lifecycle Cost Analysis:** A comprehensive cost assessment was conducted including capital expenditures (CAPEX), operational expenditures (OPEX) over the lifecycle of the plants. *Excel* and *Matlab* were used to simulate the economic model of the analyzed configurations using data provided by *Bloom Energy* and complemented by literature.
- **Economic Metrics:** The Levelised Cost of Electricity (LCOE) was calculated for each configuration both considering and disregarding Data Center lease rates opportunity costs.

Environmental Evaluation

- **Emission Analysis:** Direct and indirect emissions associated with the SOFC systems were quantified for each configuration in Table 1.1. Scientific and industrial sources were used to evaluate environmental factors including but not limiting to CO_2, NO_x, SO_x, CO, VOCs, and particulate matter.
- **Noise, Land and Water Intensity:** Similarly, scientific and industrial data was used to evaluate these variables.

Comparative Analysis with Existing Power Systems

Development and Implementation of a Comparative Framework:

- Key performance indicators (KPIs) were identified across technical, economic, environmental, and operational dimensions:
  - **Technical:** Variables compared include electrical efficiency, total efficiency, part-load efficiency, and ramp rate, which reflect the system's performance and responsiveness. On the operational side, factors such as lifespan, turn down limits to stay within emissions

[1] The configurations considered and the Data Center load were suggested by *Bloom Energy*.

compliance, availability, redundancy requirements, delivery time, installation and commissioning time, and time-to-power are considered. These help evaluate the system's durability, reliability, and readiness for deployment.

  - **Economic:** CAPEX, OPEX, and LCOE were employed.
  - **Environmental:** KPIs considered were CO_2e, NO_x, SO_x, CO, CH_4, VOCs, UHC, PM2.5, and noise. Additionally, resource use indicators such as water consumption and land use intensity are assessed. These variables help evaluate the environmental footprint and potential impacts of each system.

- A benchmarking framework was developed and implemented to compare all *Bloom Energy* system configurations from Table 1.1 against alternative power systems, including Grid supply, Gas Turbines, and Reciprocating Engines, as listed in Table 1.2.

Table 1.2: Considered power systems for benchmarking with *Bloom Energy* systems.

N	Case
1	Grid
2	Combined-Cycle Gas Turbines
3	Simple Cycle Gas Turbines
4	Reciprocating Engines (Natural Gas)

These systems were specifically modeled for the Data Center application to ensure the representativeness of the comparison.

Sensitivity Analysis

Critical parameters such as fuel prices, carbon prices, system costs, interest rates, and opportunity costs were identified for their potential impact on system performance, economic viability, and environmental results. Sensitivity analyses were performed using *Excel* and *Matlab* to quantify the influence of these variables on the LCOE across both the *Bloom Energy* system configurations and the alternatives presented in Table 1.2.

Scenario Analysis

Four different scenarios were developed: natural gas supply shocks, hydrogen, natural gas and carbon prices evolution towards 2050, the presence of CAPEX and OPEX subsidies, and that of performance incentives to analyze how resulting LCOEs varied. The complete descriptions of these scenarios can be found in subsection 4.6.1.

Expert Consultation and Iterative Model Refinement

Industry experts from Bloom Energy were consulted to validate assumptions, verify model accuracy, and refine both economic and technical evaluations. Their feedback was incorporated into iterative model updates to ensure alignment with real-world conditions. Parameters and assumptions were adjusted as necessary based on these consultations and emerging insights.

1.2.5 Contents and Structure

This thesis is organized into five chapters, each addressing a key aspect of the study: while the first one introduces the project, chapters 2 and 3 focus on the existing Data Center sector landscape and its power solutions. Chapter 4 presents the techno-economic analysis developed, and chapter 5 contains the overall conclusions of the thesis.

Chapter 1: Introduction and Project Definition. Introduces the project by outlining its context, objectives, collaboration framework, methodology, and the overall structure of the thesis.

Chapter 2: Data Center Landscape and Power Solutions. Examines the European Data Center sector, focusing on energy consumption patterns, regulatory landscape, emerging challenges, and growth trends.

Chapter 3: On-site Power Solutions. Presents an overview of on-site power generation technologies for Data Centers, including Gas Turbines, Fuel Cells, Reciprocating Engines, and Renewable Systems. Special attention is given to the potential of *Bloom Energy*'s SOFC systems as a reliable and sustainable energy solution.

Chapter 4: Techno-economic Analysis. Details the techno-economic modeling of SOFC systems, including the studied configurations, modeling methodology for *Bloom Energy* systems and competitors, and analysis of the results. Sensitivity and scenario analyses are also included.

Chapter 5: Conclusions. Summarizes the main findings, reflects on their implications, discusses limitations, and offers recommendations for future research and practical applications.

Moreover, the thesis also includes four appendices:

Appendix A. Contains specification tables and auxiliary data used in the analysis that are not included in the main chapters.

Appendix B. Provides an overview of detailed concentrated-parameter modeling of SOFC systems. Although not directly used in the analysis, it offers a conceptual foundation to complement it.

Appendix C. Presents a summary table of the key results obtained in the study.

Appendix D. Includes additional results not shown in the main body of the thesis.

Chapter 2

Data Center Sector Landscape

Chapter Description

This chapter provides an in-depth analysis of the European Data Center landscape and the associated sector constraints. It explores the increasing energy demands of Data Centers, sustainability concerns, challenges related to grid infrastructure, and the potential role of on-site power solutions.

Main Takeaways

1. **Sector Overview**: The Data Center industry is growing exponentially, and Europe is a major player in the global landscape. The sector is unevenly spatially distributed in the region, creating dense Data Center clusters that strain urban power grids, and fuel interest in decentralized on-site generation.
2. **Economics**: Power supply represents a major share of both CAPEX and OPEX. The sector is shifting towards hyperscale and colocation models, and this increases the demand for scalable, energy-efficient, and cost-optimized power solutions.
3. **Energy Consumption**: Data Centers are extremely energy intensive assets. Electricity demand in the sector is growing faster than efficiency improvements can offset, making Data Centers a primary driver of power-system expansion.
4. **Sustainability**: Energy sourcing has a major impact on Data Center sustainability, as well as cooling methods employed. Inherent impact is caused by needed frequent technology updates for computational requirements and technological obsolescence. Regulations and decarbonization goals are pushing operators to adopt low-carbon power sources and more sustainable practices.
5. **Regulatory and Policy**: Emerging EU-wide targets and fragmented national regimes create a complex compliance landscape. Pressure is increasingly being put on the sustainability of the sector.
6. **Market Spotlights**: Major markets like Germany, the UK, Ireland and Italy, face planning, grid and policy constraints that shape development strategies. On-site solutions are increasingly being considered, as well as migrations to other locations.
7. **Development Challenges**: Persistent grid-upgrade backlogs, rising costs and policy requirements or inconsistencies accelerate the shift to resilient on-site power solutions.

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2.1 Overview of the Data Center Sector in Europe

Data Centers are the backbone of the digital economy, providing the essential IT infrastructure needed to develop, operate, and deliver applications and services while also storing and managing the data linked to them (IBM, 2024). The demand for these facilities had already been increasing significantly in recent years in response to the growing importance of the digital economy in modern lives: from 2015 to 2022, internet traffic has increased 7 fold, and Data Center workloads have multiplied by over four (Table 2.1); but with the disruption of AI, increased digitization and slower gains in power usage efficiency (PUE), this tendency has escalated (Srivathsan et al., 2025; Milanesi et al., 2025).

Table 2.1: Evolution of the demand of digital services between the years 2015 and 2022 (Kamiya & Bertoldi, 2024).

	2015	2022	Change
Internet users	3 billion	5.3 billion	+78%
Internet traffic	0.6 ZB	4.4 ZB	+600%
Data Center workloads	180 million	800 million	+340%
Data Center energy use (excluding crypto)	200 TWh	240-340 TWh	20-70%
Crypto mining energy use	4 TWh	100-140 TWh	+2300-3500%
Data transmission network energy use	220 TWh	260-360 TWh	+18-64%

This global expansion is not only reshaping energy consumption patterns but also straining electricity grids and raising sustainability concerns. Europe, while representing only a share of total installations, is following these international trends in digitization, capacity growth, and infrastructure pressure. Understanding the European landscape, therefore, requires first situating it within this broader global context.

Srivathsan et al. (2025) reports that world Data Center demand in 2030 could reach 171-219 GW, from one of 60 GW, growing with a CAGR of 19-22% in the 2023-2030 period. AI-ready capacity is emerging as the dominant driver of this growth, expected to comprise nearly 70% of global demand by 2030 and growing at a staggering 33% CAGR (Srivathsan et al., 2025). This rapid growth has significant implications for how Data Centers are powered. As digital workloads grow more power-hungry, especially with the rise of AI, operators are increasingly concerned with access to reliable, scalable, and sustainable energy.

Now focusing on the European case, the continent hosts approximately 24% of the world's 11.800 Data Centers, second to the United States at 46% (Lu, 2025). Within Europe, the market is highly concentrated in Western countries—particularly Germany, the UK, France, and the Netherlands—all ranked in the global top 10 (Figure 2.1). This overall continental concentration trend signifies that approximately two-thirds of the continent's Data Center capacity are situated in this sub-region (Savills, 2024). Among these western countries, the FLAPD markets are particularly notable, representing over 20% of the continent's Data Centers (Savills, 2024; GDA, 2024a; ICIS, 2025).

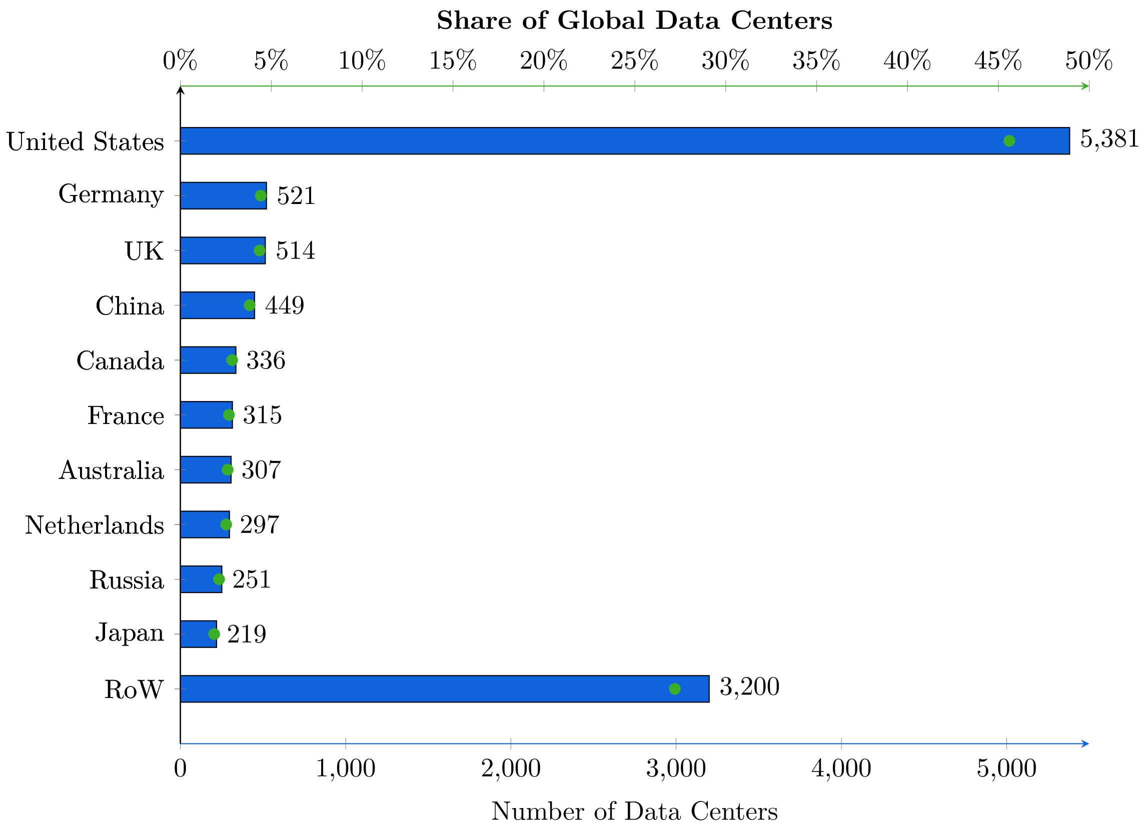
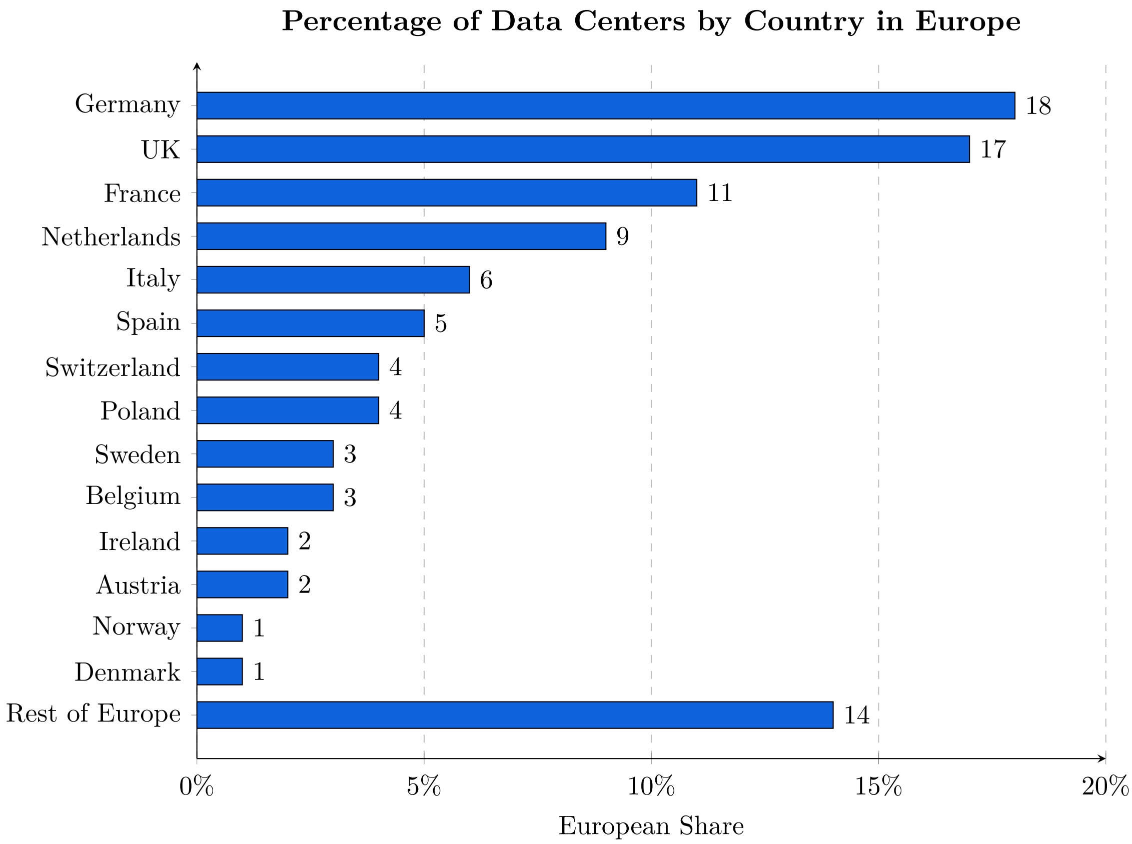


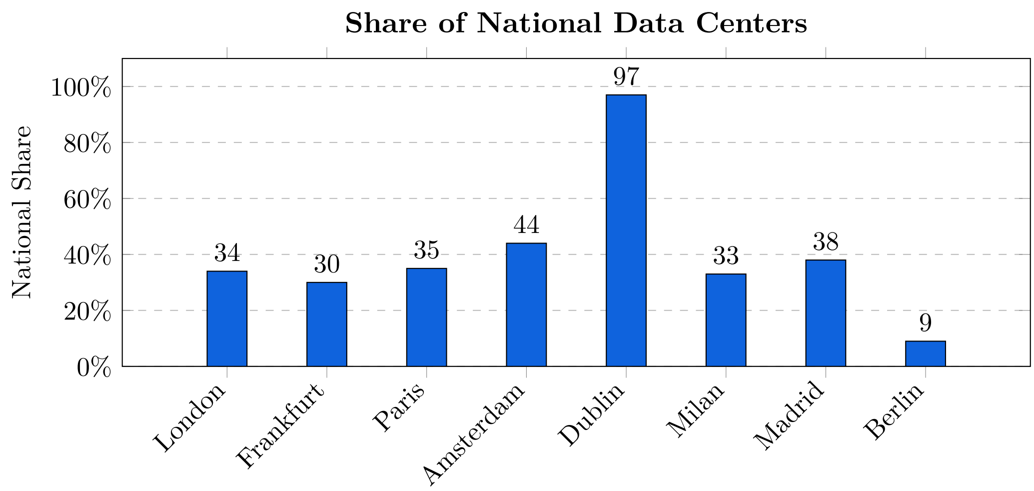
Figure 2.1: Number of Data Centers by Country and Global Share. Adapted from Taylor, 2024.

Furthermore, it is worth noticing that not only are these cities dominant at the European level, but they also play an outsized role within their respective national markets. As Figure 2.2b illustrates, London, Frankfurt, Paris and Amsterdam concentrate between 30 and 45% of the total Data Centers present in their countries. Dublin, the most extreme case, on the other hand, presents a remarkable 97% of all the Data Centers in Ireland. Considering Data Center capacity, this described situation becomes even more extreme, with the FLAPD market currently hosting the largest facilities according to ICIS (2025). This level of centralization intensifies pressure on urban grids, particularly in FLAPD cities where interconnection delays, power price volatility, and space constraints are becoming critical. As demand continues to grow in these locations, the case for decentralized and on-site generation, capable of bypassing grid bottlenecks, becomes increasingly relevant.

Currently, connection queues are lengthening in key markets, some even placing moratoriums on new Data Centers while grid authorities process the ever-increasing backlog of connection requests and assess the capacity of the grid to meet additional connections (IEA, 2025a). As the IEA (2025a) shows, connection times in Germany and the UK can extend to up to 7 years, while in the Netherlands this figure can go up to 10 years. Italy, and Spain present shorter waiting times, but Dublin, where 97% of Irish Data Centers are located, paused connections until 2030 (Table 2.2). These long periods are not uniquely due to slow bureaucracy, according to the IEA (2025a). Suboptimal connection and queue management processes, lack of system operator resources and skilled labor add to the increasingly stringent grid congestion issue, becoming a complex problem considering the demand boom Data Centers are generating (IEA, 2025a). This is extremely problematic considering the lengthy



(a) Share of Number of Data Centers in Europe by Country.



(b) Number of Data Centers and National Share

Figure 2.2: Data Center Distribution in Europe. Adapted from ICIS, 2025.

times involved in grid infrastructure updates, which can reach over 7 and 4 years for transmission and distribution, respectively, and the enormous overall grid investment needed, amounting to total annual costs in the order of €65-100 billion to 2030 at a European level (IEA, 2025a; Heussaff and Zachmann, 2025). Such bottlenecks are increasingly steering developers toward technologies that offer fast deployment and independence from traditional transmission infrastructure.

Table 2.2: Average connection times in key European markets (IEA, 2025a).

Location	Average Queue Time
Germany	Up to 7 years - 3 to 5 in Frankfurt according to Milanesi et al. (2025)
United Kingdom	5-7 years; 5-10 according to (Skidmore, 2025)
Netherlands	Up to 10 years
Italy	Less than 3 years
Spain	3-5 years
Ireland	In Dublin, paused until 2030

To understand how these leading hubs compare with other regional markets, it is useful to place Europe within the broader Europe-Middle East-Africa (EMEA) context, where Data Center maturity and infrastructure vary widely.

The total EMEA market comprises 9,4 GW operational, 2,9 GW under construction, and 8,7 GW in planning stages (Cushman & Wakefield, 2025). However, this Data Center capacity is unevenly distributed in the region, with Europe accounting for around 8,4 GW of its operational capacity, Africa and the Middle East only accounting for 292 MW and 680 MW, respectively (Cushman & Wakefield, 2025). Not only is there a concentration of capacity in Europe, but it is also unevenly distributed within the continent itself, where a limited number of markets dominate in terms of capacity. Cushman & Wakefield (2025) break down the different countries in the EMEA into four different categories in terms of their capacity and overall maturity for market characterization purposes: Powerhouse, Established, Developing and Emerging (see box below), observing that almost one half of the total capacity is located in Powerhouse markets, comprising only 5 European cities (Table 2.3).

Classification of Data Center markets in EMEA

Powerhouse. These markets are the largest in the region in terms of their capacity and committed pipelines. These include London. Frankfurt, Dublin, Paris, Amsterdam and Milan, which represent more than 47% of the operational Data Center capacity (4,4 GW) in EMEA and more than 50% of the new developments (5,8 GW) (Cushman & Wakefield, 2025).

Established. These range between 300-900 MW in total Data Center capacity and committed pipelines (Cushman & Wakefield, 2025). This category includes Helsinki, Madrid, Abu Dhabi, Dubai, Oslo, Johannesburg, Cardiff-Newport, and Berlin, which represent 13% of the total operational capacity in the region with 1.244 MW, being on track to more than double in size if the development pipeline (2.180 MW) is built out over the next few years (Cushman & Wakefield, 2025).

Developing. These range between 150-300 MW in terms of their total Data Center capacity and committed pipelines. Stockholm, Zurich, Warsaw, Tel Aviv, Copenhagen, Reykjavik and Cape Town are considered within this category, and they represent 8,3% of the operational capacity in EMEA (785 MW) (Cushman & Wakefield, 2025). Together they have a pipeline of 815 MW according to Cushman & Wakefield (2025).

Emerging. These are under 150 MW in terms of their total Data Center capacity and committed pipelines, comprising Vienna, Lagos, Barcelona, Riyadh, Brussels, Munich, Istanbul, Zaragoza, Marseille, Athens and Lisbon (Cushman & Wakefield, 2025). Together they represent less than 6,5% of the total operational capacity (608 MW) in EMEA, and they are in their early development stages, according to the same report. However, they are deemed attractive to many due to business-friendly environments, increasing consumer demand, suitable land, available power, fiber connectivity, and/or the establishment of new cloud regions (Cushman & Wakefield, 2025).

Table 2.3: Summary of European Data Center Markets by Category. Based on Cushman & Wakefield (2025).

Category	Markets	Capacity and Pipelines
Powerhouse	London, Frankfurt, Dublin, Paris, Amsterdam, Milan	47% of operational Data Center capacity (4,4 GW) and 50% of new developments (5,8 GW)
Established	Helsinki, Madrid, Abu Dhabi, Dubai, Oslo, Johannesburg, Cardiff-Newport, Berlin	13% of operational capacity (1,244 MW) and development pipeline (2,180 MW)
Developing	Stockholm, Zurich, Warsaw, Tel Aviv, Copenhagen, Reykjavik, Cape Town	8,3% of operational capacity (785 MW) and pipeline (815 MW)
Emerging	Vienna, Lagos, Barcelona, Riyadh, Brussels, Munich, Istanbul, Zaragoza, Marseille, Athens, Lisbon	Less than 6,5% of operational capacity (608 MW)

Among these groups, Powerhouse and Established markets face the most immediate energy constraints due to their scale and speed of growth. These markets are also typically subject to stricter environmental targets and stakeholder pressure, making them ideal candidates for innovative, low-carbon generation technologies that offer reliable, scalable power without lengthy grid upgrades.

Now focusing particularly on European markets, Figure 2.3 shows the current, under-construction, and planned Data Center capacities across the top ten European markets according to Cushman & Wakefield (2025). Here, it is observed that London leads the market with the highest operational capacity at 1.141 MW, followed closely by Dublin at 1.116 MW and Frankfurt at 713 MW, all of which also show significant planned expansions. This is specially true for London, which has an additional 1.260 MW in the pipeline. Paris and Milan are also undergoing substantial growth, with planned capacities exceeding their current installations. Interestingly, while some cities such as Dublin and Helsinki have moderate planned expansions compared to their existing capacity, Berlin stands out at the opposite corner, with relatively low current capacity but a significant planned increase.

Overall, the demand for Data Centers across the continent is projected to grow at a CAGR of approximately 20%, reaching around 35 GW by 2030, up from 10 GW in 2023 (Figure 2.4), and involving an investment of over $250-300 billion in Data Center infrastructure excluding power generation investment needs (Milanesi et al., 2025). According to Savills (2024), although no sector is entirely immune to macroeconomic challenges, the Data Center industry is having "secular and non-cyclical growth". In the future, 94 additional Data Centers are planned to 2027 in the region, adding approximately 2.800 MW and rising the overall capacity to 13.100 MW by 2027 (Savills, 2024), and CBRE (2024a) reports 655 MW of new Data Center supply in 2024 in Europe with forecasts of additional 937 MW in 2025. Although this is a very fast pace of Data Center construction indeed, it is expected to fall short of the overall forecast demand of 22,7 GW in 2027 (Savills, 2024).

Most of the upcoming Data Center capacity is expected to remain concentrated in the FLAPD markets, accounting for 65% of the total Data Center pipeline through 2028 (Savills, 2024). However Savills (2024) notes that future supply in these regions is projected to face constraints due to new laws and policies focused on energy consumption and sustainability, along with rising land and construction costs, which present growing obstacles for Data Center development. Alternative attractive locations for new developments include Prague, Genoa, Berlin, Munich, Düsseldorf, Milan, Cambridge, and Manchester according to Savills (2024). ICIS (2025), IEA (2024a) and Business Wire (2024), as a complement, report that other Data Center markets such as Spain, Portugal, Greece, and the Nordics are also likely to develop in the coming years due to locational advantages, a high share of renewables and low power prices. Conversely, other markets in Southern Europe, as well as most of Eastern Europe, are expected to see relatively little Data Center activity to 2035 due to a combination of power market, economic, business and political reasons.

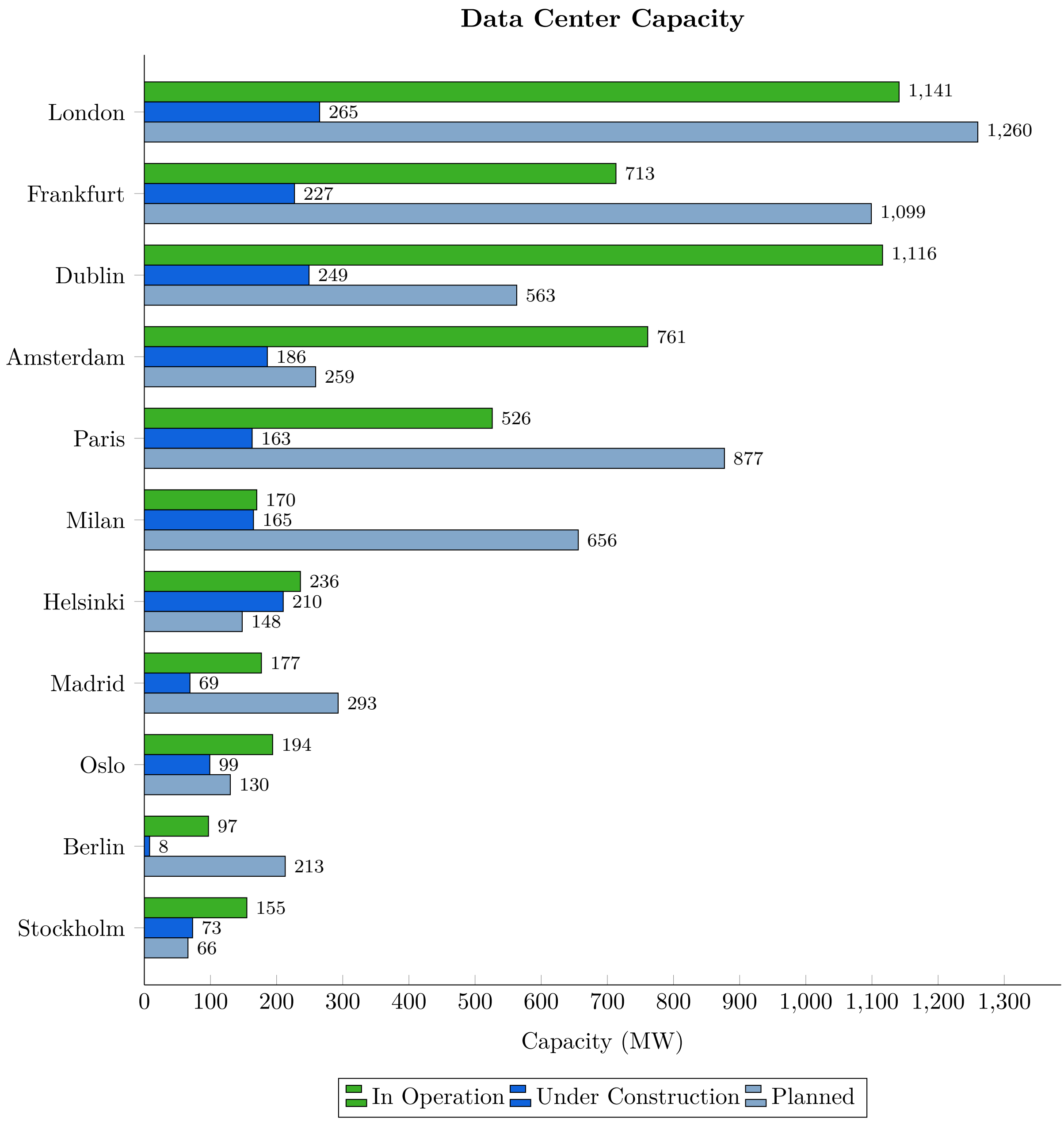


Figure 2.3: Current, under construction and planned Data Center capacities in the top 10 European Data Center markets (Cushman & Wakefield, 2025).

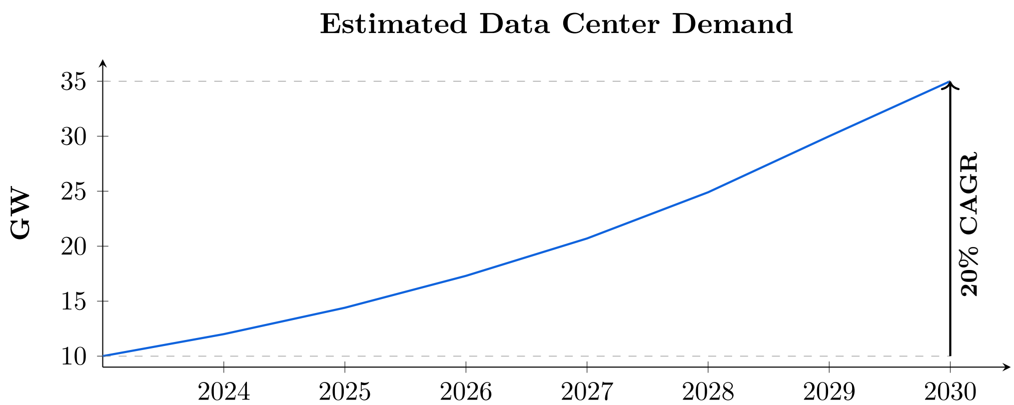


Figure 2.4: Estimated Data Center Demand in Europe (excluding crypto mining), 2023-2030. Adapted from Milanesi et al. (2025).

As outlined in this chapter, the European Data Center sector is expanding rapidly, with growth concentrated in particular urban clusters already facing severe challenges. As Europe's Data Center footprint grows, developers and operators are making increasingly complex economic decisions. These choices go beyond location and grid access: they encompass ownership models, risk-sharing strategies, cost optimization, and long-term operational resilience. To better understand these dynamics, the next chapter provides an overview of the economic structure of the European Data Center sector, examining key market actors, business models, growth trends, the role of energy, and the economic ripple effects of this critical infrastructure.

2.2 Overview of the Economics of the Data Center Sector

Data Centers are among the most capital and energy intensive assets in the modern economy, with billions of dollars invested each year in real estate, power, and infrastructure. Understanding the economic dynamics behind their development and the consequences they have is essential to generate a comprehensive assessment of the sector.

In this section, the economic dimension of the Data Center sector is unpacked. First, the three main ownership archetypes are defined, and the evolution of their market shares is analyzed. Next, market size, revenue growth, and competitive structure are quantified, with segments and players that will set the pace over the coming decade being highlighted. Finally, the sector's broader economic footprint is examined to show how Data Centers act as powerful catalysts for regional economies.

2.2.1 European Data Center Market Overview

Europe's Data Center market is in the midst of a dramatic shift: from predominantly owner-operated facilities toward hyperscale and colocation models (see box below).

Classification of Data Centers

Hyperscalers. These offer large-scale cloud computing services with the ability to rapidly scale up or down, managing vast global networks of data centers to provide infrastructure as a service and platform as a service offerings (Milanesi et al., 2025).

Colocators. They offer physical space, power, and cooling in their data centers for customers to house their own servers and networking equipment, providing a secure, managed environment where businesses can rent space and maintain control over their hardware (Milanesi et al., 2025).

Enterprise. These are facilities that companies own and operate to house their own IT infrastructure, fully controlled by the organization, and typically located on the company's premises or at a dedicated off-site location to meet specific business needs (Milanesi et al., 2025).

In 2023, enterprise-owned Data Centers accounted for 40% of European capacity, while colocation providers together held 35%, split between 13% leased to hyperscalers and 22% to enterprises (Figure 2.5). Hyperscalers themselves operated 48% of capacity, of which 46% was leased from colocators. Looking ahead, Milanesi et al. (2025) projects that by 2028 hyperscalers will control 65% of the market—over half of which will be through colocation leases—while enterprise-owned share will shrink to 23%. This showcases a dramatic shift in the market dynamics, moving away from self-owned facilities towards larger-high tech approaches, reshaping demand profiles and energy requirements, and setting the stage for new power-supply strategies. Hyperscalers present high, stable power requirements and stringent uptime needs. Consequently, energy infrastructure must adapt through more resilient and efficient supply models.

This realignment of ownership models is already influencing where capital flows and which segments capture the biggest shares. As a whole, the European Data Center Market had a total value of USD 42,98 billion in 2023, and is expected to grow to USD 64,5 billion by 2029, reflecting a CAGR of 7%

(Business Wire, 2024), with Hyperscalers expected to drive up to 70% of the demand (Milanesi et al., 2025).

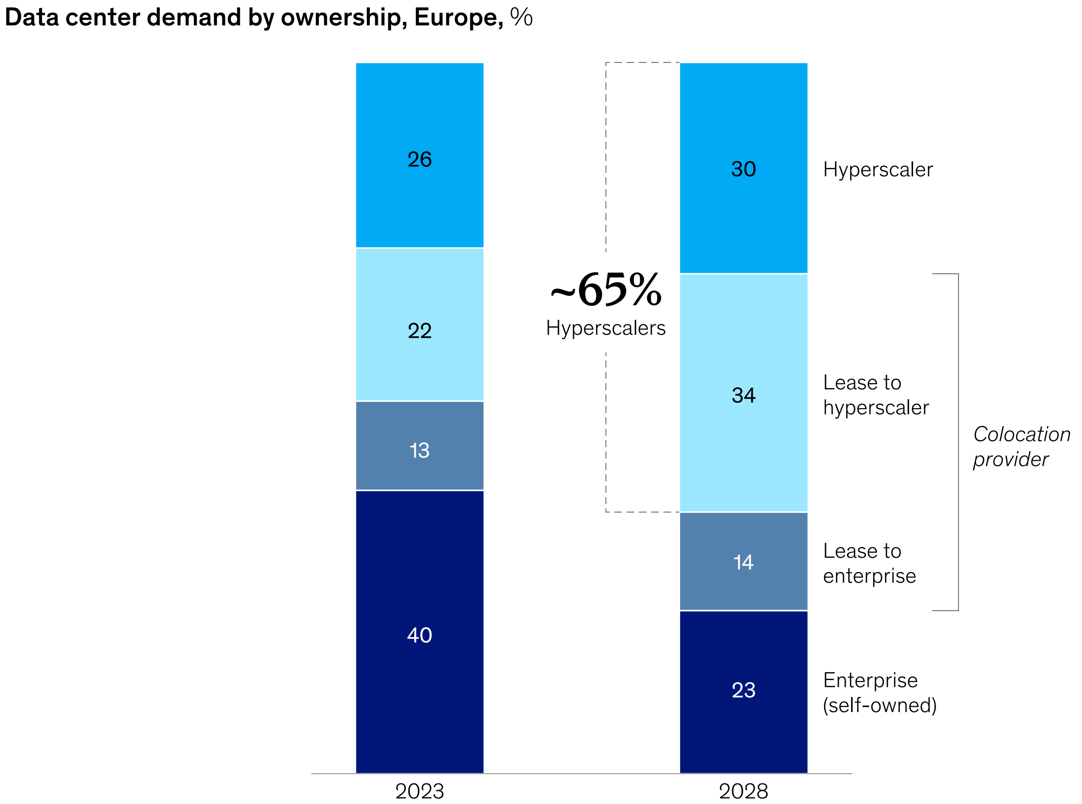


Figure 2.5: Data Center demand by ownership in Europe (Milanesi et al., 2025).

The colocation market size, particularly, reached a value of USD 16,99 billion in 2023, and is expected grow to USD 31,59 billion by 2028, rising at a CAGR of over 13% with Ireland, Poland, Denmark, the UK, Norway, and Spain surpassing the 10% CAGR threshold (GlobeNewswire, 2024a).

This market presents no clear dominance of any players, with currently 233 colocation operators in the region, and the 10 biggest ones controlling only 35% of it (Savills, 2024). While Tier 3 Data Centers currently dominate the market in Europe, Tier 4 ones are the ones expected to be the highest growing segment, achieving a CAGR of 15.5%[1] (GlobeNewswire, 2024a). This shift is primarily driven by the growing use of hyperscale colocation services by cloud and telecom companies, who require the highest degrees of reliability, with notable uptake in countries such as Austria, Germany, Spain, and Sweden (Mordor Intelligence, 2025a).

Having mapped how the Data Center market is evolving, next the economic footprint of these facilities, and how energy costs and investment models will shape their future, is examined.

2.2.2 Data Center Sector Economic Impacts

Data Centers play a crucial role in Europe's digital economy, influencing both employment and broader economic metrics. According to GDA (2024a), the sector is not only responsible for the direct and indirect jobs for their construction and operation, but also for the creation of digital ecosystems, fostering the implementation of other companies in the areas where they are settled as they act as the foundational infrastructure for the digital economy. European scale values for the gross value added (GVA) of the sector were not found in the literature, but as illustrative figures of the overall situation, in the UK, the Data Center sector contributes with £4,7 billion in GVA to the economy (techUK,

[1]The tier system is a four-level system to rate the redundancy and resiliency of data centers developed by the *Uptime Institute* where Tier IV represents the highest level (IBM, 2024).

2024), the ICT sector in Ireland contributes approximately 20% of the total GVA (Conefrey et al., 2023), and in Germany, €250 billion in GVA is triggered by cloud use (Eco, 2025).

The Data Center industry drives economic growth through both construction and operational activities, generating direct, indirect, and induced impacts. Direct impact stems from spending on design, installation, and infrastructure during construction—covering materials, planning applications, and labor costs. Operationally, ongoing expenditures on electricity, cooling systems, and staff salaries further contribute. Indirect impact arises as suppliers paid by Data Centers engage in additional business-to-business transactions, amplifying economic activity. Meanwhile, induced impact is fueled by supply chain employees spending their earnings on goods and services, stimulating broader economic growth.

As shown in Table 2.4, employment in the Data Center sector varies widely across Europe, reflecting differences in market maturity, national strategies, and industry structure. France, Germany and the UK lead in direct employment, underscoring their established roles in the European Data Center ecosystem. Notably, Germany and the UK also show a one-to-one ratio between direct and indirect jobs, suggesting a well-developed local supply chain. In contrast, Spain presents a striking imbalance: despite only 1.500 direct employees, it accounts for 40.000 indirect jobs, pointing to a reliance on broader service networks rather than in-house staffing. Italy shows a similar trend, with indirect employment more than double the direct, indicating strong downstream economic effects.

Table 2.4: Employment figures by country in the Data Center sector in Europe (GDA, 2024a; techUK, 2024).

Country	Direct	Indirect/Induced
France	28.000	17.000
Germany	25.000	25.000
Italy	8.000	20.200
Netherlands	5.500	7.300
Spain	1.500	40.000
UK	±20.000	±21.500

While these employment figures may represent only a small fraction of the overall labor market, it is crucial to recognize that Data Centers underpin the digital economy. By enabling a wide range of online services and digital transactions, they act as economic catalysts—stimulating growth across multiple sectors and generating ripple effects far beyond their physical footprint.

techUK (2024) reports that in the building phase, each job funded by Data Center construction supports between 1,4 and 3,1 jobs in the wider economy, while during operations, between 1,4 and 2,5 jobs per direct job are created in the wider economy. As a reference, USCC (2017) reports that a \$215,5 million initial CAPEX for typical large Data Center of 15.340 m^2 in the US supports 1,688 jobs during the 18-24 month construction phase, generating \$77,7 million in wages and creating \$243,5 million in economic activity for local communities. During its annual operation, the Data Center sustains 157 jobs and \$7,8 million in wages, contributing \$32,5 million in economic activity to the local communities annually (USCC, 2017). On the same topic, GDA (2024a) indicates that, in the UK, every new Data Center adds between £397 million and £436 million in GVA each year, while the annual contribution of each existing Data Center is estimated to be between £291 million and £320 million.

Having mapped the economic architecture of Europe's Data Center sector, it becomes critical to understand the underlying power consumption that shapes those economics. In the next section, focus on global and European electricity demand trends, load projections, and national market concentrations, as well as the role of energy in Data Center cost structure is put.

2.3 Energy Consumption Patterns

2.3.1 Global and European Data Center Sector Consumption Patterns

The history of Data Center electricity demand shows a complex interaction between efficiency improvements and rising service demand (Figure 2.6). Studies presented by the IEA (2025a) show that in the period 2005-2015, although the digital economy expanded rapidly—evidenced by over 25% annual growth in indicators such as global IP traffic, active mobile broadband subscriptions, and social media accounts—Data Center electricity consumption increased by only 3% per year. This decoupling of demand for digital services and energy use could be largely attributed to improvements in hardware and overall efficiency, including a 28% annual decline in energy use per computing task, a notable reduction in the share of less-efficient enterprise Data Centers, which fell by 22% annually, and an improvement in the PUE. Furthermore, the increased adoption of more energy-efficient hyperscale and colocation facilities contributed to the amplification of these trends.

However, the period 2015-2023 brought a change in the trend, with a significant acceleration in Data Center electricity demand to an annual growth rate of around 10%. Even if data shows that energy use per computing task continued to decline, the rate of improvement slowed considerably, evidencing diminishing returns from incremental efficiency upgrades. At the same time, the overall stock of servers in data centers doubled its annual growth rate to 8%, reflecting the rising demand for cloud services, streaming media, social platforms, and artificial intelligence workloads. Despite continued gains in Data Center efficiency, the sector's energy footprint grew in response to an explosion of new digital activities enabled by high-performance, accelerated computing. These servers, while more energy-efficient per task, facilitated entirely new classes of computation, contributing to increased total energy use.

The data presented evidences a key dynamic change in the sector: while technological progress in efficiency initially outpaced demand growth, later the situation changed as service demand surged and the marginal gains from efficiency improvements diminished. This showcases a central challenge in the electricity consumption of the Data Center sector: efficiency alone is not enough to offset the exponential growth in computational demand, especially as AI and high-bandwidth digital services are becoming increasingly employed.

The IEA (2024a) reports that in 2022, Data Centers, cryptocurrencies, and artificial intelligence were responsible of the consumption of about 460 TWh of electricity worldwide, almost 2% of the total electricity demand, and that this value would increase to 620-1050 TWh in 2026, with a base case scenario of about 800 TWh. More recent estimates, also from the IEA, on the other hand, state that global electricity demand from the sector-excluding cryptocurrency-is expected to more than double, growing from an estimated 415 TWh in 2024 to approximately 945 TWh in 2030 in the base case scenario (IEA, 2025a). Other scenarios developed by the organism, considering different degrees of AI adoption, digitalization rates, and regulatory support, place these values at 700-1700 TWh for 2035 (Figure 2.7). This sharp increase observed on the base scenario, reflecting a CAGR of about 15%, contrasts the considerably slower pace of electricity demand growth across other sectors. While Data Centers currently account for 1,5% of global electricity consumption, their share is projected to reach 3% by 2030, and although this represents a relatively small portion of total demand, the rate and scale of this evolution showcases a significant shift in the structure of electricity use globally, accentuating the influence of digital infrastructure on energy systems (IEA, 2025a).

The IEA (2025a) shows that the increased adoption of accelerated servers, which are mainly fueled by the proliferation of AI, are one of the main responsible of this growth. Electricity demand from these kinds of servers is projected to increase by 30% annually, largely outpacing conventional ones, which are expected to grow at 9% per year (IEA, 2025a). The same report from the organism shows that around half of the total increase in Data Center electricity demand is attributed to accelerated servers, while conventional servers contribute with around 20%, with the remaining growth divided between other IT equipment (10%) and infrastructure such as cooling systems (20%).

Europe is following this global trend, standing together with the US and China as the places where Data Center electricity demand is expected to remain the highest in the future. Here, Data Center

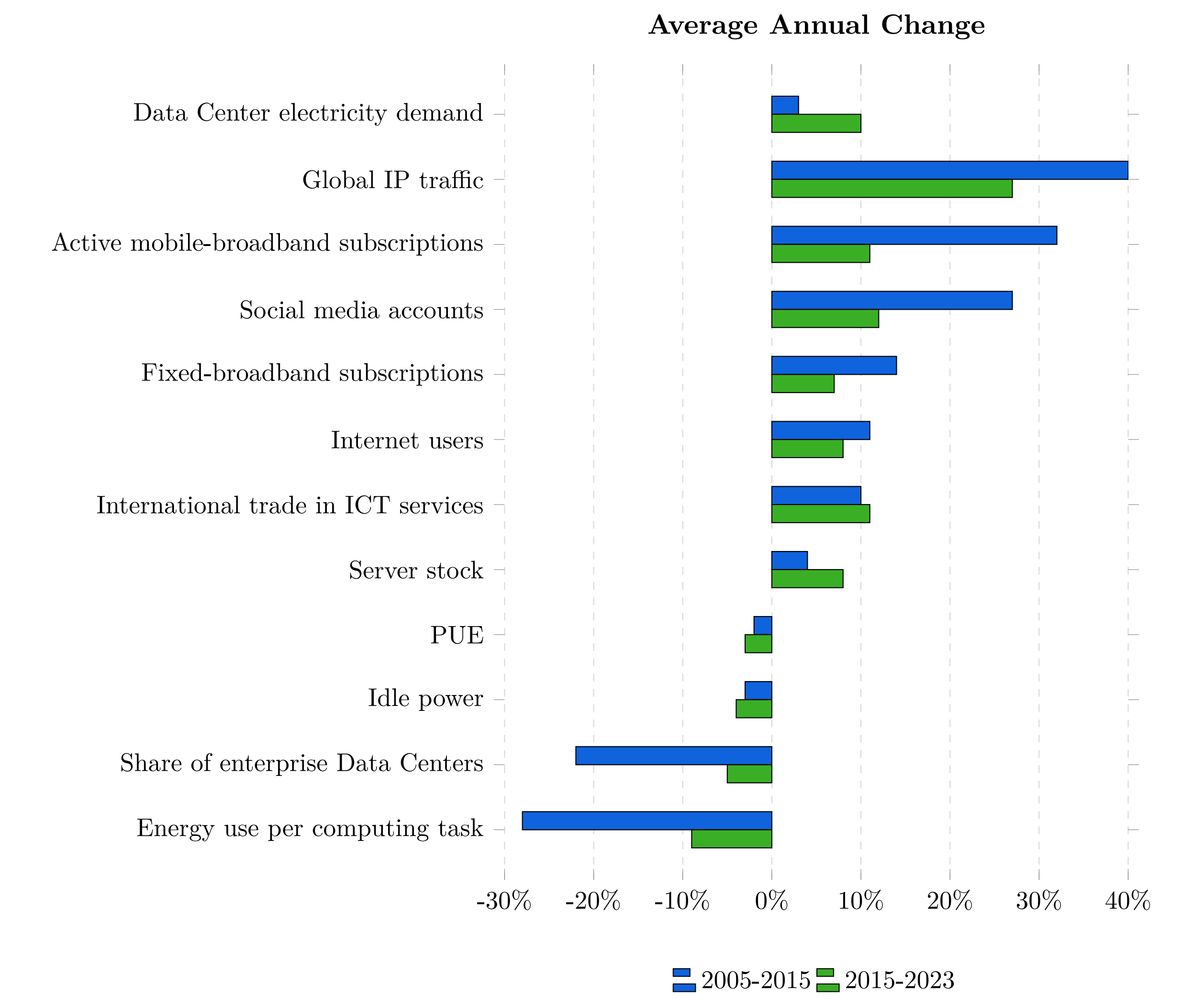


Figure 2.6: Global average annual change in key drivers of Data Center electricity consumption (IEA, 2025a)

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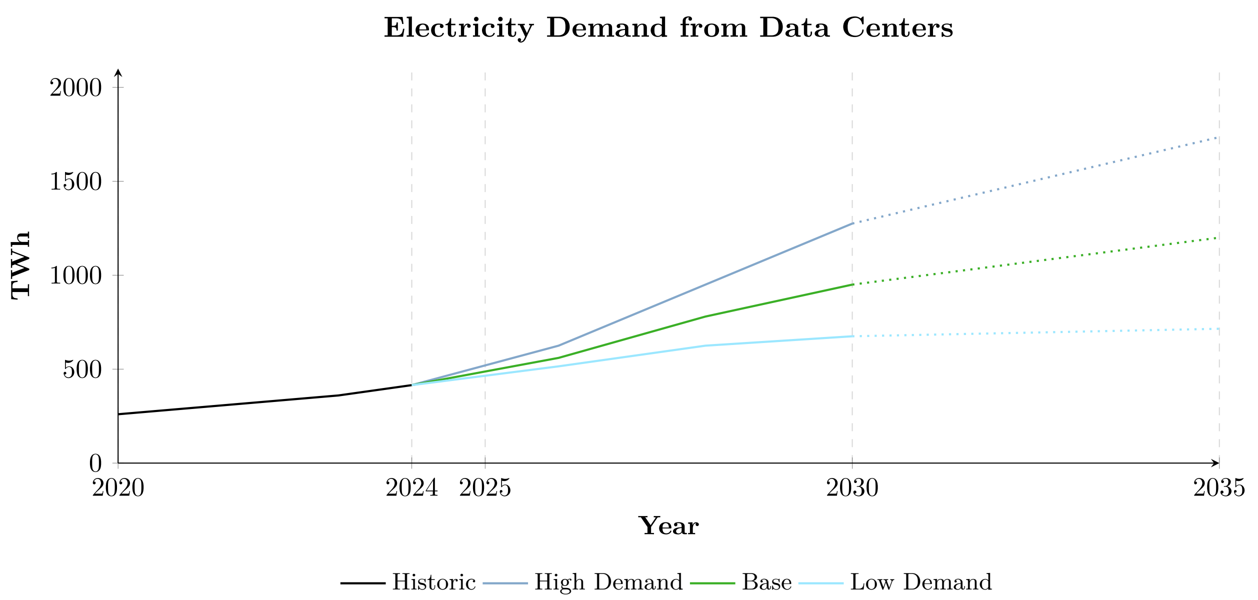
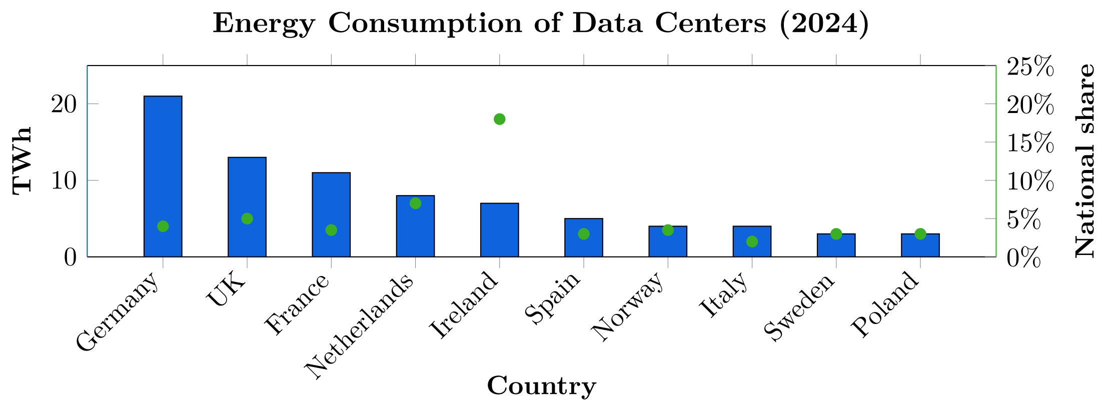


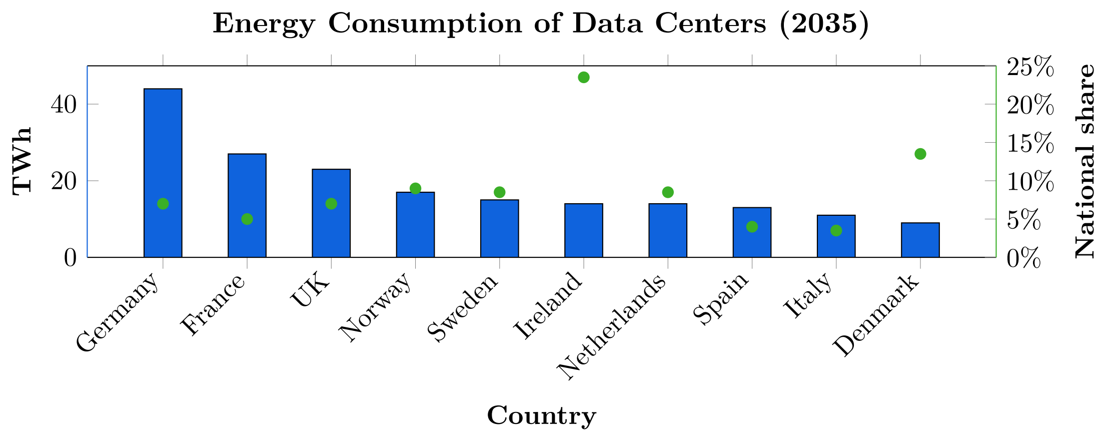
Figure 2.7: Global electricity demand from the Data Center sector depending on AI adoption, digitalization rates, efficiency and regulatory support (IEA, 2025a).

electricity consumption represented around 100 TWh in 2022, and this value is expected to rise to almost 150 TWh by 2026 (IEA, 2024a)[2]. Excluding cryptocurrency, Milanesi et al. (2025) reports that Europe's Data Center power consumption is expected to surge significantly, nearly tripling from the current 62 TWh to more than 150 TWh by 2030. Moreover, with the net-zero commitments made by key industry players, it is expected that much of this increasing demand will be met through renewable energy sources (Milanesi et al., 2025).

As it was previously mentioned, the Data Center market is highly concentrated, with Germany, the UK, France, the Netherlands and Ireland making up around 62% of the total Data Center European electricity demand (ICIS, 2025). As illustrated in Figure 2.8a, Germany, with almost 21 TWh, is the country with the largest consumption, followed by the UK (13 TWh) and France (11 TWh). According to ICIS (2025), the leading 10 national markets are forecast to account for 79% of the power demand from Data Centers in the next decade, with markets like Germany, France and Great Britain likely to keep the highest levels of Data Center power demand over this period due to a combination of their population size, total power demand levels, renewable availability, educated workforces, and strong GDP growth (Figure 2.8b). The same report suggests that there will also be smaller markets that will continue to be hot spots in the coming decade due to either their power market and climate advantages, like the Nordics or their business environment, like Ireland, but will eventually reach a level of saturation where growth will be forced to slow down due to their adverse impact on the power grid (ICIS, 2025).



(a) Energy Consumption of Data Centers (2024)



(b) Energy Consumption of Data Centers for the top 10 markets (2035).

Figure 2.8: Data Center power demand by country for top 10 countries in Data Center sector consumption. Adapted from ICIS (2025).

Ireland perhaps constitutes one of the most extreme cases in Europe. Here, demand from the Data Center industry reached 5,3 TWh in 2022, representing 17% of the country's total demand and being

[2] Note that ICIS (2025) presents more conservative estimates, with an electricity consumption of 96 TWh for Europe as a whole in 2024.

equivalent to the total consumption of the urban residential sector (IEA, 2024a). What is more, if this trend continues, the Data Center industry in the country might double its electricity consumption by 2026, reaching a share of 32% of the country's total electricity demand in 2026 if the majority of the approved projects are successfully connected to the grid (IEA, 2024a). Denmark, another heavy player in the sector, is home of 34 Data Centers, with 50% of them in Copenhagen, and electricity demand from this sector is expected to grow to 6 TWh by 2026, covering around 20% of the total electricity demand of the country (IEA, 2024a). According to Spencer and Singh (2024), this will constitute the main driver of electricity demand growth in the country.

In section 2.6, particular focus in spotlight markets is placed, but next, the role the Data Center sector in the overall European electricity demand is presented.

2.3.2 Electricity Demand in Europe and the Role of the Data Center Sector

European Union

After years of stability and recent decline, electricity demand in the EU is expected to rebound and grow steadily through 2026, driven by a combination of economic recovery and structural shifts in energy consumption. In this landscape, the Data Center industry is place as a key contributor to this surge, rising significance as a structural load in Europe's energy system.

Growing throughout the 2010s, the electricity demand in the EU peaked in 2008, and since then, it remained largely stable with only small declines (Ember, 2024b). Recently, weak economic landscapes, higher costs that manifested in a sharp decrease in industrial electricity consumption, milder weather, and energy efficiency measures caused consecutive decline years, resulting in the lowest electricity demand levels since 2001 (Figure 2.9) (Ember, 2024b). However, last year this tendency was reversed: demand in the EU rose by 1,4% y-o-y in 2024 (IEA, 2024a). Despite this, according to IEA (2024a), demand is still below that in 2021 and is not anticipated to reach similar levels until at least 2027, provided that the expected CAGR of 1,7% over the 2025-2027 period materializes.

The IEA (2024a) reports that the EU's electricity demand will grow through 2026, and that this growth is expected to be driven not only by a gradual economic recovery but also by key factors such as electric vehicles, heat pumps, and Data Centers, which are projected to contribute to half of the total demand increase (Figure 2.9), something also highlighted by Milanesi et al. (2025). As it is shown in Figure 2.9, over 17% of the growth projected to 2026 will be due to the Data Center sector in the EU.

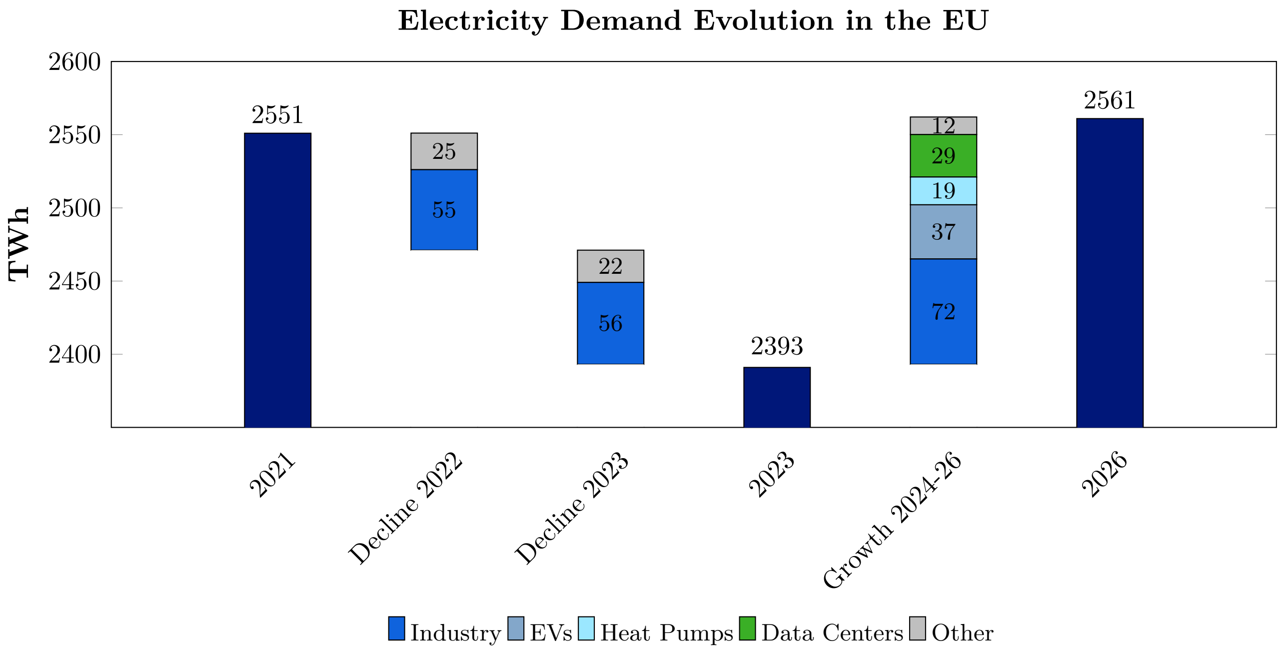


Figure 2.9: Estimated drivers of change in electricity demand in the EU, 2021–2026. Based on IEA (2024a).

Europe

In Europe as a whole, electricity demand followed a similar trend. After steady annual growth of 1,4% throughout the 2000s, with a peak in 2008, electricity demand has largely remained stable in the years that followed. However, since 2021, demand has steadily declined at an annual rate of approximately 3%, falling short of expectations for a post-COVID-19 recovery (Weiss et al., 2025). Particularly for the recent years, it decreased by 2,4% year-on-year in 2023, after a 3,6% drop in 2022 (IEA, 2024a).

Weiss et al. (2025) point out that after the financial crisis of 2008, GDP and electricity demand de-linked from the almost exact correlation observed in the 2000-2008 period. The slowdown in demand growth in the past years, according to the same study, can be largely attributed to the COVID-19 pandemic and the Ukraine conflict. The war-induced gas shortage led to rising prices, and this, coupled with reduced nuclear output in France and low hydroelectric production, accelerated a de-industrialization process and a dampening of electricity demand. Additionally, energy efficiency improvements, structural economic shifts (including offshoring and the rise of a service-based economy) and milder winters have further reduced consumption (Weiss et al., 2025).

If we do a sector analysis over the years, electricity demand shows varied growth patterns characteristics in the period (Table 2.5). It is observed that only the building sector, with a shy 0,6%, resulted in positive growth in electricity demand in the 2000-2023 period. While the transport and industrial sectors showed different trends along the years, they ultimately achieved a de-growth in the analysis interval. For the industry sector, a notorious fall in the 2021-2023 period can be observed, coming from 2 decades of stagnation, while for transport, recent electrification motivated an equally strong demand increase in the last years.

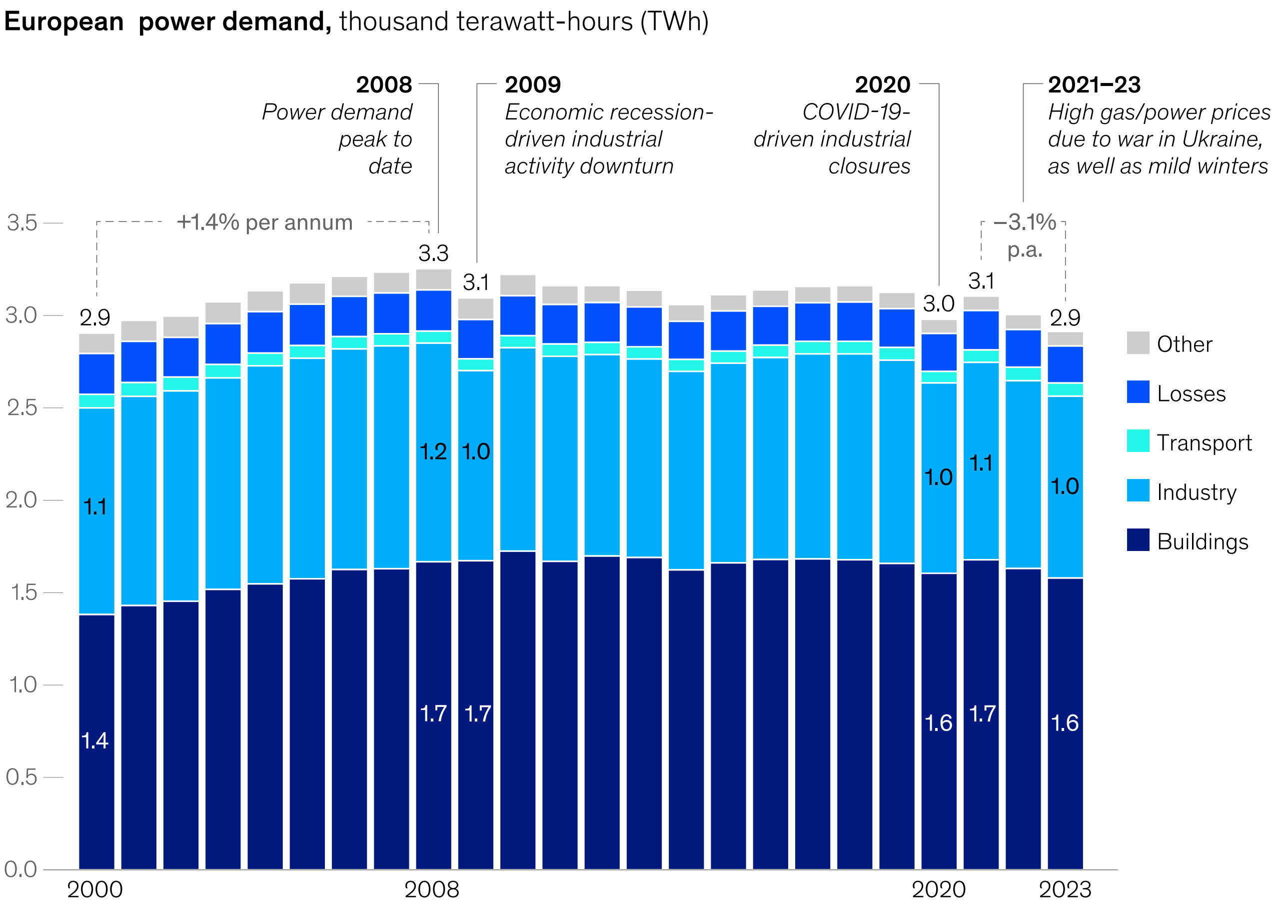


Figure 2.10: European electricity demand in the 21st century (Weiss et al., 2025).

Table 2.5: CAGR of Electricity Demand by Sector (%) (Weiss et al., 2025).

	2000–10	2010–19	2021–23	2000–23
Transport	−1, 2	0, 6	2, 1	−0, 2
Industry	−0, 1	0, 0	−2, 7	−0, 6
Buildings	2, 0	−0, 4	−2, 0	0, 6

These evolving demand trends across sectors over the past two decades have shaped the current electricity consumption landscape in Europe. Today, electricity consists of around 22% of the total final energy consumption, with industry (36,5%), residential (29,9%) and commercial and public sectors (28,6%) as the main consumers, together accounting for 95% of the total (IEA, 2025b). These sectors consume 1240 TWh, 1016 TWh and 973 TWh, respectively (IEA, 2025b), eclipsing that of the Data Center sector, estimated at around 96 TWh in 2024 (ICIS, 2025).

Table 2.6: Final Electricity Consumption by Sector in Europe (IEA, 2024a; ICIS, 2025)-

Sector	Electricity Consumption [TWh]	Share
Industry	1.240	36,5%
Residential	1.016	29,9%
Commercial and Public Services	973	28,6%
Transport Sector	85	2,5%
Data Centers	96	3,1%

Similar to the EU, electricity demand in Europe is projected to increase through 2026, driven by a recovery in industrial activity, further electrification of heating and transport sectors, and growth in the Data Center sector, resulting in a CAGR of 2,4% (IEA, 2024a). Weiss et al. (2025) highlight that the growing population and rising GDP are anticipated to drive higher overall energy consumption, something which, along with the ongoing electrification, has led projections of annual electricity demand increases of 1-7% through 2030 (Figure 2.11)(Weiss et al., 2025).

Even though an increase of 460 TWh in demand is forecast by 2030, analyses performed by Weiss et al. (2025) suggest that around 40% (180 TWh) of this might not materialize (Figure 2.12). The study notes that, in addition to reduced demand from industry, other major demand drivers, such as electric vehicles and heat pumps, may experience slower growth than anticipated. Weiss et al. (2025) classifies this reduced demand increase forecast in the buildings, transport, industry, green hydrogen, and Data Centers sector, pointing out the different uncertainties present with their causes and effects. It is noted that transport and industrial electricity demand surge, which are expected to be the main overall drivers according to the study, are also the ones with the highest uncertainties in the estimation.

In particular for the Data Center sector, rising workloads, advancements in hardware, and data residency regulations within the European Union are key factors driving demand growth, but this increase may be moderated by uncertainties associated with AI-driven load growth, grid connection challenges, and new EU regulations (Weiss et al., 2025). Despite this, 25,2% of the total demand increase in Europe to 2030 in the baseline growth scenario of Weiss et al. (2025) would come from this sector, representing 70 TWh of the 277 TWh forecast (Weiss et al., 2025). This means that on the baseline scenario, the Data Center sector is the second main driver in electricity demand-together with transport, only staying behind the Green Hydrogen sector. Moreover, the Data Center sector's electricity demand increase is one of the most certain to occur fully, with high confidence in 75% of the 91 TWh actually occurring. The high confidence level in projected demand growth reflects the sector's criticality and growing role in modern society.

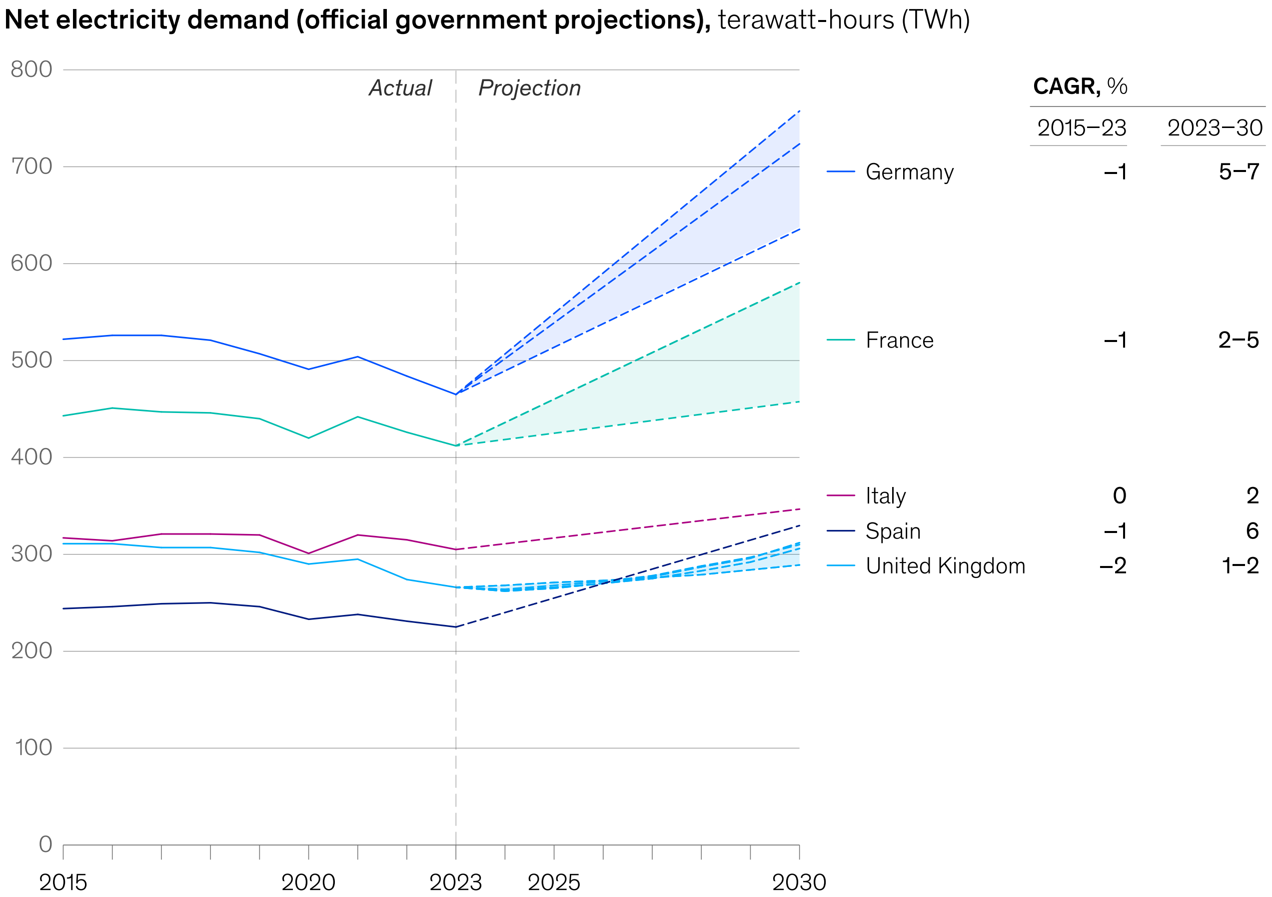


Figure 2.11: European electricity demand in the period 2015-2023 and projections to 2030 (Weiss et al., 2025).

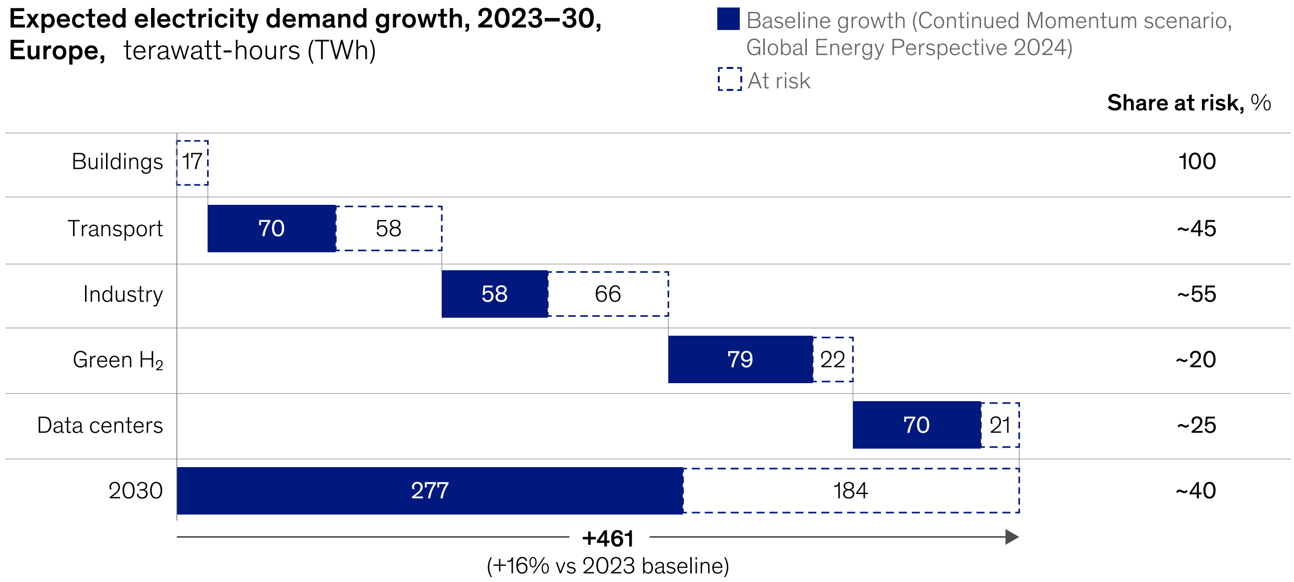


Figure 2.12: Electricity demand increase by sector in Europe to 2030 (Weiss et al., 2025).

While overall electricity demand in Europe remains evolving, it is clear that the Data Center sector stands out for its predictable and concentrated growth. This makes its energy profile both a challenge for infrastructure and sustainability and an opportunity for decarbonization. But a question still left to answer is what do Data Centers need power for, and what impact this has on their cost structure.

2.3.3 Electricity Demand in Data Centers

Data Centers represent highly stable and predictable loads, typically operating with load factors between 80% and 90% (ICIS, 2025). Electricity consumption in this facilities is primarily driven by two components: computing and cooling. While minor increases can be observed during business hours, corresponding to slight peaks in computational activity, these variations remain marginal (ICIS, 2025). Seasonal fluctuations are also limited, with annual variability mainly influenced by temperature-dependent cooling requirements (ICIS, 2025).

Some sources such as Baldor (2024) and Ramachandran et al. (2025) attribute approximately 40% of Data Center power consumption to computing and 40% for cooling systems, the remaining 20% being attributed to other associated IT equipment, but a recent report by the IEA offers a more nuanced breakdown. By differentiating consumption patterns across various Data Center archetypes, it becomes evident that the power consumption distribution varies significantly among them (Figure 2.13). While in enterprise Data Centers computing power consumption accounts for barely over 40% of overall consumption, using all the rest for non IT power, in hyperscalers this value reaches over 70%. This higher share is largely due to their highly optimized infrastructure, capable of running massive workloads with minimal overhead (Milanesi et al., 2025).

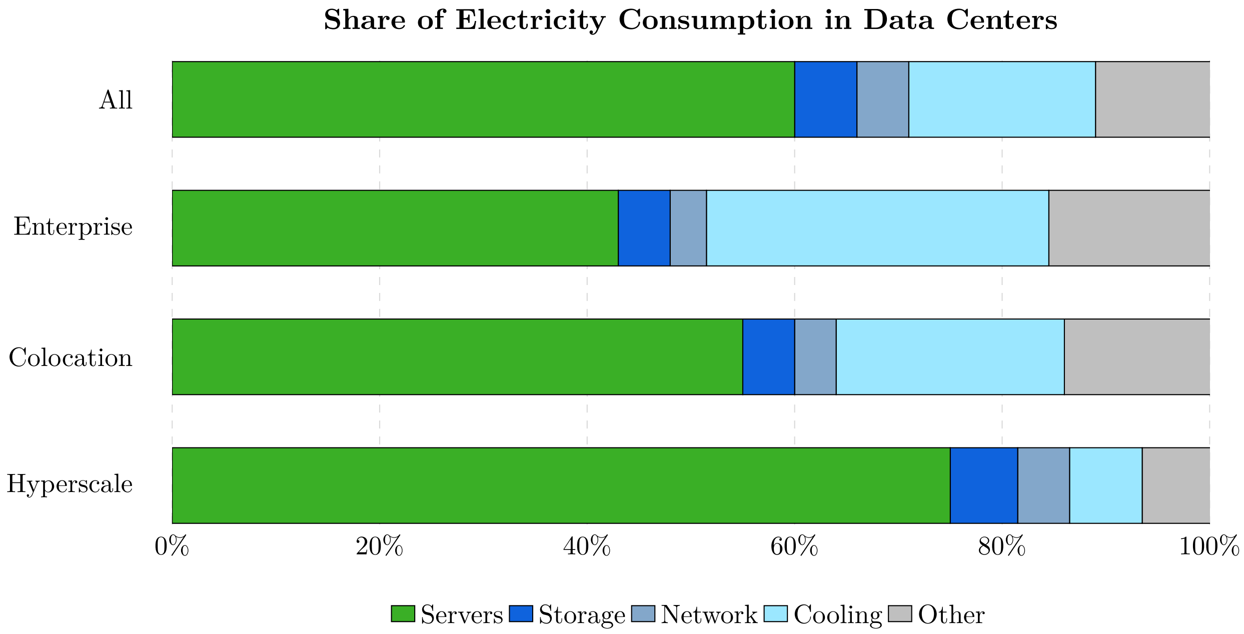


Figure 2.13: Energy consumption share in a Data Center (IEA, 2025a).

Over the past two decades, the share of cooling in total power consumption has declined substantially, thanks to technological improvements—a trend reflected in the evolution of the Power Usage Effectiveness metric. Already mentioned before as an efficiency metric, PUE is one of the most widely used ratios to measure efficiency in Data Centers (Savills, 2024). This ratio measures the total power consumed by a data center relative to the power used by its IT equipment alone, thus indicating the proportion of energy dedicated to IT operations versus other facility services (Baldor, 2024). In Europe, the current average PUE highly varies along the sources: while the Joint Research Centre (2023) reports that EU Data Centers have an average PUE of 1,6, ICIS (2025) and GDA (2024a) report and average of 1,5, and Savills (2024) one of 1,2 already. Something which is highly agreed, though, is that over the years, there has been a significant declining trend of these values across the industry, and will continue to do so, albeit at a likely lower pace. ICIS (2025) reports that apart from technological advancements, the increase in hyperscale Data Center diffusion also has an impact in driving further improvements in PUE, given that large companies managing these facilities can invest in state-of-the-art systems with the best efficiency measures. Moreover, PUE gains are also likely to stem from EU and national legislation enforcing efficiency gains, as well as from improvements in the cooling systems of facilities, driving the average PUE in Europe to an estimate of 1,35 by 2035, from

1,5 currently, according to ICIS (2025) (Figure 2.14).

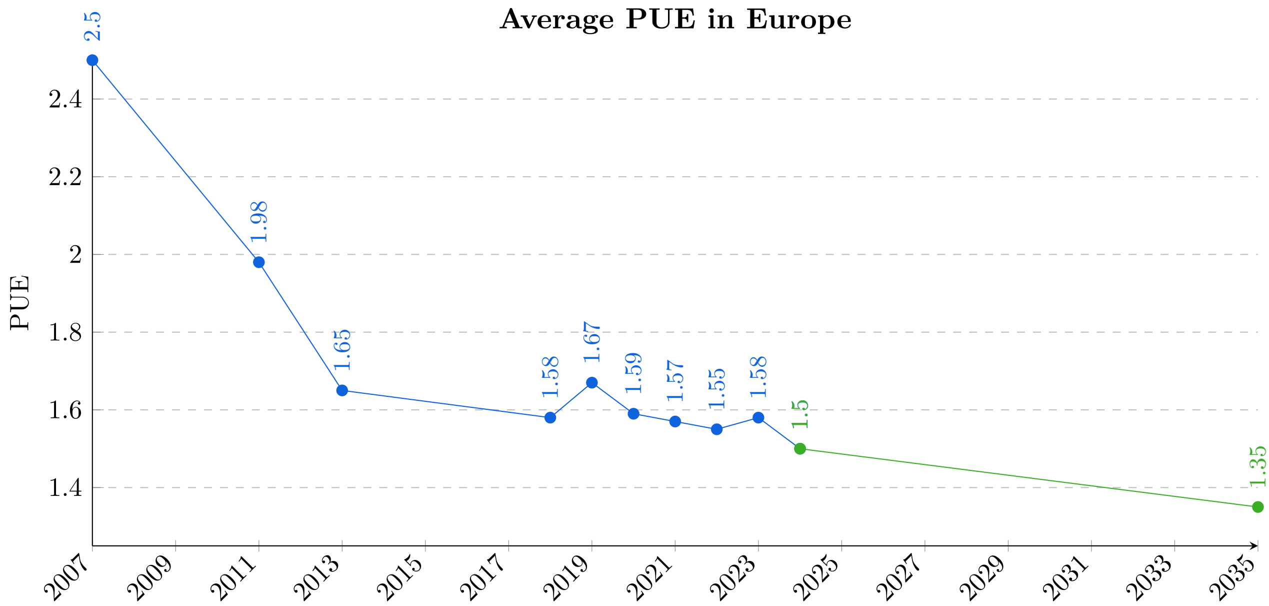


Figure 2.14: European Data Center Average PUE in the period 2008-2024 and forecasts to 2035 (Berger, 2023; ICIS, 2025).

Reducing the PUE is essential for both economic and environmental sustainability in the Data Center sector. A lower PUE translates to more efficient energy use, directly reducing operational costs by minimizing wasted electricity and decreasing reliance on more costly cooling and auxiliary power systems. Additionally, as Data Centers become increasingly power-intensive, improving energy efficiency is crucial for managing growing electricity demands without excessive infrastructure expansion. From a sustainability standpoint, reducing PUE helps reduce the carbon footprint by lowering overall energy consumption. With stricter environmental regulations and sustainability commitments, improving PUE is not just an economic imperative but also a strategic need for Data Center operators.

Given the centrality of energy in Data Center operations, it is essential to explore the impact that it has in Data Center development and operations.

2.3.4 The Role of Energy: Data Center Costs Breakdown

Electricity is a fundamental driver of both capital and operational expenditures in Data Centers. Moreover, as Data Centers expand to support growing digital demands, including energy-intensive applications like AI, their reliance on electricity becomes even more pronounced, highlighting this phenomenon.

On the CAPEX side, construction costs are highly dependent on factors such as density, redundancy, and scale (Savills, 2024). According to Savills (2024), high-density spaces present additional cooling needs, resulting in higher costs, redundancy improves reliability but involves extra expenses by duplicating critical components to mitigate downtime, and conversely, higher scale facilities benefit from more cost-effective procurement. A breakdown of all these costs can be found in Table 2.7 for two different scenarios: High and Low Costs. As it can be observed in Figure 2.15, electrical systems represent 40-45% of the total construction costs, being by far its major contributor. This reflects not only the power intensity of these facilities but also the need for redundancy, uptime guarantees, and grid backup systems. On the other hand, according to the USCC (2017), land acquisition and construction costs account for around 27,1% of the total initial investment in a Data Center, being the remaining 72,9% attributed to purchasing and installing mechanical and electrical equipment.

Table 2.7: Breakdown of Construction Costs per MW (Savills, 2024; Zhang, 2023).

Cost components	Description	Low cost [$/MW]	High cost [$/MW]
Land	Includes land acquisition costs	280.000	859.031
Building shell	Building shell, raised floor	896.000	1.832.599
Powered shell	Combination of land and building shell	**1.176.000**	**2.691.630**
Electrical systems	Backup generator, batteries, PDU, UPS, switchgear, transformers	3.136.000	5.268.722
HVAC, mechanical, cooling (HVAC+)	CRAC, CRAH, air-cooled chillers, chilled water storage, pipes	1.400.000	2.462.555
Fire suppression	Fire suppression system	168.000	286.344
Building fit-out	Lobby/entrance, MMR, shipping & receiving area	1.120.000	2.290.749
Tech requirements	Sum of electrical, cooling, and fit-out costs	**5.824.000**	**10.308.370**
Total		**7.000.000**	**13.000.000**

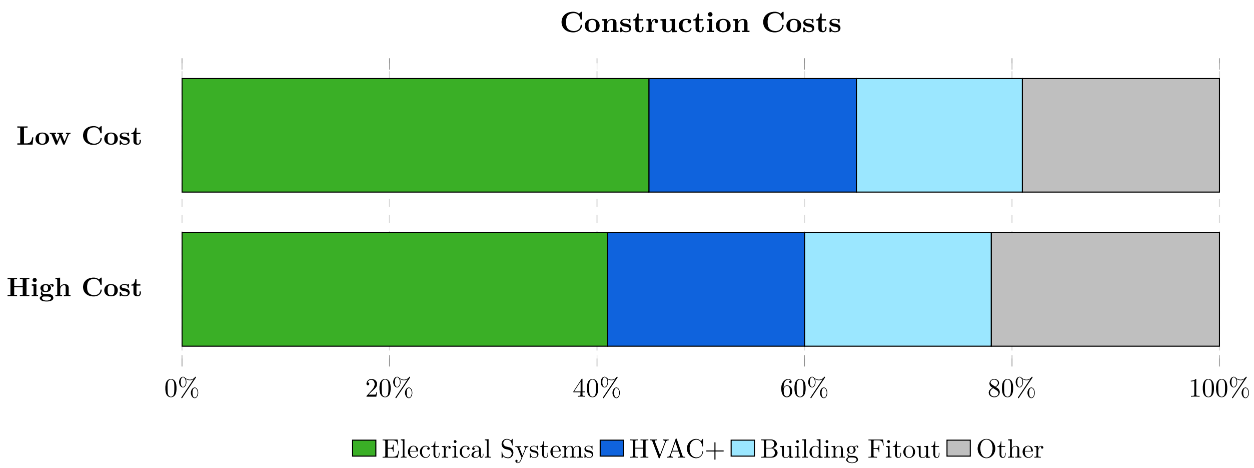


Figure 2.15: Breakdown of construction costs per MW for low and high-cost scenarios. Based on Savills (2024)

Regarding OPEX, according to the IDC (2024), it involves around 8,6% of the initial CAPEX, and it has electricity as its largest contributor, representing 46% of it for enterprise Data Centers and 60% for service provider ones. The USCC (2017), on the other hand, reports similar findings, with power (40%), followed by staffing (15%), real state taxes (5,5%) and maintenance and all other administrative expenses (39,5%) as the main OPEX components. As it was previously mentioned, this electricity dominance in OPEX is expected to intensify as demand for performance increases, especially with the rise of AI and real-time computing workloads, which push both compute density and cooling requirements (IDC, 2024).

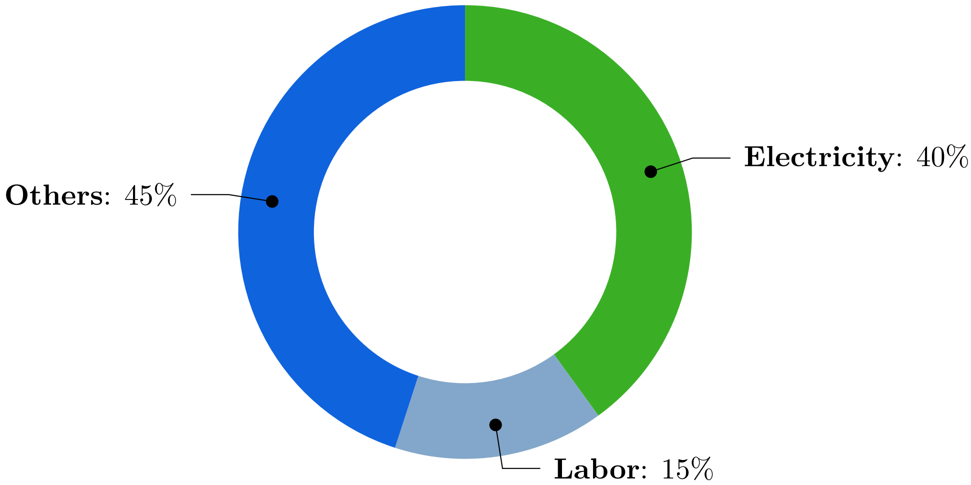


Figure 2.16: Energy consumption share in OPEX. Adapted from USCC (2017).

The economic structure of Data Centers, where power is both the largest cost and a key constraint, makes them uniquely exposed to energy market dynamics and, conversely, uniquely positioned to benefit from cost-stable, low-carbon power solutions. This last point is becoming increasingly important as Data Centers are has sharpened scrutiny around its environmental impact. The following section explores these sustainability challenges and the pressure mounting on operators to respond with greener architectures and accountability frameworks.

2.4 Sustainability of the Data Center Sector

The rapid and large-scale deployment of Data Centers has brought about a wide array of environmental challenges, ranging from soaring energy use and greenhouse gas emissions to resource-intensive hardware production, electronic waste, and water consumption (Zorman, 2024; Sar, 2024; Hodgson, 2024).

Data Centers are extremely high energy intensive assets. Considering their rapid deployment, this means an increased need of electricity generation to match this demand, as well as substantial investments in expansion and modernization of transmission and distribution infrastructure (Sar, 2024). That is, not only is the sector having direct impact on emissions due to electricity consumption (*scope I-II*), but at the same time it is driving indirect environmental impacts across the power generation value chain—namely, infrastructure development, fuel production, and upstream emissions (*scope III*). Specifically regarding *scope I-II* emissions, Bitpower (2024) presents and estimate of the CO_2e emissions of the Irish Data Center sector by multiplying its electricity consumption by the grid carbon intensity of Ireland. Applying the same methodology to the top 10 most power consuming markets in Europe concerning Data Centers, the results presented in Table 2.8 are obtained.

These illustrate significant differences in the CO_2e emissions of Data Center operations across different regions. Germany ranks as the highest emitter, with sector emissions reaching 6,9 Mton CO_2e, largely due to its high electricity consumption of 21 TWh and a relatively elevated grid carbon intensity of 329 gCO2e/kWh. Moreover, Ireland particularly stands out with the highest share of Data Center emissions relative to its total national emissions, accounting for 2,3%, despite a relatively modest consumption of 6 TWh. This reflects the country's significant Data Center sector coupled with a high grid carbon intensity of 260 gCO_2e/kWh. Similarly, the Netherlands also exhibits a relatively high share of 1.25%, with 2,1 Mton CO_2e emissions stemming from 8 TWh consumption. On the other end of the spectrum, countries such as France, Norway and Sweden report lower absolute emissions and smaller shares relative to their national totals, with France emitting 0,55 Mton CO_2e, accounting for 0.14% due to its low-carbon grid, and Norway's and Sweden's emissions remain negligible at 0,08 Mton CO_2e and 0,03 CO_2e, respectively. Overall, the aggregated data for the EU-27 shows that the Data Center sector contributes 21 Mton CO_2e, representing 0,67% of the total EU emissions.

If now the center is on the lifecycle emissions of the power supply of the Data Center sector for the EU and the focus countries Germany, the UK, Ireland and Italy, the results present a correlation with the ones presented in Table 2.8. Table 2.9 shows that Germany, Ireland, and Italy presents similar values, while the UK emerges as the country with the lowest environmental impact in lifecycle carbon emissions regards[3]. As these emissions not only include the direct emissions produced during energy generation but also encompass upstream and downstream processes, such as fuel extraction, infrastructure development, and decommissioning, they offer a more holistic view of the environmental impact associated with electricity consumption in the Data Center sector. However, more recent comprehensive values were not found. This highlights the need for more up-to-date lifecycle assessment studies to better reflect recent developments in energy systems and their associated environmental impacts.

In general, it can be stated that countries with cleaner grids (e.g., France, Norway, Sweden) offer a natural sustainability advantage for Data Center siting, both for regulatory compliance and reputational value. On the other hand, in high-emission grids (Germany, Poland), mitigation will require aggressive renewable integration, carbon offsets, or direct investments in cleaner power procurement. Sar (2024) points out that to mitigate the impact stemming from the large power consumption of the sector, renewable power sources should be further incorporated, and Data Center development should focus where renewable generation has the biggest potentials. Moreover, the same author highlights that energy efficiency innovations in all the Data Center system components are key to minimize energy consumption, and that the development of AI algorithms to do so could potentially succeed.

[3]Note that these are 2021 values, so they are only presented for illustrative values. Newer values were not found.

Table 2.8: Annual carbon emissions of the Data Center sector in the top 10 most power-consuming markets in Europe.

Country	Sector Consumption [TWh]		Grid Carbon Intensity [gCO_2e/kWh]		Sector Emissions [Mton CO2e]	Total Emissions [Mton CO_2e]		Share
Germany	21	(ICIS, 2025)	329	(EEA, 2025a)	6,91	782	(EEA, 2025b)	0,88%
UK	13	(ICIS, 2025)	207	(ITP, 2025)	2,69	305	(World in Data, 2025)	0,88%
France	11	(ICIS, 2025)	50	(EEA, 2025a)	0,55	391	(EEA, 2025b)	0,14%
Netherlands	8	(ICIS, 2025)	263	(EEA, 2025a)	2,10	168	(EEA, 2025b)	1,25%
Ireland	6	(ICIS, 2025)	260	(EEA, 2025a)	1,56	68	(EEA, 2025b)	2,29%
Spain	5	(ICIS, 2025)	158	(EEA, 2025a)	0,79	262	(EEA, 2025b)	0,30%
Norway	4,5	(ICIS, 2025)	18	(Nowtricity, 2025)	0,08	37	(EEA, 2025b)	0,22%
Italy	4,5	(ICIS, 2025)	225	(EEA, 2025a)	1,01	398	(EEA, 2025b)	0,25%
Sweden	4	(RISE, 2025)	8	(EEA, 2025a)	0,03	6	(EEA, 2025b)	0,53%
Poland	4	(ICIS, 2025)	614	(EEA, 2025a)	2,46	348	(EEA, 2025b)	0,71%
EU-27	100	(IEA, 2024a)	210	(EEA, 2025a)	21,00	3138	(EEA, 2025b)	0,67%

Table 2.9: Lifecycle CO_2 emissions from Data Center power consumption.

		EU-27	Germany	United Kingdom	Ireland	Italy
Data Center consumption [TWh]		100 (IEA, 2024a)	21 (ICIS, 2025)	13 (ICIS, 2025)	6 (ICIS, 2025)	4,5 (ICIS, 2025)
LC CO_2e						
	kg/MWh	321,6 (JRC, 2021)	438 (JRC, 2021)	282 (JRC, 2021)	442 (JRC, 2021)	383 (JRC, 2021)
	MTon/yr	32,2	9,2	3,7	2,7	1,7

Concerning other pollutants such as nitrous oxides (NO_x), sulfur oxides (SO_x) and non-methane volatile organic compounds ($VOCs$), the sector presents little influence. Table 2.10 shows the overall emissions and shares of these gases for the EU-27 and the market spotlights, calculated based on grid intensity emissions for each location.

NO_x emissions, which are primarily attributed to the Transport sector (EEA, 2024c), present little contribution from the Data Center sector in general, in all cases being less than 1% with the exception of the Irish case, which given the relevance the already mentioned relevance the sector has in the country. For the case of SO_x, whose main emitters are the industrial and energy sectors, the contribution is slightly more significant, all values lying around the 1-1,5% figure, with the clear exceptions of Ireland and Italy. While the Data Center sector in Ireland shows the same characteristics as presented before, the Italian Data Center sector's contribution to SO_x emissions is significantly limited, being approximately 0,1%. These can be largely attributed to the relatively low SO_x grid intensity factor and Data Center sector development, as well as the heavy influence that industry has in the country, accounting for almost half of the total SO_x emissions (EEA, 2024c). Finally, the influence of the Data Center industry in $VOCs$ emissions is null, in all cases being less than 0,05% of the total. These emissions are largely dominated by the industry and agriculture sectors (EEA, 2024c).

Table 2.10: Data Center sector annual emissions in selected countries and EU-27.

	Variable	EU-27	Germany	UK	Ireland	Italy
	Data Center consumption [TWh]	100 (IEA, 2024a)	21 (ICIS, 2025)	13 (ICIS, 2025)	6 (ICIS, 2025)	4,5 (ICIS, 2025)
CO2eq	Grid carbon intensity [gCO2e/kWh]	210 (EEA, 2025a)	329 (EEA, 2025a)	207 (ITP, 2025)	260 (EEA, 2025a)	225 (EEA, 2025a)
	Sector CO2e emissions [Mton]	21,00	6,91	2,69	1,56	1,01
	Total CO2e emissions [Mton]	3138 (EEA, 2025b)	782 (EEA, 2025b)	305 (World in Data, 2025)	68 (EEA, 2025b)	398 (EEA, 2025b)
	Share	0,67%	0,88%	0,88%	2,29%	0,25%
NO_x	Grid intensity [g/kWh]	0,27 (EEA, 2024a)	0,41 (EEA, 2024a)	0,23 (NAEI, 2023)	0,24 (EEA, 2024a)	0,10 (EEA, 2024a)
	Sector emissions [kton]	27,2	8,6	2,9	1,4	0,5
	Total emissions [kton]	5380 (EEA, 2024c)	942 (EEA, 2024c)	578 (UK Government, 2024)	94,4 (EEA, 2024c)	620 (EEA, 2024c)
	Share	0,5%	0,9%	0,5%	1,5%	0,1%
SO_x	Grid intensity [g/kWh]	0,16 (EEA, 2024a)	0,20 (EEA, 2024a)	0,10 (UK Government, 2025a)	0,06 (EEA, 2024a)	0,03 (EEA, 2024a)
	Sector emissions [kton]	16,4	4,1	1,3	0,4	0,1
	Total emissions [kton]	1290 (EEA, 2024c)	255,4 (EEA, 2024c)	95 (UK Government, 2024)	9,46 (EEA, 2024c)	88,1 (EEA, 2024c)

Table 2.10 continued from previous page

	Variable	EU-27	Germany	United Kingdom	Ireland	Italy
	Share	1,3%	1,6%	1,4%	3,7%	0,1%
VOCs	Grid intensity [g/kWh]	0,020 (EEA, 2024a)	0,014 (EEA, 2024a)	0,013 (UK Government, 2025a)	0,010 (EEA, 2024a)	0,010 (EEA, 2024a)
VOCs	Sector emissions [kton]	2,0	0,3	0,2	0,1	0,0
VOCs	Total emissions [kton]	6291 (EEA, 2024c)	1034,5 (EEA, 2024c)	628 (UK Government, 2024)	111,1 (EEA, 2024c)	823,3 (EEA, 2024c)
VOCs	Share	0,03%	0,03%	0,03%	0,05%	0,01%

Many Data Center operators and the broader technology sector have set ambitious goals for reducing emissions and procuring clean energy, using different strategies to do so. Additionally from sourcing electricity from the grid mix, these strategies include Power Purchase Agreements (PPAs) with renewable energy generators, the purchase of renewable energy certificates, and the co-location of Data Centers with more sustainable power generation assets (IEA, 2025a). Moreover, technology supporters have been supporters of the innovation in alternative sustainable generation technologies, such as small modular reactors (SMRs) and geothermal.

PPAs are one of the most widely used strategies to meet environmental targets overall, and technology companies are one of the leaders in the corporate PPA spectrum: globally, around 120 GW of operational renewable energy capacity has been procured through corporate PPAs at the moment, and technology companies operating Data Centers account for over 30% of it (IEA, 2025a). The organism estimates that in 2024, renewables PPAs contracted by technology companies were sufficient to cover approximately 20% of the global electricity demand from Data Centers, and that 20% of them were located in Europe. The IEA (2025a) notes, though, that PPAs in most cases are just financial agreements for annual energy supply and they are not tied to hourly profiles of Data Center consumption and renewable generation, which is most of times located far from where the energy is to be consumed. According to the organism, this means that, even if these PPAs help reach the companies' green goals, the physical energy consumed by the facilities is supplied by other sources; often times, fossil fuels. As a consequence, the physical mix actually consumed by the Data Center is different from the financial that is recorded.

On the other hand, on-site generation is increasingly been seen by the industry as a potentially cost saving - faster development solution, with downsides being higher complexity, potentially increased permitting requirements, higher investment costs, potentially lower reliability and a greater maintenance burden (IEA, 2025a). This interest is evidenced by notable partnerships in the industry, the IEA (2025a) highlighting *Google*'s with *Intersect Power* and *TPG Rise Climate* to develop co-located clean energy projects with Data Centers, the one from *Chevron* and *Engine No. 1* with *GE Vernova*, planning to supply up to 4 GW of natural gas capacity, and *Amazon*'s and *Talen Energy*'s 10-year PPA for 300 MW to 960 MW of nuclear energy from the Susquehanna nuclear plant to supply a co-located Data Center. Demonstrating its leadership in clean energy technology, *Bloom Energy* procured a Gigawatt Scale agreement with *American Electric Power* (AEP) to Power AI Data Centers.

Apart from direct emissions from energy consumption, Sar (2024) indicates that the carbon footprint of server production is often overlooked, even if each server generates approximately 1300 kg of CO_2 during manufacturing, has a lifecycle of only 2-3 years, and producing the 56,9 million servers needed for the projected world power demand to 2030 would add an additional 73,9 Mton CO_2[4]. This issue is worsened when considering hardware disposal. The short replacement cycle of servers—driven by rapidly advancing workloads—combined with their hazardous material content, makes electronic

[4] This is equivalent to 3,5 times the EU Data Center annual electricity consumption emissions presented in Table 2.8.

waste one of the sector's most pressing environmental concerns according to Zorman (2024). Sar (2024) suggests that extending the lifecycles of equipment and optimizing their disposal and recycling represent one key consideration to improve the sustainability of the sector.

Water usage is another of the main sustainability concerns of the sector. Employed mainly for cooling purposes, the amount of water used by Data Centers can create a strain on local water resources, creating debates in water-stretched regions and disputes with other sectors like agriculture and human consumption (Zorman, 2024). To showcase the degree of the sectors impact on the resource, Hodgson (2024) reports that in 2023, US Data Centers consumed the equivalent to the amount that London consumes in 4 months (Hodgson, 2024). Moreover, Hodgson (2024) shows that it is not rare for Data Centers to be located in water-stressed areas. The report highlights that *Microsoft* stated that 42% of the water it consumed globally came from water-stressed areas in 2023, while for *Google* this figure was 15%. This problem is particularly preoccupying both for Europe, where there has been a steady decline in groundwater stored in its aquifers, and the world in general, as it is estimated that droughts could affect over three-quarters of the population (Savills, 2023).

Despite ongoing sustainability concerns, the Data Center sector has been making significant progress. In 2021, over 100 Data Center operators and associations in Europe developed a self-regulatory initiative with the support of the EU Commission to achieve climate neutrality by 2030 (CISPE, 2025). This initiative, known as the Climate Neutral Data Center Pact (CNDCP), identified 5 key focus areas as essential to achieving carbon neutral Data Centers: Energy Efficiency, Clean Energy, Water Conservation, Recycling, Reuse and Repair of equipment, and Circular Energy Systems.

Building on these commitments, recent trends in the EMEA Data Center market are reflecting the sector's shift towards sustainability. As reported by Cushman & Wakefield (2025), the growing use of Green Hydrogen as a fuel in Data Centers represents a promising trend that could help mitigate the sector's emissions. Moreover, the integration of renewable electricity generation, either through direct Data Center integration or via power purchase agreements (PPAs), along with increased waste heat utilization, further supports this goal (Cushman & Wakefield, 2025). On the water management and cooling sides, closed-loop and alternative cooling circuits are being actively promoted, with major industry players setting water use efficiency targets (Savills, 2023).

In chapter chapter 4, a benchmark of different grids and leading on-site generation solutions against the discussed sustainability KPIs is presented, showing how each technology performs on factors such as carbon intensity, water use, and overall emissions. Next, as sustainability, as well as infrastructure and security concerns, have motivated a expanding array of efforts from authorities, the main regulations and policy initiatives concerning the Data Center sector in Europe are presented.

2.5 Regulatory and Policy Overview

The rapid expansion of the Data Center industry across Europe has led to an increased regulatory volume, particularly concerning energy efficiency, grid capacity, and sustainability. As a result, both EU-wide and national policies have been developed to manage the sector's growth while aligning with broader decarbonization and energy security goals. These regulations comprise efficiency standards for equipment, mandatory reporting on energy usage, and broader initiatives to modernize electricity infrastructure and support industrial competitiveness. According to the IEA (2023), the key energy-related legislation regarding Data Centers in the EU consists of:

- Regulatory and voluntary initiatives aimed at enhancing energy efficiency at the component level, including ENERGY STAR and the EU Ecodesign Regulations for servers and data storage equipment (IEA, 2023).
- Energy efficiency guidelines, standards, ratings, certifications, and labeling systems for buildings-based Data Centers , such as the EU Code of Conduct on Data Center Energy Efficiency, CLC/TS 50600-5-1, and BREEAM SD 5068 (United Kingdom) (IEA, 2023).
- The Corporate Sustainability Reporting Directive (CSRD), introduced by the European Commission and set to take effect from 2024, mandating large organizations, including technology firms, to disclose sustainability metrics along with energy usage and carbon emissions (IEA,

2023).

- The Energy Efficiency Directive (EED), implemented in May 2024, establishing energy and sustainability reporting obligations for Data Centers in the European Union with an installed capacity exceeding 500 kW. This includes reporting on total energy consumption, the proportion derived from renewable sources, water usage, and waste heat utilization, with the potential for additional performance standards based on the analysis of these metrics (IEA, 2023).

Furthermore, not directly related to Data Centers but highly influencing them, the EU has developed a comprehensive grid policy framework, including the Grid Action Plan of November 2023 and amendments to the Electricity Market Design. These initiatives aim to expand, digitalize, and optimize the use of electricity transmission and distribution networks (Ember, 2024a).

Additionally, the European Commission's Clean Industrial Deal, proposed in February 2025, seeks to increase Europe's industrial competitiveness by de-risking power purchase agreements, simplifying state aid rules, and supporting support for energy-intensive industries and the clean-tech sector, something that might affect the Data Center sector (Payne & Abnett, 2025).

According to Savills (2024), there are increasingly restrictive regulations on new Data Center development, something largely attributed to grid constraints, and often resulting in permit delays or refusals. Furthermore, Savills (2024) notes that although this issue could impact much of Europe, the risk of development restrictions is especially pronounced in the FLAPD markets, where the dense population, business, and industry are already placing significant strain on the national grid.

2.6 Market Spotlights

Given the attractiveness that the German, British, Irish and Italian markets present due to a combination of their Data Center market size, the industry's penetration and impact, and the general opportunities available for *Bloom Energy*, special focus is placed on this markets for analysis[5].

2.6.1 Germany

Sector Overview

Germany holds a key position in the European market, with Frankfurt ranking as the second largest location on the continent and Berlin emerging as an increasingly significant player (Cushman & Wakefield, 2025). While other cities in the country, such as Munich and Hamburg, do not yet have a large presence, they still contribute to Germany's status with four major data center hubs, which will soon be expanded with the addition of the Rhineland Region (GDA, 2024b).

The sector adds considerable value to the local economy: the gross value added triggered by cloud use in the country is approximately 250 billion euros, with Data Centers also significantly contributing to employment, as 5,9 million people were employed in companies dependent on the cloud[6] in 2024, up from 2,8 million in 2022 (Eco, 2025). The Data Center sector itself provides a total of over 50.000 jobs in Germany (GDA, 2024a), with some estimates even reaching 65.000 jobs (GDA, 2024b).

As of Q4 2023, the total Data Center capacity in the country, including operational, under construction, committed, and early-stage supply, exceeded 3,5 GW (DC Byte, 2024). This meant that the German Data Center Market size had a total value of USD 7,71 Billion in 2024, and is projected to grow to USD 12,84 Billion by 2030, exhibiting a CAGR of 8,87% (Yahoo Finance, 2025). Furthermore, according to GDA (2024b), the IT capacity of operational colocation Data Centers in the country is projected to grow from the current 1,3 GW to 3,3 GW by 2029.

The Data Center market in the country is highly concentrated in Frankfurt: the city has 745 MW of operational capacity, with 542 MW under construction and 383 MW planned (GDA, 2024b), representing almost 75% of the total German Data Center capacity (DC Byte, 2024)[7]. On the other

[5] These specific markets were suggested by the company.
[6] That is, a company whose business model would not be possible without the cloud (Eco, 2025).
[7] Note that this values differ from the ones presented by Cushman & Wakefield (2025), who report 713 MW opera-

hand, the second biggest market in the country, Berlin, only represents 16,5% of the total Data Center operational capacity (DC Byte, 2024), counting with 92 MW operational and 285 MW in the total pipeline (GDA, 2024b)[8]. Munich, the third biggest player, only accounts for 5,2% of the total operational capacity, and Düsseldorf, Hamburg and Stuttgart together account for less than 4% , highlighting the consierable degree of concentration (GDA, 2024b).

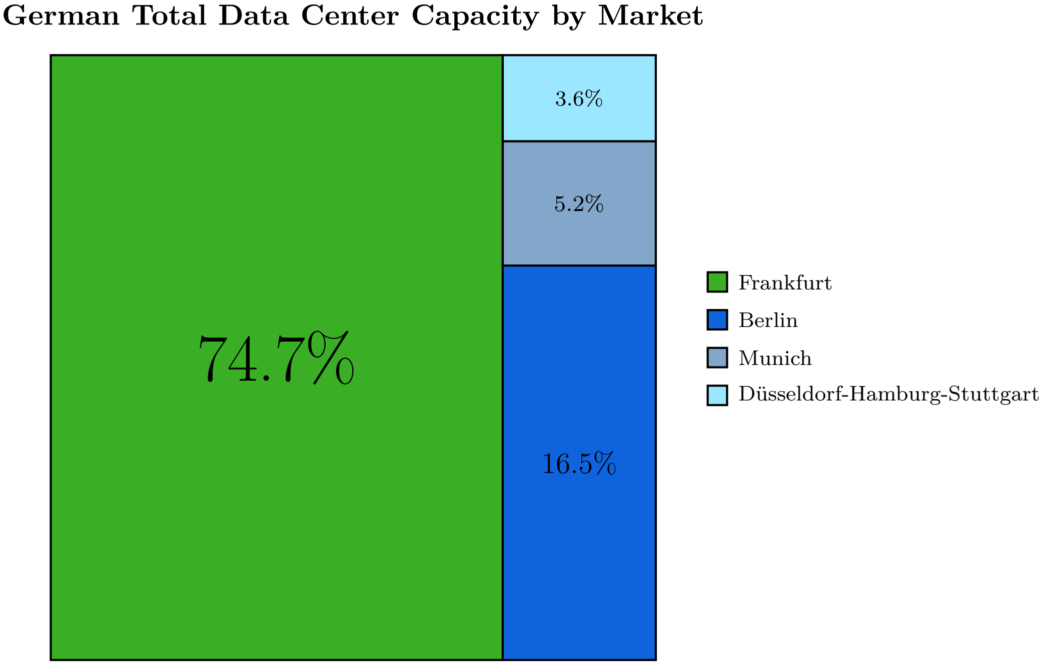


Figure 2.17: Total Data Center capacity distribution across major German markets, considering operational, under construction, and planned. Based on DC Byte (2024).

Frankfurt's central location in Europe makes it a prime hub for data traffic, and this is one of the main drivers of its Data Center market relevance (Cushman & Wakefield, 2025). The market in the city is experiencing tremendous growth: the sector doubled its operational capacity to 745 MW over the past five years, and in the first quarter of 2024, while 23 MW of new supply was introduced, the take-up was 20 MW, the highest across all Data Center markets (GDA, 2024b). Moreover, in 2023, a total of 134 MW were added, making it the most successful year on record for a European Data Center market (GDA, 2024b). This is putting Frankfurt in a strong position to narrow the gap with London, the European leader in the sector (GDA, 2024b).

However, challenges in Frankfurt have played a role in the surge of secondary markets in Berlin and Munich, both now consisting of over 20% of Germany's total Data Center capacity (DC Byte, 2024). Berlin's tech-focused economy, and relatively lower land prices compared to Frankfurt make it a viable alternative, together with its strategic location (Cushman & Wakefield, 2025). In recent times, Berlin's operational Data Center capacity has remained largely stable. However, the city's growth potential is considerable, with new developments achieving high to full pre-leasing rates (Cushman & Wakefield, 2025; GDA, 2024b). Although it is a relatively small market, there are currently 76 MW under construction and a notable 219 MW in the planning stages, with approximately 36 MW added in 2024 (GDA, 2024b).

Energy Consumption Patterns

Electricity demand in Germany is set to rebound after years of stagnation, with Data Centers emerging as a key driver of future growth. Although the country experienced a decline in electricity consumption from 2015 to 2023, including a 4,8% drop in 2023 alone mainly due to lower industrial

tional, 227 MW under construction and 1099 MW planned.

[8]Note that this values differ from the ones presented by Cushman & Wakefield (2025), who report 97 MW operational, 8 MW under construction and 213 MW planned.

output, forecasts indicate a turnaround, with demand expected to grow steadily through 2030 (IEA, 2024a; Weiss et al., 2025). Underpinned by structural trends in electrification, forecasts suggest a that demand expected to rise by 5–7% between 2023 and 2030[9] (Weiss et al., 2025) and a growth of 2,6% until 2026 (IEA, 2024a).

In terms of current consumption, electricity in Germany represents 20% of total final energy consumption (IEA, 2025c). The IEA (2025c) reports that electricity consumption here is primarily driven by industry, which accounted for 43,4% of total electricity consumption in 2022. Residential consumption was the second-largest category, making up 28,1%, and Commercial and public services followed closely, consuming 24,6% of the total electricity.

The Data Center sector stands out for its rapid growth trajectory. Currently responsible for 4,4% of national electricity consumption (21 TWh), its share is projected to exceed 6% by 2035, reaching 44 TWh (ICIS, 2025). This would represent nearly 9% of Germany's net electricity demand growth from 2024 to 2035, highlighting the sector's disproportionate impact on future capacity requirements (Ember, 2024b; McKinsey, 2025).

Regulatory and Policy Overview

Germany leads the EU in regulating Data Center sustainability, imposing strict requirements on energy efficiency, renewables, and grid access, with implications for project development and operational planning.

The country has taken a leading role in enforcing EU-wide sustainability mandates for Data Centers, becoming the first country to enact the European Energy Efficiency Directive through a national law. The resulting Energy Efficiency Act introduces ambitious targets for energy efficiency, renewable sourcing, and heat reuse, placing Data Centers under significant operational and planning pressure. At the same time, evolving grid access rules and stricter data protection frameworks add further regulatory complexity.

The European Energy Efficiency Directive (EED), published in 2023, sets out broad EU goals for reducing energy consumption and emissions, but leaves implementation to national governments. Germany responded quickly, becoming the first member state to pass a nationwide Energy Efficiency Act, which came into force in early 2024 (Judge, 2023a, 2023b; Mayer Brown, 2025).

Specifically, this regulation applies to all Data Centers with a non-redundant nominal electrical connected load of 300 kW or more (Mayer Brown, 2025), and it mandates that Data Centers annually report their energy performance for the previous year into a centralized European database, covering elements such as floor area, installed power, data volumes, energy consumption, PUE, temperature set points, waste heat utilization, water usage, and use of renewable energy (Judge, 2023b).

To ensure compliance, this Act introduced four core regulations:

- **Energy efficiency:** According to White & Case (2025), "Data Centers that start or have started operations before July 1 - 2026 must be constructed and operated to achieve a sustained annual average PUE of less than or equal to 1,5 as of July 1 - 2027, and less than or equal to 1,3 as of July 1 - 2030. Data Centers that begin operations on or after July 1 - 2026, must achieve a PUE of less than or equal to 1,2". This signals a clear regulatory push toward more energy-efficient infrastructure, effectively raising the baseline for technological innovation and operational performance in both existing and future Data Centers.
- **Waste heat utilization:** In addition to efficiency targets, new Data Centers that start operation on July 1 - 2026 or after are enforced to have a minimum share of 10% reused energy, and this value will gradually increase to 15% when operation starts on July 1 - 2027, and to 20% on July 1 - 2028, or after[10] (Mayer Brown, 2025).
- **Power supply:** Another major requirement is that Starting from January 1, 2024, Data Centers are mandated to source 50% of their electricity consumption from renewable sources, with the

[9]Note that many observe that more realistic scenarios place electricity demand growth increase at 1-2% per year due to a weak economy and a slower ramp-up of e-mobility and heat pumps (McKinsey, 2025).

[10]Note that there are exceptions for certain cases.

requirement increasing to 100% by January 1, 2027, being the purchase of guarantees of origin sufficient (Mayer Brown, 2025; White & Case, 2025). This requirement accelerates the transition to carbon-neutral operations and forces Data Centers to engage more directly with the renewables market, either through on-site generation or the procurement of green energy certificates. It opens the door for hybrid systems—such as those combining grid supply with on-site systems to ensure reliability and compliance.

- **Energy and environmental management systems**: Finally, by July 2025, Data Centers are required to implement an energy management system in line with DIN EN ISO 50001 or an environmental management system that adheres to EU standards (Mayer Brown, 2025). By mandating certified management systems, the regulation pushes operators toward systematic monitoring, reporting, and continuous improvement of environmental performance.

In parallel, regulatory reforms are reshaping grid access. Recent regulatory changes in Germany's power supply aim to address the growing demand for electrical power and the scarcity of available grid capacity. The local grid operators and the Federal Network Agency (Bundesnetzagentur) are developing new procedures for allocating grid connection capacity, moving away from the "first come, first served" principle (Lars Reubekeul, 2024). This shift aims to ensure a fairer distribution of scarce resources but may also introduce new challenges. For instance, it could lead to delays or reduced capacity for individual Data Center projects, potentially impacting their scaling, operational planning, and timelines.

Finally, Germany continues to enforce stringent data protection laws. Alongside the EU General Data Protection Regulation (GDPR), the national Federal Data Protection Act (BDSG-new) imposes additional requirements on data processing, placing high legal expectations on operators handling sensitive information (Site24x7, 2025).

Main Challenges

Despite strong market growth, the German Data Center sector is constrained by several challenges, especially grid bottlenecks, land scarcity, tightening regulations, and talent shortages. These barriers are pushing operators to explore microgrid solutions and even consider shifting capacity to other European countries.

Power availability is the most pressing issue. Industry leaders agree that current grid infrastructure cannot meet the rising demand driven by AI and high-performance computing. Grid upgrades are often slow, and in some regions, connection wait times can exceed ten years (Kallenbach, 2024). According to Isabel Strecker (*Eversheds Sutherland*) and Prof. Adrian Altenburger (*J. Willers Engineering AG*), energy transition efforts further complicate grid reliability, requiring new models for stable and clean power delivery (GDA, 2024b).

Closely tied to power constraints is the issue of land and renewable energy availability. Suitable sites—particularly those with access to fiber infrastructure and energy access—are increasingly scarce. Urban expansion, competing land uses, and rising property prices have made it harder for operators to secure viable locations. As a result, growth is increasingly limited to medium and long term timelines, with some developers deferring or relocating planned investments (Kallenbach, 2024).

At the same time, tightening regulations are raising the bar for compliance and operational performance. The Energy Efficiency Act imposes ambitious targets for energy efficiency, renewable sourcing, and waste heat reuse, all of which increase project complexity and cost. While these measures support sustainability goals, they also introduce uncertainty and may make other EU markets more attractive by comparison (Kallenbach, 2024).

Responding to these infrastructure and regulatory pressures requires rapid technological innovation. As power and cooling demands rise, solutions such as Direct Liquid Cooling are becoming more critical. Philipp Müller (*Rittal*) stresses that close industry collaboration will be essential to meet these evolving requirements without compromising reliability or sustainability (GDA, 2024b).

Furthermore, the sector also faces a growing human capital gap. Talent acquisition and retention are increasingly cited as top concerns. Dr. Dirk Turek (*CBRE*) and Michillay Brown (*STACK*

Infrastructure) emphasize that without a robust and skilled workforce, operational resilience is at risk. In fact, 65% of colocation operators outside Frankfurt identify workforce shortages as their most significant obstacle (GDA, 2024b).

Finally, these core challenges are further compounded by external pressures such as supply chain disruptions, inflation, and delays in permitting. As Björn Oellrich (*ADK Modulraum*) and Paul Lewis (*Telehouse*) note, these factors add further friction to project timelines and cost structures, making it even more difficult for developers to respond swiftly to market demand.

2.6.2 United Kingdom

Sector Overview

The UK Data Center sector is rapidly becoming a critical pillar of the national economy, driven by surging digitalization and technological advancements such as 5G, cloud computing, AI, big data, and the Internet of Things (Business Wire, 2025). According to techUK (2024), this growing importance is reflected in significant investments aimed at expanding Data Center capacity and capability across the country. Due to this, the sector is increasing its critical importance to the UK economy, and investment is directed towards expanding Data Center capacity and capability in the the region (techUK, 2024).

London dominates the UK Data Center market, accounting for around 80% of the total leased capacity. Here, available capacity has plummeted as supply is struggling to keep pace with the surge in demand reaching an all-time-low vacancy rate of 11% (CBRE, 2024b). The city is the largest market in EMEA and the second largest globally, with 1.141 MW in operation, 265 MW under construction and 1.260 MW planned (Cushman & Wakefield, 2025). To gain perspective of the degree of concentration the UK has in its Data Center market, its second biggest player, Manchester, only counts with 24 MW, and only 244 MW remain outside this 2 markets (techUK, 2024).

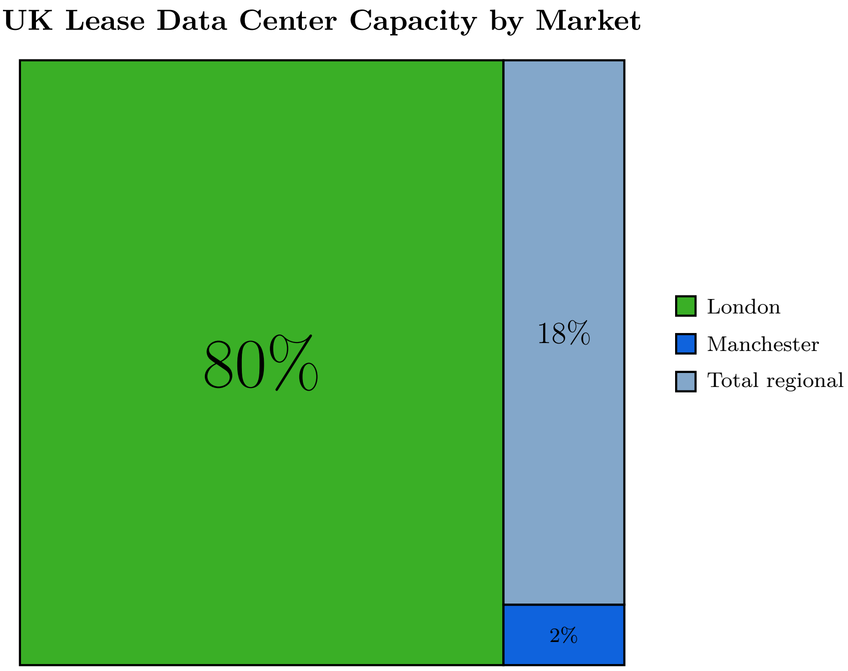


Figure 2.18: Data Center leased capacity distribution in the UK (techUK, 2024).

The market in the country is soaring. In 2024, it had a total value of USD 10,69 billion, and it is projected to grow to USD 22,65 billion by 2030, rising at a CAGR of 13,33% (GlobeNewswire, 2025). In terms of economic impact, the Data Center sector has a major impact as well, contributing with £4,7 billion in gross value added to the economy, creating around 43.500 jobs in total and leaving around £630 million in taxes to the government (techUK, 2024).

Studies developed by techUK (2024) show a potential significant supply-demand gap: while UK Data Centers have grown by an average of 10% a year in the last four years, future capacity demand has been put in the 10-20% range. Matching this increased demand, though, can bring considerable opportunities for the country. If the UK were to increase its supply capacity to 15% a year to 2035, this would mean a total of £44 billion in GVA, £9,7 billion in taxes, 18.200 construction jobs and 40.200 operational ones (techUK, 2024).

Energy Consumption Patterns

Electricity demand in the UK is expected to reverse its long-standing decline and begin growing again, driven by electrification in key sectors such as transport, industry, and Data Centers. The IEA (2024a) reports that electricity consumption is expected to increase by an average of around 2% per year to 2026, while Weiss et al. (2025) reports values of between 1% and 2% to 2030.

This marks a turning point after years of decline. In 2023, electricity consumption dropped by 3,4% to approximately 263 TWh, driven by high energy costs, warmer weather, and sluggish economic growth (IEA, 2024a; Martin, 2024; NESO, 2025), putting electricity demand levels at a low that had not been seen since the 1980s (Martin, 2024). In fact, this tendency is going on for a while, the region exhibiting an average -2% CAGR from 2015 to 2023 (Weiss et al., 2025).

Currently, electricity demand equally distributed between the residential (35,1%), industrial (31%) and commercial sectors (29,6%) (NESO, 2025). Analyses by NESO (2025) show that to achieve the Nationally Determined Contribution (NDC) emissions target for 2030 and the Climate Change Committee's carbon budgets, an electricity demand growth of 11% to 287 TWh in 2030 from 263 TWh in 2023 is to be expected. According to the same study, this increase in demand would be driven mainly by the transport and industrial and commercial sectors, and Data Centers are expected to play a major role in this transition: the National System Energy Operator of the UK points out that electricity demand from the sector could amount for around 22 TWh in 2030 and reach 35 TWh in 2050, representing 6% of the total demand (NESO, 2022). The Data Center sector thus would shadow the growth of other divers such as Hydrogen, reaching an electricity demand of 11 TWh by 2030 (NESO, 2022).

Regulatory and Policy Overview

As part of the UK's goal to achieve net-zero carbon emissions by 2050, Data Centers are increasingly being pressured to minimize their carbon footprint. Regulations like the Climate Change Act and the Streamlined Energy and Carbon Reporting (SECR) framework mandate operators to disclose their energy usage and carbon emissions, encouraging the adoption of more sustainable practices, such as incorporating renewable energy sources and implementing energy-efficient technologies (Holt, 2024).

Complementing these national regulations, the UK has retained key EU environmental policies that affect the sector. The Industrial Emissions Directive (IED) is a regulation aimed at reducing pollution from industrial activities by setting limits on emissions, waste, and resource use (techUK, 2021). Data Centers are affected by the IED primarily due to their reliance on backup diesel generators, which can exceed emission thresholds. This regulation influences Data Center design, encouraging the use of cleaner energy sources, improved efficiency, and the implementation of mitigation strategies to minimize environmental impact.

In parallel with environmental policies, regulatory efforts have also focused on strengthening the resilience and security of Data Center infrastructure. In September 2024, UK Data Centers were designated as Critical National Infrastructure, thus strengthening regulatory support (Cushman & Wakefield, 2025; Reuters, 2024). Additionally, in the previous year, the updated National Planning Policy Framework (NPPF) offered more explicit guidance to local authorities and support for the industry, encouraging development that aligns with sustainability, economic growth, and infrastructure objectives (Cushman & Wakefield, 2025).

Recognizing the increasing role of Data Centers in the economy, the UK government has integrated energy planning with its technology development strategies. The UK government has an ambitious plan to establish AI Growth Zones, aiming to enhance the nation's AI infrastructure by facilitating the development of Data Centers. This initiative includes a commitment to allocate 500 MW of power to support these zones, with the inaugural site planned for Culham, Oxfordshire (Gooding, 2025). At the same time, leading technology firms have been advocating for the implementation of zonal electricity pricing, potentially making areas like Scotland, known for abundant renewable energy, more attractive for energy-intensive AI data center operations with cheaper and easier to access power (Guardian, 2025).

Beyond environmental and infrastructure considerations, regulatory frameworks also emphasize data protection and cybersecurity. In the UK, the Data Center industry is governed by different key laws and regulations, summarized by Grow (2025). The Data Protection Act 2018 (DPA 2018) implements the General Data Protection Regulation within the UK, ensuring that personal data is handled responsibly while maintaining alignment with EU standards post-Brexit. Complementing this, the UK GDPR establishes fundamental principles, rights, and obligations for data processing. The Network and Information Systems Regulations 2018 (NIS Regulations) enhance the security of critical infrastructure, requiring operators, including Data Centers, to adopt robust cybersecurity measures. The Privacy and Electronic Communications Regulations (PECR) complements the GDPR and the DPA, safeguarding privacy in electronic communications, such as emails, texts, and cookies. Beyond legal requirements, the Cyber Essentials Scheme, a government-backed initiative, helps organizations defend against cyber threats, often serving as a standard for contractual compliance. Similarly, ISO/IEC 27001 is an internationally recognized standard that Data Centers adopt to establish an Information Security Management System (ISMS) for protecting sensitive information. Additionally, the Human Rights Act 1998 has implications for privacy, influencing Data Center policies on surveillance and information access. Lastly, the Computer Misuse Act 1990 aims to protect computer systems from unauthorized access and cyber attacks, requiring Data Centers to implement strong cybersecurity measures to prevent breaches that could result in criminal offenses.

Main Challenges

Similar to the wider European scale, access to reliable and sufficient power is a critical factor for the Data Center industry (techUK, 2024; Holt, 2024). As it is pointed out by techUK (2024), ensuring consistent, reliable, and sufficient power supply in the UK is heavily affected by delays in securing grid connections. This issue is highly accentuated in the London region, amplified by the city's aging power grid infrastructure and the ever-increasing demand for electricity (Holt, 2024). Here, there are 400 GW of connection requests in the queue, and 60-70% are estimated to fail to materialize (Cushman & Wakefield, 2025). However, Ofgem, the UK office that regulates the gas and electricity markets, is working to solve this. The office is planning a reform to change the "first-come, first-serve" basis for grid connections to adopt a “targeted approach which prioritizes quicker connections for the right projects in the right place" (Skidmore, 2025), as part of the UK's Clean Power Action Plan. This aims to accelerate grid connection lead times by focusing on projects with proper funding and planning permits, on optimal locations.

Even if grid connection is secured, the cost of energy remains a significant factor to consider due to the high impact it has on the operating cost structure[11]. The UK faces challenges in this regard as well, with energy costs being the highest in Europe (techUK, 2024). What is more, electricity price volatility and geopolitics have been a major constraint in the sector's development and in the economy in general: according to a survey to 750 energy-decision making executives from private businesses in the UK developed by PwC (2025) showed that almost 90% saw profits go down in the last year due to these. What is more, over 90% expect this situation to worsen in the near future (PwC, 2025).

On another topic, skilled labor force shortage remains a big challenge in the sector. According to techUK (2024), aging workforce, limited entry-level talent, lack of diversity and inclusion, international competition and negative perceptions of the sector are identified as the main drivers of this skills gap.

Moreover, the rapid growth of Data Centers has intensified environmental concerns. The usual vast amounts of water these facilities consume exacerbate water scarcity in certain regions. For example, the development of AI growth zones in water-stressed areas has raised concerns about potential shortages (Horton, 2025). Additionally, Data Centers' significant energy consumption has sparked local

[11] See subsection 2.3.4

opposition in various communities, highlighting tensions between business interests and environmental sustainability (K. Chan, 2025). Furthermore, the sector's high carbon footprint also poses challenges to the UK's net-zero ambitions, making it a focal point in discussions on balancing economic growth with sustainability goals (PwC, 2025).

2.6.3 Ireland

Sector Overview

Ireland is one of the most prominent and fastest-growing Data Center hubs in Europe, with activity highly concentrated in Dublin and facing increasing power and planning constraints. The country offers a unique set of advantages for the tech industry and Data Centers , including political stability, low exposure to natural hazards, EU membership, English language use, a strategic transatlantic location, a moderate climate, a mature supply chain, an abundant skilled workforce, and a favorable corporate tax regime (KPMG, 2024; Cushman & Wakefield, 2025; DC Byte, 2023).

The sector plays a major role in the country's economy. The ICT sector in Ireland contributes approximately 20% of the total GVA and employs around 6,4% of the national workforce (Conefrey et al., 2023). Furthermore, over the 2017-2022 period, the sector experienced a significant 40% growth (Kavanagh & Turner, 2022), reflecting its expanding role in the economy. The sector employs approximately 164.900 people, with hyperscalers alone directly responsible for 17.000 of these jobs (Bitpower, 2024), and the role of the sector as a job creator is largely acknowledged by the population. In a recent survey developed by Digital Infrastructure Ireland (2024), 68% of Irish respondents associated Data Centers with job opportunities, a figure above the European average.

Positioned as one of the key players in Europe, the country has a total Data Center IT power capacity of 1.062 MW (Bitpower, 2024). According to Mordor Intelligence (2025b), Dublin's market dominance is extreme, accounting for approximately 97% of it. The city is one of the powerhouse EMEA markets, as catalogued by Cushman & Wakefield (2025), with 1.116 MW operational capacity, 249 MW under construction and 563 MW planned.

Dublin's dominance is likely to continue in the near future, as around 85% of the upcoming Data Center capacity will be concentrated here and in Ennis (GlobeNewswire, 2024b). However, as noted by DC Byte (2023), the city's power challenges are leading to future developments in the Greater Dublin area and along the West Coast. These initiatives aim to utilize underutilized grid capacity and leverage the increasing number of future renewable energy projects in the west and south of the country (DC Byte, 2023).

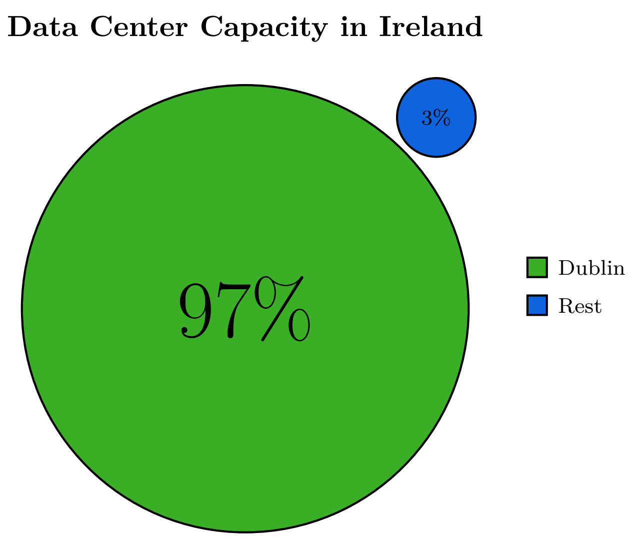


Figure 2.19: Data Center capacity distribution in Ireland (Mordor Intelligence, 2025b).

Investment in Data Center construction in Ireland has grown steadily over the past decade. From relatively modest levels in the early 2010s, spending has surged, exceeding €2 billion in recent years and amounting for €15 billion in total (Bitpower, 2024). Despite this momentum, challenges are beginning to affect future investments. Nearly €1 billion in planned projects is uncertain due to power constraints and planning delays, and looking ahead, investment levels are expected to stay above €2 billion annually, yet a significant portion of this future pipeline remains at risk (Bitpower, 2024). Bitpower (2024) reports that over the coming years, between €8 and €10 billion in potential projects could face delays or even cancellation if infrastructure and regulatory issues are not addressed.

Energy Consumption Patterns

Ireland is experiencing one of the fastest-growing electricity demand trajectories in Europe, largely driven by the rapid expansion of the Data Center industry. Since 2015, electricity demand has increased by 24% (Devine et al., 2025), and this trend is expected to accelerate. The IEA (2024a) forecasts average annual growth of nearly 7% between 2024 and 2026, the highest in Europe, primarily due to the Data Center sector. Far from being a circumstantial phenomenon, this has been an observed trend in the country for the last years: electricity demand from this sector has increased by 412% since 2015 being responsible for over 88% of the increased electricity demand observed in the last 10 years in Ireland (SEAI, 2024).

Here, Data Center electricity consumption was of around 5,3 TWh in 2022, reflecting a 31% rise from the previous year (IEA, 2024a). This meant that the sector's consumption accounted for a staggering 17% of Ireland's electricity demand in that year (IEA, 2024a). Considering a high-case scenario, the IEA (2024a) estimates that the sector could consume around 12 TWh by 2026, representing over 30% of the electricity demand in the country. Further into the future, analyses such as the on presented by ICIS (2025), mention that the Data Center industry could reach a level of saturation where growth may be forced to slow down due to their adverse impact on the power grid. For 2035, ICIS (2025) reports electricity consumption estimates of 14 TWh, representing around 23% of the overall electricity consumption in the country.

Currently, electricity consumption in Ireland is dominated by the commercial and public services sector, which accounts for nearly half of total demand with 48,4% (IEA, 2025d). This reflects the country's strong reliance on industries such as Data Centers, and service-based businesses that require significant energy use. The residential sector follows as the second-largest consumer, making up just over a quarter of total electricity consumption (27%), and the industrial sector follows as the last relevant sector, consuming over one-fifth of the total electricity demand, with 22,3% (IEA, 2025d). The Data Center industry alone, placed at 21% of total metered electricity demand in 2023 according to ICIS (2025), thus constitutes a major player, being comparable with the electricity consumption of both industrial and residential sectors.

EirGrid (2024) reports that a major contributor for electricity demand in Ireland for the future will be the connection of new large energy users, among which Data Centers stand out. In 2030, between 37 TWh and 47 TWh of electricity demand are expected, up from 30,6 TWh in 2023 (EirGrid, 2024; CSO, 2024), with between 25% and 33% of it coming from Data Centers (Walsh, 2024). This means that even on a high electricity demand overall growth and a low Data Center growth scenario, the sector would be responsible for almost 40% of the net electricity demand growth of the country in the period 2022-2030[12]. Considering a low overall demand growth with a high Data Center growth scenario, on the other hand, this number would rise to around 90%[13].

Regulatory and Policy Overview

Data Centers are a key focus for Irish policies and regulations given their national relevance. The country is tightening regulatory oversight of the sector to balance its economic value with grid con-

[12] This is considering a total electricity demand of 29,5 TWh in 2022 (CSO, 2022), one of 47 TWh for 2030 (EirGrid, 2024), a Data Center demand of 5,3 TWh in 2022 (IEA, 2024a) and a 25% Data Center share in electricity consumption in 2030 (Walsh, 2024).

[13] This is considering a total electricity demand of 29,5 TWh in 2022 (CSO, 2022), one of 37 TWh for 2030 (EirGrid, 2024), a Data Center demand of 5,3 TWh in 2022 (IEA, 2024a) and a 33% Data Center share in electricity consumption in 2030 (Walsh, 2024).

straints and decarbonization goals.

In July 2022, the Irish government published a statement of the role of Data Centers in the country's enterprise strategy, adopting a set of principles to harness the economic and societal benefits that the sector could bring, and aligning it with policy objectives (DETE, 2022). Acknowledging both the importance of Data Centers and the strain they place on the electricity grid, as well as the need for decarbonization, the government stated that would favor projects that contribute significantly to economic activity and employment, efficiently utilize grid capacity, and demonstrate a commitment to renewable energy use. Also, that preference would be given to Data Centers that co-locate with or are near renewable energy sources, have a clear decarbonization strategy, and engage with local communities while supporting SMEs. This principles evidence a clear view on the sector and has manifested in several regulations.

Furthermore, in late 2021, the Commission for Regulation of Utilities (CRU) issued its decision regarding the new requirements for both new and existing Data Center grid connection applications. These requirements include three assessment criteria to determine whether a connection offer can be made (IEA, 2024a):

1. The location of the Data Center in relation to whether it falls within a constrained area of the electricity grid.
2. The capability of the Data Center to provide onsite dispatchable generation or storage that meets, at a minimum, its demand.
3. The capacity of the Data Center to offer demand flexibility by reducing consumption upon request from a system operator.

These requirements reflect the local government's focus on granting connections to operators who can utilize the grid efficiently without overburdening it, while also integrating renewable energy sources to support decarbonization goals (IEA, 2024a). What is more, this institution recently defined that new Data Centers are currently mandated to provide generation or storage to match the amount of energy they use and participate in the electricity market, the Data Center operators being left to decide how they fuel and power themselves (Murphy, 2025).

On the sustainability front, the Irish government transposed the EU Energy Efficiency Directive into national regulations in March 2024, requiring Data Centers with an IT power demand exceeding 500 kW to report energy performance metrics annually from 2024 onward (Department of the Environment & Communications, 2025; Mason Hayes & Curran, 2024). The regulation mandates reporting on key sustainability indicators, including power usage effectiveness (PUE), water usage effectiveness, energy reuse factor, and renewable energy factor (Mason Hayes & Curran, 2024). While Ireland's current implementation does not impose explicit limits on these metrics, the increased transparency may pave the way for future regulatory measures to enhance energy efficiency and sustainability in the Data Center sector.

Main Challenges

The biggest concerns for Data Center developers in Ireland lie on securing sufficient power and navigating complex approval processes (DC Byte, 2023; Bitpower, 2024).

With the surge in Data Center construction, the national grid is under pressure, and new projects increasingly require additional investment in energy solutions to ensure long-term viability (Bitpower, 2024). The advancement of the electrical grid and electrical power generating capacities while sticking to decarbonization targets for 2030, has been highlighted by Cushman & Wakefield (2025) as the single biggest challenge of the sector. In response to these, Irish regulators have introduced new policies to manage the strain on the grid and ensure sustainable growth. The CRU decision, prioritizing projects in unconstrained regions and those capable of reducing electricity consumption during peak demand marked a major shift in how power access is regulated, made it more difficult for new Data Centers to secure connections without flexibility measures, such as on-site generation or storage (Mason Hayes & Curran, 2025). Moreover, concerns over the legally binding Ireland's Climate Action Plan targets have fueled further scrutiny of the industry, prompting the government to outline national principles for Data Center development (Mason Hayes & Curran, 2025).

On another topic, according to a survey developed by Digital Infrastructure Ireland (2024), Irish people are among the most informed about Data Centers in and their role in powering digital services, with 54% acknowledging their significance[14]. Despite this, this awareness also brings increased scrutiny. Over half (51%) of the respondents of this survey view Data Centers as having a negative impact on local communities due to high energy consumption, being the highest percentage among the surveyed countries and reflecting sustainability concerns. Moreover, Ireland, France and the Netherlands, rank highest in perceiving land use by Data Centers as a potential drawback (36%), representing a significant public concern. This growing opposition from local communities poses a serious challenge for the industry. Resistance can lead to delays in project approvals, stricter regulations, and even bans on new developments. Without public support, companies may face difficulties in securing permits and maintaining long-term operations, adding another layer of complexity to an already challenging landscape.

2.6.4 Italy

Sector Overview

The Italian Data Center market, in line with the broader European trend, is experiencing a rapid increase in demand from both investors and operators. Italy, and especially Milan, hold a strategic position with a high centrality in information routes, thanks to its strong connectivity and submarine backbone connections, making it a highly attractive location for Data Center operation (Colliers, 2025; Decode39, 2024). According to Mordor Intelligence (2025c), the sector has a current capacity of 550 MW and is expected to reach one of 1.390 MW by 2030.

Arizton (2025) reports that the Italian Data Center market has a current value of USD 3,1 billion and is expected to grow to USD 6,2 billion in 2030, rising at a CAGR of over 12%. This growth is accompanied with a heavy investment surge: investments into Italy's Data Centers are expected double to 10 billion euros in the 2025-2026 period compared with the 2023-2024 period (Reuters, 2025), and there is even a company proposing a €30 billion Data Center project in Italy (Swinhoe, 2024).

The sector holds a significant role in employment. The Italian Data Center Association (IDA) shows that a total of about 17.000 people are employed in Italian Data Centers and in the companies that are part of the industry supply chain based on 2022 data (IDA, 2025). The GDA (2024a), on the other hand, shows bigger figures for Italy, the sector creating around 8000 direct jobs and more than 20.000 indirect/induced ones. What is more, projects in the pipeline to 2028 in the country could create 70.000 new employees according to estimates presented by Decode39 (2024).

Milan is currently the most developed hub for Data Center development in Italy, something mainly attributed to its particularly advantageous strategic location and connectivity (Colliers, 2025). At the moment, research done by Cushman & Wakefield (2025) shows 170 MW in operation with 165 MW under construction and 656 MW planned. Colliers (2025), on the other hand, shows similar values, with currently around 500 MW between operational and under construction Data Centers and a further pipeline of about approximately 700 MW. The majority of the supply in the city has been concentrated on the southern and western sides, due to the interconnection of multiple internet backbones and the Milan Internet Exchange, but the limited availability of suitable sites, challenges in securing power, and stricter regulations are prompting operators to explore alternative locations, including other cities (Colliers, 2025).

Energy Consumption Patterns

Following broader European trends, Italy's electricity demand is expected to rebound after recent declines, with the Data Center sector playing an increasingly important though still modest role in long-term consumption growth. After a period of contraction driven by economic stagnation and

[14] Only Spain and the Netherlands have higher recognition rates

energy efficiency gains, Italy's electricity demand is projected to resume steady growth—fueled by electrification trends and supported in part by the expanding Data Center sector.

Electricity demand in the country was 305,6 TWh in 2023, down 3% on the previous year and following a reduction of 0,8% in 2022 (Terna, 2025; IEA, 2024a). Although wholesale energy prices declined, demand has continued to fall due to a sluggish economy and significant progress in energy savings (IEA, 2024a). The IEA (2024a) reports that in the building sector, the *Super Bonus* program was a major contributor to reduced electricity consumption, with Italian households submitting over 400.000 applications for energy efficiency tax deductions by October 2023—approximately 78% of them in 2022 and 2023. The observed economic slowdown, on the other hand, can be partly attributed to sluggish domestic demand for goods and services, along with a decline in industrial activity, especially in energy-intensive sectors (IEA, 2024a). However, the IEA (2024a) forecasts that electricity demand is expected to grow at an average annual rate of 1,8% between 2024 and 2026. Moreover, Elettricità Futura (2023) forecasts that electricity demand could grow to 360 TWh in 2030, fueled mainly by by economic growth, the increasing adoption of heat pumps, the rise of electric vehicles, and the shift to electric cooking.

In Italy, electricity represents around 22% of final energy consumption, with industry as the main consumer, accounting for almost 39% of electricity demand (IEA, 2025e). Commercial and public services (33%), and residential (23%), complete the podium, while the Data Center sector in the country presents a modest role, consuming around 4,5 TWh of electricity and representing 1,5% of the total final electricity consumption (ICIS, 2025). However, according to ICIS (2025), the sector's relevance in electricity demand is going to expand, reaching a share of around 3,5% in total demand with a consumption well above the 10 TWh figure.

As a whole, electricity demand could reach values in the range of 347-362 TWh in 2030 and 375-397 TWh in 2035 from the 305,6 TWh 2023 demand (Terna, 2024; Terna, 2025). Taking into consideration the average 2035 scenario presented above, approximately 7,5% of the net growth in electricity demand could be attributed to the Data Center sector[15]

Regulatory and Policy Overview

The Italian Data Center sector has developed without clear laws regarding Data Center development, something even ironically been put in the news as "*According to Italian law, Data Centers do not exist*" (Invernizzi, 2024). Currently, regulation in the country is comprised of different non-specific laws such as the Consolidated Environmental Act, the Consolidated Building Act, municipal regulations, and ministerial interpretations. Industry experts have been calling for the introduction of a national law to streamline development, standardize procedures, and strengthen the national electricity grid, aiming to officially classify Data Centers as separate technology infrastructure, providing a clearer regulatory framework (Cushman & Wakefield, 2025).

This lack of regulation has potentially dampened investments and obstructed the sector's growth (Morri Rossetti & Franzosi, 2024), and affected the national dynamics, as more Data Center developments have been conducted in regions where local regulations were introduced (Cushman & Wakefield, 2025). This is the case of Lombardy, where guidelines were introduced to facilitate Data Center construction, defining Data Centers by size, energy use, and computing power, specifying environmental requirements, and encouraging the redevelopment of inactive sites and brownfields (Cushman & Wakefield, 2025; ADVANT, 2024). Invernizzi (2024) reports that in the absence of national laws procedures, times, and outcomes vary significantly depending on the location: in Lombardy it is possible to obtain a building permit and environmental authorizations within a year while in Rome this can take 4 or 5.

Despite the lack of a clear national regulatory framework for Data Centers, Italy is still subject to EU regulations that govern various aspects of the sector. These include the already mentioned General Data Protection Regulation (GDPR), and the Energy Efficiency Directive (EED), among others.

[15]That is considering 386 TWh average 2035 scenario presented by Terna (2024) and a growth from 4,5 TWh to 10,5 TWh presented by ICIS (2025).

Main Challenges

One of the biggest challenges the Data Center sector is facing in Italy is the cost of electricity, as well as grid bottlenecks in major hubs — issues also shared by other major Data Center markets (Decode39, 2024; Colliers, 2025). Moreover, the unclear and underdeveloped regulatory environment mentioned above continues to pose a major challenge for developers, dampening investments and technological advancements in the sector (Morri Rossetti & Franzosi, 2024).

In addition to power and regulatory challenges, the skills gap remains a serious obstacle to sustaining the sector's growth, a concern similarly noted in other European nations (Decode39, 2024). Furthermore, meeting the sustainability goals set by the country represents an additional challenge for developers, as adhering to these targets often increases costs and requires substantial technological and infrastructural investments.

This set of challenges are shifting local dynamics. A tendency that has been observed lately in major Italian hubs is that land scarcity, regulatory impediments, underdeveloped urban development frameworks, and ESG considerations have fueled increased interest in brownfield sites and alternative locations, intensifying competition and driving up land prices (Colliers, 2025).

While the previous sections have examined the specific dynamics and challenges shaping the Data Center landscape in key national markets, it is evident that there are some common challenges emerging at the European level. These issues are affecting the sector's ability to scale and meet surging demand across the continent, regardless of local conditions. The following section outlines these structural barriers, which increasingly define the continent-wide development outlook for the Data Center sector.

2.7 European Data Center Development Challenges

Even at the current fast Data Center supply pace, the new number of Data Centers being built is not able to keep up with their demand. In 2023, take-up exceeded the new supply added in Europe, being the fourth year with this condition in the last eight years (CBRE, 2024a), and this tendency is expected to increase in the future: Savills (2024) estimates that Europe's Data Center capacity will need to increase threefold by 2027 to reach 22,7 GW, highlighting a significant shortfall as the planned infrastructure is projected to provide only 13,1 GW by then. Different markets may find themselves in a similar situation: Data Center supply deficit is forecast to be more than 15 GW in the United States alone by 2030 (Srivathsan et al., 2025).

To meet the sector's growing demand, a strategy will be needed to overcome the existing bottlenecks that are currently limiting its progress in the region. According to KPMG (2024), CBRE (2024a), Lockton (2024) and Cooper-Bevan (2024), power, regulations, and land comprise the main key challenges of the sector. Milanesi et al. (2025), on the other hand, adds that sustainability concerns, inadequate upstream power infrastructure, shortages of power equipment for Data Centers, and a lack of skilled electrical workers for building facilities and infrastructure as additional key challenges in accommodating the growing demand.

Power challenges. Power sourcing and its cost represent major challenges for Data Center development, especially in Europe, where grids are struggling to keep pace with the surge in electricity demand from the sector (KPMG, 2024). This phenomenon is highly accentuated in the FLAPD market, whose high concentration of energy intensive Data Centers is placing an ever-growing burden on local grid infrastructure (Lockton, 2024). Currently, in most cases, the major bottleneck slowing power access is not generation but limited capacity to connect to the grid (Milanesi et al., 2025). In markets such as Dublin and Frankfurt, to give a hint of the extent of the problem, time-to-power for new Data Centers can reach over 3-5 years, with lead times for electrical equipment alone often surpassing 3 years (Milanesi et al., 2025). This means that, even in in locations with access to grid power, there are further constraints on the supply of critical power equipment such as transformers, on-site backup generators, and power distribution units, something that has worsened in the last years (Figure 2.20). In a more general sense, Turner & Townsend (2023) reports that delays to projects in the past year due to global material shortages are present in 83% of Data Center project developments, 80% have seen lead times in critical equipment increase, with over a third of those delays being 12 weeks or more. This scenario is specifically relevant when time to market is reported to be the single most important consideration when deploying new Data Center capacity (Milanesi et al., 2025), even surpassing location, as Turner & Townsend (2024a) show that power availability is more important than location for 92% of the cases in their research.

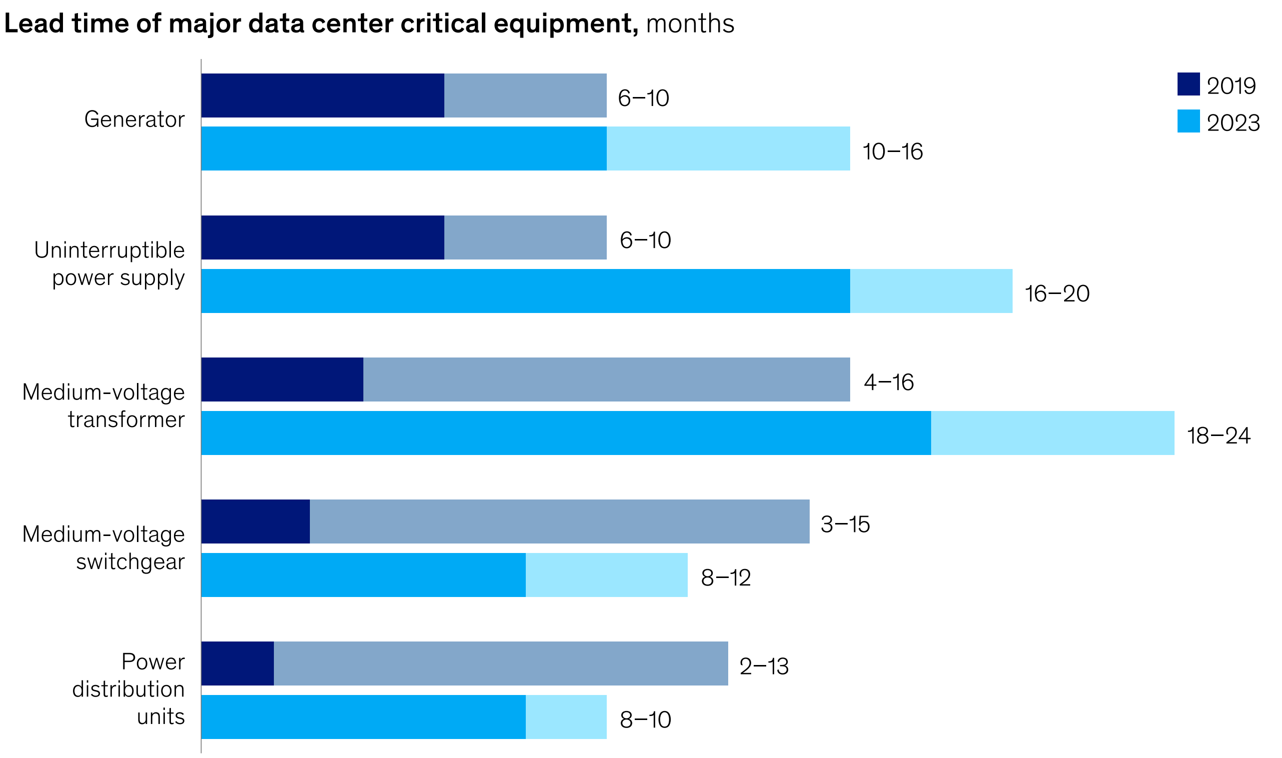


Figure 2.20: Lead times for power supplies (Milanesi et al., 2025). Note: "Generator" here refers to back-up generator.

Regarding high power costs as a deterrent for Data Center development, this is a phenomenon especially accentuated for the explored British and Italian cases, where this was an issue highlighted by many experts (techUK, 2024; Colliers, 2025; Decode39, 2024)

Strict Regulations. Regulations in Europe tend to be more complex than competitor regions, particularly regarding data privacy, environmental standards, and planning laws, something which can hinder Data Center development (KPMG, 2024). Moreover, last years have seen an increasingly tightened and more restrictive regulatory environment for operators (Lockton, 2024; Savills, 2024). In some markets, such as Italy, another factor that has hindered Data Center development and advancements in the sector is the unclear and underdeveloped regulatory environment, countries presenting different local regulations without nation-wide frameworks (Morri Rossetti & Franzosi, 2024).

Land Cost and Availability. In Europe, land tends to be more expensive and more difficult to secure than in competitor regions (KPMG, 2024), and land availability decline in core areas is driving exploration of new markets (CBRE, 2024a). Moreover, as it is observed in Milan, brownfield sites are more largely being considered (Colliers, 2025).

Labor Shortage. The shortage of skilled workers in Data Centers is a shared concern around Europe, and it is something expected to further exacerbate, influenced by the slowly declining working-age population in the continent (GDA, 2024a; Savills, 2022; BBC News, 2025). Turner & Townsend

(2023) reports that 94% of Data Center developers indicate a shortage of experienced construction teams. This skills shortage is a major influence of labor costs, causing wages to highly increase in the sector (Turner & Townsend, 2023; Savills, 2025). The phenomenon is not unique for Europe: globally, the broader digital infrastructure sector is estimated to have a shortfall of 300.000 people in 2025 according to Masons (2024).

Sustainability Concerns. Sustainability in Data Centers is a pressing issue in the continent, with all the stakeholders, including customers, regulators, investors and the public at large, increasingly demanding greater verifiable efforts on the topic (Savills, 2024). Renewable energy integration, either with PPAs or on-site renewable generation, as well as general efficiency improvements, enhanced waste heat recovery, and optimized water management systems are one of the key initiatives of the sector (Savills, 2024; GDA, 2024a).

Adding to these, rising costs represent another obstacle. Overall, Savills (2024) shows that Data Center construction costs have significantly increased since 2020, driven by various factors such as supply chain disruptions, inflation, labor shortages, and challenges related to land availability. Globally, average costs rose by over 6% year-on-year from 2022, while in Europe, construction costs for 2023 saw a 6,5% annual increase, reaching $9,1 million per MW (Savills, 2024).

Particularly highlighting the power dimension of the challenges presented, energy availability, security, and costs, along with the need to reduce energy dependency represent a growing concern in the sector (Savills, 2022). Power grids are often nearing capacity limits, lead times for new connections are increasing, and in some regions, green energy remains scarce or grid constraints limit access to reliable power, and in response, operators are turning to on-site power generation, exploring technologies such as Small Modular Reactors, Fuel Cells, and Renewable Energy infrastructure (Milanesi et al., 2025; Savills, 2024). These energy challenges are expected to persist for at least the next few years, reinforcing the need for on-site generation while sustainability regulations continue to drive a shift toward cleaner energy solutions (Savills, 2024).

In the next chapter, the different on-site power solutions available in the market are presented, along with the role they have in the sector, their main technical, economic and environmental characteristics, and the opportunities for Bloom in this evolving landscape.

Chapter 3

On-site Power Solutions

Chapter Description

This chapter provides an overview of on-site power solutions for Data Centers, highlighting the role and main challenges of Gas Turbines, Fuel Cells, Reciprocating Engines, and Renewable Systems. Later, particular emphasis is placed on the opportunities of deploying *Bloom Energy*'s SOFC systems as a reliable and sustainable power source.

Contents

3.1 On-Site Power Systems

As it was previously mentioned, given the significant bottlenecks and challenges that power access represents, on-site generation is an increasingly widespread choice. Traditionally, on-site generation has been used as a back-up system in case of grid failures, but due to the landscape painted above, these systems are increasingly being seen as a primary generation solution (Figure 3.1).

Next, an overview of different on-site generation systems is presented, and later, particular focus on *Bloom Energy*'s SOFC systems is put.

3.1.1 On-site Power Generation Systems Overview

Recent studies published by Bloom Energy (2025a) show that approximately 30% of all Data Center sites are expected to use on-site power solutions by 2030, with a total announced on-site capacity of up to 8,7 GW, 4,8 GW of them expected before 2030. In Europe, the landscape is qualitatively similar, as Milanesi et al. (2025) along with many others point out that alternative strategies for on-site generation are widely being considered.

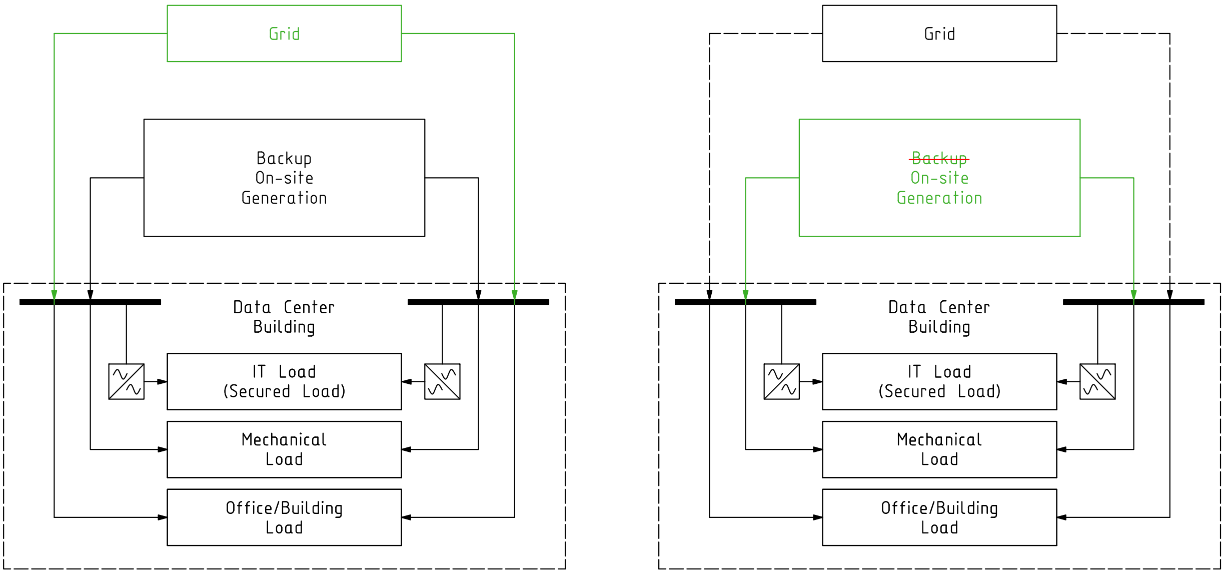


Figure 3.1: Paradigm shift in Data Center power systems: on-site power solutions are increasingly being considered as a main power source. Left: traditional systems with grid as main power, Right: on-site generation for primary power with optional grid connection. Green represents main power source. Based on Youssef et al. (2021).

Reports presented by Bloom Energy (2025a) and Diezinger et al. (2024) show a changing landscape: historically, Data Centers have used on-site power mostly for backup purposes, but new trends show a shift toward on-site power generation as a primary source of power. On-site generation presents different alternatives, but according to Bloom Energy (2025a), most of current solutions consist on Simple Cycle Gas Turbines. New announcements to 2030 challenge the status quo, though: Fuel Cells rise to the top of the table along with Gas Turbines as the main players, with Reciprocating Engines and Solar Systems remaining as secondary options (Figure 3.2).

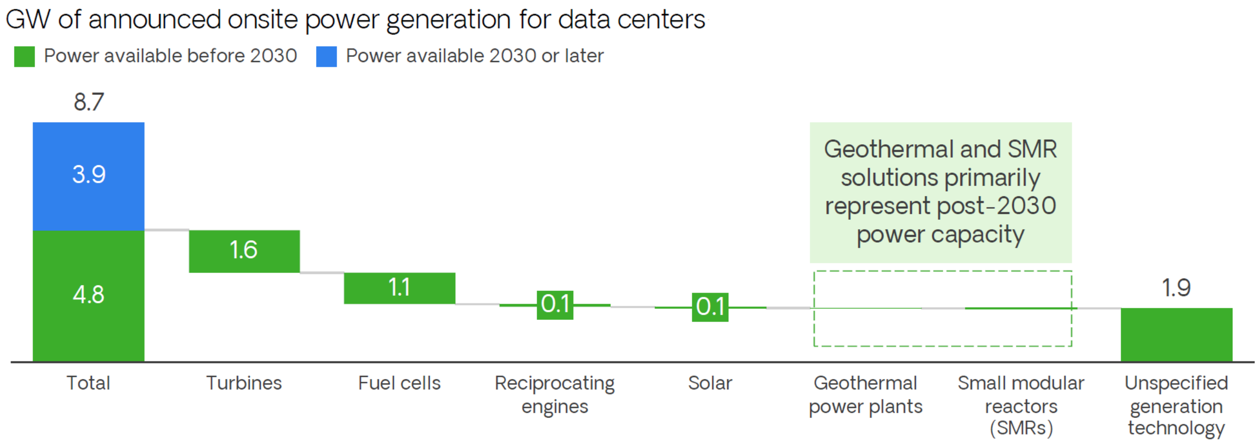


Figure 3.2: Global announcements of on-site power generation for Data Centers (Bloom Energy, 2025a).

Having being identified as the main on-site generation solutions for the Data Center industry, following, a simple and brief description of each power system is presented.

Gas Turbines

Gas Turbines are turbo-machines that represent the most widely adopted power solution for on-site generation in Data Centers (Bloom Energy, 2025a). According to Diezinger et al. (2024) and GE Vernova (2025e), these provide scalable, reliable, cost efficient and high-quality power, with potentially lower carbon emissions when compared to many grids.

There are several possible Gas Turbine system configurations, the simplest of which consisting of the open cycle power plant (Figure 3.3). This setup has efficiencies ranging between 35-43% (Diezinger et al., 2024), with the possibility of leveraging the hot exhaust gas to improve it, something which is done in Combined Cycle systems.

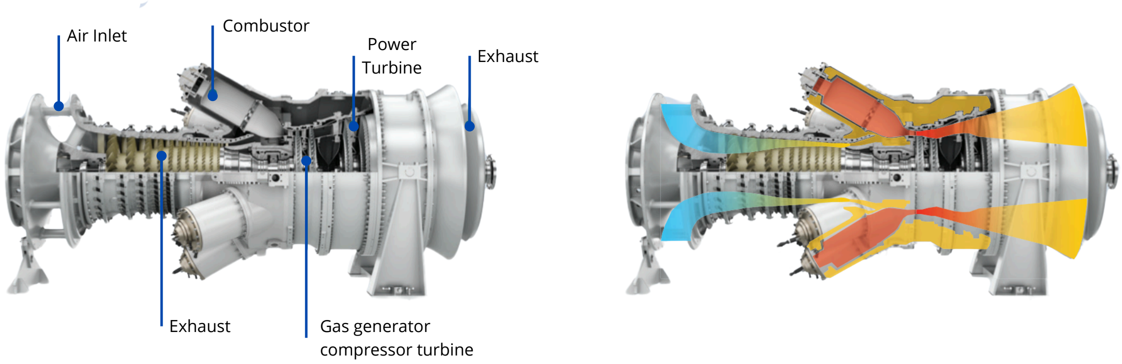


Figure 3.3: Gas Turbine diagrams (Diezinger et al., 2024). Process (Diezinger et al., 2024): The incoming air is compressed to 20–40 bar by the rotating compressor blades. Next, the combustion system injects fuel, mixing it with the high-pressure, pre-heated air, and ignites the fuel-air mixture at around 1.500–1.700 degrees. The resulting hot, pressurized exhaust gases power the compressor and turbine while expanding and cooling. The exhaust, with temperatures between 450–600 degrees, can be used to further enhance efficiency.

Combined Cycle Gas Turbines (CCGTs) can potentially improve electrical efficiency by over 15% by taking advantage of the waste heat from the gas turbine to produce steam to power a steam turbine (Diezinger et al., 2024), and efficiencies of over 63% are possible to be achieved. However, it is important to note that CCGTs are primarily seen in systems that require 500 MW or more capacity, as they are cost effective at this scale. Smaller capacity Data Centers often rely on simple cycle turbines, sometimes paired with batteries (Bloom Energy, 2025a).

LCOEs for these machines are highly dependent on the application and the capacity factor, the price of natural gas and that of Carbon, but Badouard et al. (2020) place this value at around 95 €/MWh in 2018, and Lazard (2024) estimates it as between 45 and 108 €/MWh with an average of 76 €/MWh for a combined cycle in 2024. Future forecasts suggest a significant price increase for these technologies: Kost et al. (2024) reports that in Germany, the LCOE for CCGTs is projected to increase from 109-181 €/MWh in 2024, to between 141-405 €/MWh by 2045, driven by rising CO_2 prices and decreasing full load hours in the period. For simple cycle ones, something similar is expected, as the generation from these is expected to rise from 154-327 €/MWh in 2024 to 186-405 €/MWh in 2045 (Kost et al., 2024)[1].

Regarding capital costs, the EIA (2024a) reports that the construction cost had an average of 722 $/kW for CCGT and 1006 $/kW for simple GTs in the US, while Lazard (2024) places the total installed costs as between 850-1,300 $/kW for the case of a combined cycle. Kost et al. (2024), for the german case, reports total investment costs of 450-700 €/kW for a gas turbine and 900-1300 €/kW for a CCGT[2].

With the Data Center sector landscape described above as one of the main drivers, the global Gas Turbine market is witnessing a substantial increase in orders, with leading companies such as *Siemens Energy*, *GE Vernova*, and *Mitsubishi Power* facing record-high backlogs[3] in 2024 (Gas Turbine Hub, 2025), reporting delivery times for new turbines stretching out to 2029 or later (Arun, 2025). Even though this shows positive demand signs for the Gas Turbine market, it also brings up concerns for current and potential customers regarding delivery timelines, maintenance support, and overall market

[1] Note that the values reported here are not specific for Gas Turbines to power Data Centers , they are only reported for general information purposes.

[2] Again, note that the values reported here are not specific for Gas Turbines to power Data Centers , they are only reported for general information purposes.

[3] The backlog is the accumulated volume of orders that a company has received but has not yet fulfilled (Gas Turbine Hub, 2025).

stability (Gas Turbine Hub, 2025). Moreover, these major Gas Turbine actors, rather than potentially overinvest in the face of rising demand and suffer the consequence of falling prices, are committed to capital discipline, lengthening their order book (Arun, 2025).

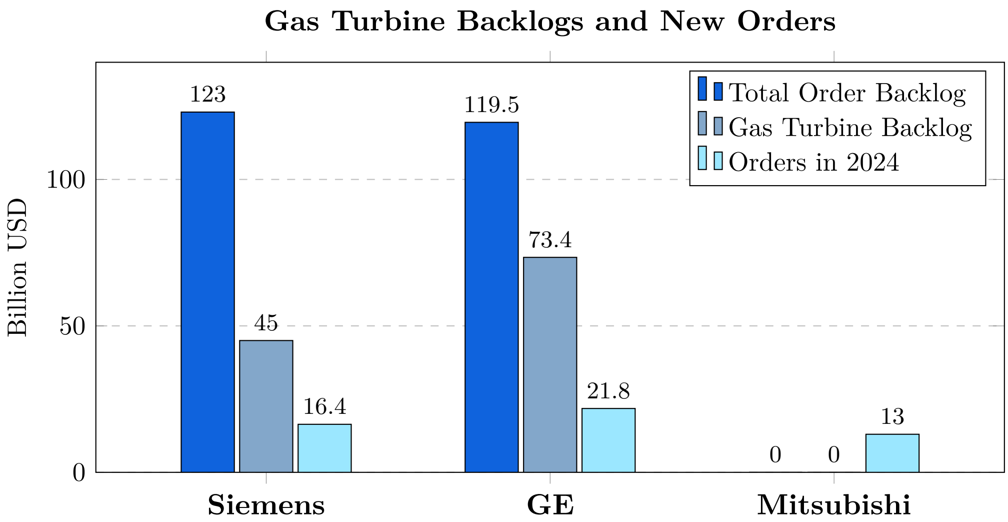


Figure 3.4: Gas Turbine backlogs and new orders. *Note*: backlog not reported by *Mitsubishi* (Gas Turbine Hub, 2025).

According to the Gas Turbine Hub (2025), this situation may bring significant consequences to the Gas Turbine market, including project delays, compromise of replacement components' availabilities, and higher costs (see box below).

Consequences of the record-high Gas Turbine Backlogs

- **Project Execution Delays**: Extensive backlogs can disrupt project timelines and result in increased costs. In some cases, delays may extend up to 7-8 years for certain models, significantly impacting project development (Dale, 2025).
- **Pressure on Maintenance and Spare Parts Availability**: Extended maintenance turnaround times are now common, with overhaul lead times reaching about 350 days, far exceeding the previous norm of 120 days (Gas Turbine Hub, 2025).
- **Higher Costs for End-Users**: The high demand and backlog have shifted pricing leverage to original equipment manufacturers (OEMs), leading to increased prices for customers.
- **Uncertainty in Decarbonization Plans**: Many energy producers are investing in hydrogen-compatible Gas Turbines to meet their long-term net-zero targets. However, delays caused by backlogs could slow this transition, forcing utilities to rely on traditional fossil fuel assets longer than anticipated.

Fuel Cells

Fuel Cells are electrochemical conversion devices that transform the chemical energy contained in fuels to electricity without combustion (FCHEA, 2025). Unlike the multi-step chemical-thermal-mechanical-electrical processes in combustion-based heat engines, Fuel Cells operate through a single-step process, offering numerous advantages such as high efficiency, lower environmental impact, compatibility with renewable energy sources and modern energy carriers, reduced noise and vibration, as well as enhanced modularity and application flexibility (Sharaf & Orhan, 2014). The use of this technology is expected to increase significantly in the following years: while the global Fuel Cell market in Data Center applications had a value of around USD 175 million in 2024, it is projected to grow to USD 400 million by 2030 (MarkNtel, 2024).

At a fundamental level, Fuel Cell power systems consist of three main components: the cells, where electrochemical reactions occur; the stacks, where individual cells are assembled into modular units to achieve the desired output capacity; and the balance of plant, which includes components responsible for feed stream conditioning, thermal management, electric power conditioning, and various other ancillary and interface functions (EG&G Technical Services, 2004).

Cells are the central component of a Fuel Cell, and here the chemical-electric conversion process occurs. Their basic structure consists of an electrolyte layer positioned between an anode and a cathode, with each electrode on opposite sides (Figure 3.5). Fuel is fed to the anode, at the same time that an oxidant, typically consisting of oxygen from the air, is supplied to the cathode. The electrochemical reactions occurring at the electrodes generate a flow of electric current through the electrolyte, which in turn drive a complementary current to perform work on the load (EG&G Technical Services, 2004).

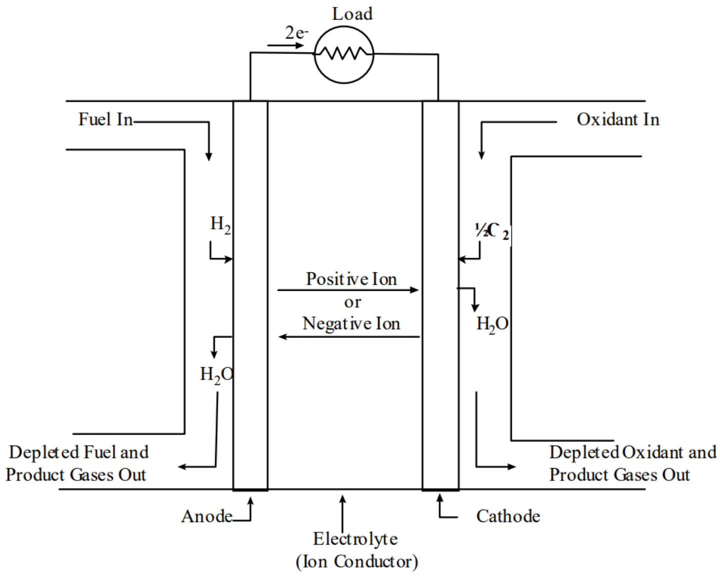


Figure 3.5: Schematic of a cell (EG&G Technical Services, 2004).

For most practical uses, individual cells must be assembled into a stack to reach the necessary voltage and power output. Along with the stack, Fuel Cell systems require various additional "Balance of Plant" subsystems and components, which, depending on the application, account for a substantial portion of the system's weight, volume, and cost (EG&G Technical Services, 2004).

The main form of Fuel Cells classification relies on the type of electrolyte used in the cells, and currently, five major kinds of Fuel Cells can be identified: Polymer Exchange Membrane Fuel Cells (PEMFCs), Alkaline Fuel Cells (AFCs), Solid Oxide Fuel Cells (SOFCs), phosphoric acid (PAFCs), and Molten Carbonate Fuel Cells (MCFCs) (Jawad et al., 2022).

Within these, PEMFCs and SOFCs are the leaders in the general stationary Fuel Cell segment (Benstead, 2024), and the types that are used for Data Centers according to Plug Power (2024) and Latitude Media (2025). Moreover, Coherent (2024) reports that almost 70% of the overall Fuel Cell market is dominated by PEMFC, and according to MarkNtel (2024), PEMFCs hold more than 40% share in the Fuel Cell for the Data Center market in the world. On the other hand, the expansion of the stationary Fuel Cell market is expected to be led by SOFC systems, driven by their fuel flexibility and large MW scale power outputs in the Data Center segment (Markets and Markets, 2023; Benstead, 2024), while PEMFCs will grow in the small-scale backup power applications segment (Benstead, 2024). Given this landscape, PEMFC and SOFC will be given some more detail.

PEMFC. These use a proton-conducting polymer membrane electrolyte and are limited to hydrogen as a fuel (DOE, 2025). Their relatively low operation temperatures allow for rapid dynamic responses, making them particularly well-suited for mobile applications (DOE, 2025). Furthermore, as Jawad et al. (2022) report, they exhibit high energy density and efficiency, low working noise, cost and working temperature, short startup time, and relatively long life.

The fundamentals of its operation can be seen in Figure 3.6. In this process, protons produced at the anode from the hydrogen fuel pass through the proton exchange membrane to reach the cathode; at the same time, electrons travel from the anode to the cathode through an external circuit via graphite plates, resulting in the formation of water on the cathode side (Jawad et al., 2022).

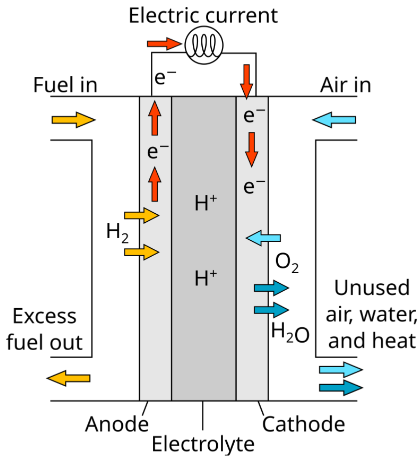


Figure 3.6: PEMFC Diagram (Wikipedia, 2025).

Cell Reactions

$$\begin{aligned} &\text{Anode:} && H_2 \longrightarrow 2\,H^+ + 2\,e^- \\ &\text{Cathode:} && \tfrac{1}{2}\,O_2 + 2\,H^+ \longrightarrow H_2O \\ &\text{Overall:} && \tfrac{1}{2}\,O_2 + H_2 \longrightarrow H_2O \end{aligned} \tag{3.1}$$

SOFC. Solid Oxide Fuel Cells use a thin ion-conducting ceramic layer as a the electrolyte to conduct oxide ions. These Fuel Cells operate at a wide range of high temperatures: from 700-1.000°C with zirconia-based electrolytes to as low as 500°C with ceria-based electrolytes. This, partially enables SOFCs to be fuel flexible, being capable of utilizing natural gas, biogas, and hydrogen as fuels, as well as permitting system configurations involving Gas Turbines (DOE, 2025). SOFC systems are capable of generating electricity and heat with very high conversion efficiency and almost no pollutant emissions into the atmosphere (Gandiglio et al., 2024). Their high efficiency, cost-effectiveness and its fuel flexibility gives it large protagonism in the Fuel Cell sector (Singh et al., 2021).

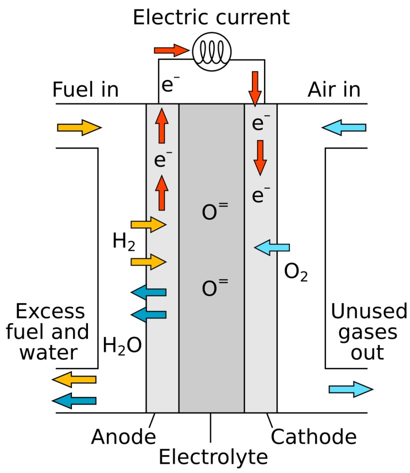


Figure 3.7: SOFC Diagram (Sakurambo, 2007).

The operating principle is defined by NETL (2025) as the following (Figure 3.7): Fuel is fed to the anode, while the oxidizing agent is supplied to the cathode. The porous structure of the electrodes permits the diffusion of both fuel and air toward the electrolyte, while also allowing the reaction byproducts at the anode to exit. Oxygen ions, generated by the reduction of oxygen at the cathode, are conducted through the electrolyte to the anode. At the anode/electrolyte boundary, the fuel reacts with these oxygen ions in a catalytic reaction, producing electrons. These electrons travel through an external circuit, thereby producing electrical power.

When hydrogen is used as fuel, the reactions developed are according to the following reactions: (Singh et al., 2021).

$$\begin{aligned}
&\text{Anode:} && H_2 + O^{2-} \longrightarrow H_2O + 2\,e^- \\
&\text{Cathode:} && \tfrac{1}{2}\,O_2 + 2\,e^- \longrightarrow O^{2-} \\
&\text{Overall:} && H_2 + \tfrac{1}{2}\,O_2 \longrightarrow H_2O
\end{aligned}$$

On the other hand, when utilizing methane, depending on the fuel composition, the typical reactions occurring in a SOFC are the steam reforming, the dry CO_2 reforming, and the water-gas shift reaction (WGSR) (Singh et al., 2021). These are:

$$\begin{aligned}
&\text{Anode (Reforming):} && CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \\
&\text{Anode (Reforming):} && CH_4 + 2\,H_2O \rightleftharpoons CO + 4\,H_2 \\
&\text{Anode (Dry Reforming):} && CH_4 + CO_2 \rightleftharpoons CO + 2\,H_2 \\
&\text{Anode (WGS):} && CO + H_2O \rightleftharpoons CO_2 + H_2 \\
&\text{Anode (Oxidation):} && H_2 + O^{2-} \longrightarrow H_2O + 2\,e^- \\
&\text{Cathode:} && \tfrac{1}{2}\,O_2 + 2\,e^- \longrightarrow O^{2-} \\
&\text{Overall:} && CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O
\end{aligned}$$

Gandiglio et al. (2024) assessed the performance for different SOFC modules fueled by natural gas under field conditions, and AC efficiency ranged from 51% to 61% under rated conditions, with thermal efficiencies between 18% and 28%. Moreover, a very high electrical efficiency spanning from 45% to 65% was found for the 50–100% modulation range. These efficiency values place SOFCs as the best performer when compared to other Fuel Cell technologies and Gas Turbines, presenting also the characteristic of having ensuring stable and optimal performance under a big modulation range. (Gandiglio et al., 2024).

Comparison. Qasem and Abdulrahman (2024) present a recent and thorough qualitative and quantitative comparison of the main different types of Fuel Cells in the market (Table 3.1).

It is observed that PEMFCs, which operate at low temperatures (60–110°C) and exhibit a relatively high system efficiency of 40–55%, having a lightweight and compact design, along with a fast startup time, make them ideal for transportation and portable power applications. However, their reliance on high-purity hydrogen as fuel and sensitivity to impurities pose challenges. Additionally, their relatively short lifespan and dependence on expensive catalysts such as platinum further limit their long-term viability in stationary applications.

SOFCs, on the other hand, offer high fuel flexibility and can work with hydrogen, natural gas, biogas, and coal gas, making them a very versatile choice for stationary power generation and CHP applications. Normal efficiencies found in the literature range from 40–60%, with CHP efficiencies reaching over 90%, positioning them as one of the most efficient technologies for large-scale power plants. However, the high operating temperature leads to long startup times, limited shutdown cycles, and material degradation over time, reducing overall system lifespan. Despite these drawbacks, SOFCs are well suited for integration with Gas Turbines in hybrid power cycles, further enhancing efficiency. These systems represent an optimal choice for stationary applications.

Table 3.1: Comparison of Fuel Cell Technologies (Qasem & Abdulrahman, 2024). Note that SOFC values do not reflect Bloom's commercial product, they are literature reported values compiled by Qasem and Abdulrahman (2024).

Characteristics	PEMFCs	SOFCs	AFCs	PAFCs	MCFCs
Temperature (°C)	60–110	500–1000	60–250	150–210	500–700
System efficiency (%)	40–55	40–60	60–70	40–50	50–60
Combined heat and power efficiency (%)	70–90	<90	>80	>85	>80
Stack power (kW)	1–100	0.5–2.000	1–100	100–400	300–3.000.000
Energy density (kWh/m^3)	112,2–770	172–462,1	—	—	25–40
Power density (kW/m^3)	3,8–6,5	4,20–19,25	1	0,8–1,9	1,5–2,6
Lifespan (h)	2.000–3.000	1.000	8.000	>50.000	7.000–8.000
Cell voltage (V)	1,1	0,8–1,0	1,0	1,1	0,7–1,0
Nominal current density (A/cm^2)	0,5–1	—	0,1–0,3	0,15	0,14–0,16
Electrolyte	Polymer membrane	YSZ	KOH	Phosphoric acid	Molten carbonate
Fuel type	Hydrogen	Hydrogen, natural gas, biogas, coal gas	Hydrogen, ammonia	Hydrogen, methanos	Natural gas, biogas, coal gas
Startup time	<1 min	60 min	<1 min	—	10 min
Advantages	Small size, lightweight, quick startup time and load response, low temperature	High efficiency, fuel flexibility, solid electrolyte, suitable for CHP, Hybrid/Gas Turbine cycle	A wider range of stable materials allows components to be priced lower, low temperature, quick startup	Suitable for CHP, increased tolerance to fuel impurities	Fuel flexibility, high efficiency
Disadvantages	Sensitivity to low temperature, humidity, salinity, and fuel impurities	High temperature, long startup time, limited number of shutdowns, intensive heat	Sensitive to CO_2 in fuel and air, need of electrolyte management (aqueous), electrolyte conductivity,	Expensive catalysts, long startup time, sulfur sensitive	Slow response time, highly corrosive, low power density
Applications	Transportation, portable power, unmanned aerial vehicles (UAVs)	UAVs, transportation, power plants, auxiliary power units	Transport, military, auxiliary power units, aerospace	Building, utilities, distributed generation	Distributed generation, Utilities

The capital costs of Fuel Cell systems are highly sensitive to production volumes and system scales. According to the Battelle Memorial Institute (2016), a 100 kW PEMFC CHP system costs approximately \$2,745/kW when producing 100 units, but this drops significantly to \$1,624/kW at a scale of 50,000 units. Similarly, for a 250 kW PEMFC CHP system, costs decline from \$1,907/kW at 100 units to \$1,131/kW at 50,000 units. For SOFC CHP systems, the same report estimates lower costs at comparable scales. A 100 kW SOFC system is reported to cost \$1,517/kW at 100 units and \$962/kW at 50,000 units. For the 250 kW size, costs fall from \$1,194/kW to \$787/kW as production scales from 100 to 50,000 units. Notably, the fuel cell stack accounts for approximately 20% of total system costs in PEMFC systems and about 30% in SOFC systems (Battelle Memorial Institute, 2016).

Regarding LCOE, studies present a wide variety of results. Lai and Adams (2024) evaluated four SOFC power plant configurations fueled by natural gas: a standalone SOFC plant, a standalone SOFC with a steam bottoming cycle, an SOFC/GT hybrid, and an SOFC/GT hybrid with a steam bottoming cycle. The study reported LCOEs of 327 \$/MWh, 194 \$/MWh, 38,5 \$/MWh, and 35,1 \$/MWh, respectively. Notably, the last two configurations showed lower LCOEs than the baseline natural gas combined cycle plant used for comparison (Lai & Adams, 2024). In a separate analysis, Roy et al. (2024) assessed a CHP SOFC application in the UK residential sector, finding LCOEs of 0,167 £/kWh when fueled with natural gas and 0,527 £/kWh with hydrogen. These will be later contrasted with the results obtained for the Data Center case study using *Bloom Energy* SOFCs.

Reciprocating Engines

A reciprocating engine is an internal combustion engine in which the energy released by the sequential fuel combustion in multiple cylinders is converted from reciprocating motion of pistons into rotational motion, in this case, driving an electric generator (EIA, 2017). Additionally, waste heat from the engine can be recovered to produce hot water and/or steam (EIA, 2017).

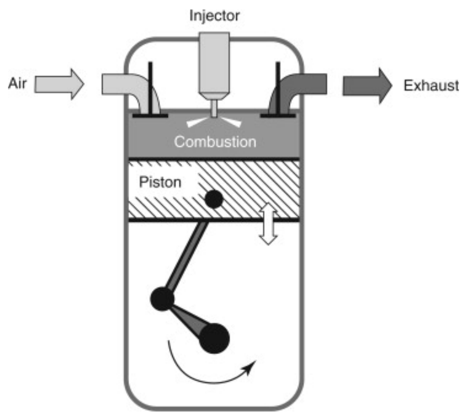


Figure 3.8: Simple reciprocating engine diagram (Kass, 2008).

Reciprocating engines have been widely used in many applications for their load following capabilities, offering rapid start-stop responses and the flexibility to function as either peaking or base load resources (Burns & McDonnell, 2025). With their ability to be quickly engineered, procured, and deployed, reciprocating engines are becoming an attractive solution for Data Center developers seeking to fast-track approvals and permitting for large-scale projects, demands that often strain the capacity of local grids (Burns & McDonnell, 2025). Their electric efficiencies range from 30-40 % LHV for small naturally aspirated engines, and near 50% for larger turbocharged ones (EIA, 2017).

Typically, these generators are diesel powered (Clark, 2024), but growing sustainability regulatory pressures on tougher tax regimes may favor other technologies (Ansett, 2021; Caterpillar, 2023). Gas engines have been rising as an alternative, with on site fuel storage challenges, poor utility connections, high initial CAPEX and design adaptations that should be performed as main deterrents (Ansett, 2021).

The EIA (2024a) places construction costs for overall internal combustion engines at 1788 \$/kW, while the particular case of gas-fueled ones at 1677 \$/kW.

Hybrid Renewable Systems

The use of renewable systems to power Data Centers is something widely found in the literature as a way to minimize the environmental impact of these facilities. However, these come with several technical and economic challenges if they are considered as primary power. Next, a very brief description of the Solar and Wind concepts is presented.

Solar PV. On-site solar photovoltaic (PV) electricity generation has emerged as a viable option for powering Data Centers, with several ones opting for this technology to reduce operating costs and lower the environmental impact (Hyvönen et al., 2024; Mordor Intelligence, 2025d). This phenomenon has been highly motivated by a sharp decrease in the LCOE of the generation technology from 0,132 $/kWh in 2015 to nearly 0,044 $/kWh in 2024 (Mordor Intelligence, 2025d; IRENA, 2024), and recent studies such as Hyvönen et al. (2024) have analyzed their techno-economic performance using different configurations (Figure 3.9).

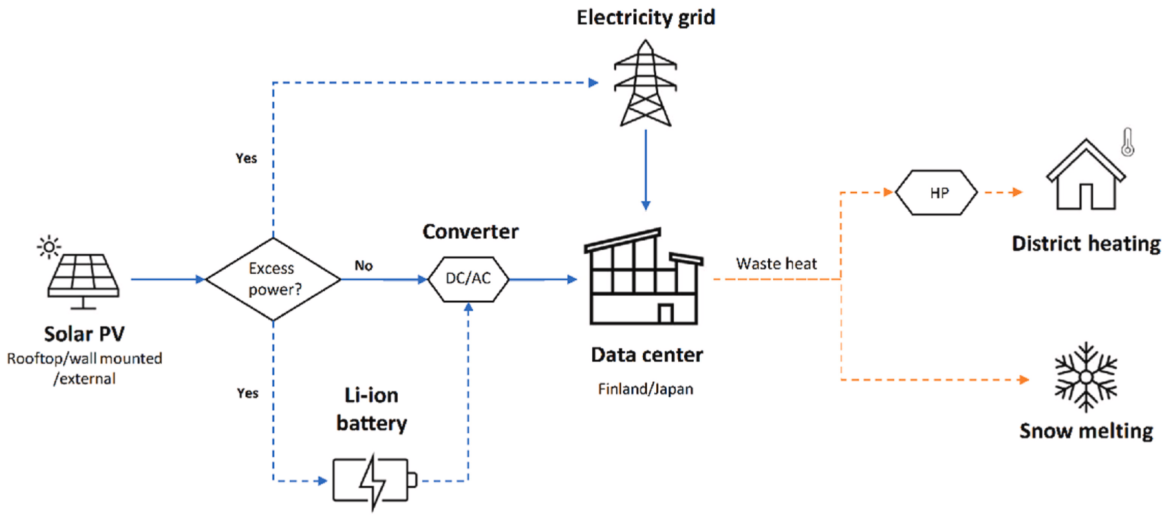


Figure 3.9: Simple schematic of the PV system proposed by Hyvönen et al. (2024).

Nevertheless, there have been factors hindering this development. Especially in northern regions, skepticism about solar irradiation is added to a lack research on the cost-effectiveness of PV for Data Center applications (Hyvönen et al., 2024) and to lack of space, something not favored by the low PV energy density (Oró et al., 2015; Mordor Intelligence, 2025d). Additionally, due to the inherent power source intermittency and the continuous power demand Data Centers have, large energy storage systems are required if these are planned for primary power. These presents both a technical challenge, if the strict Data Center reliability requirements are to be met, and an economic one, given the associated cost increase.

Wind. Wind energy generation has a much bigger power density when compared to other renewable sources such as solar. Moreover, even though it is intermittent and non dispatchable, its intermittency tends to be less of that of PV systems. However, as it was the case for PV, its characteristics make that for on-site power, large energy storage systems or auxiliary power solutions are a requirement. Additionally, wind turbines must also typically be installed far from urban centers because of land costs and wind availability. Even though this is the case for some Data Centers , others are built in dense regions, not having wind energy as an on-site power feasible solution (Tozzi, 2024).

Ambitious studies such as the one developed by Haddad (2019), explore design methods for a hybrid renewable energy infrastructure composed of wind turbines, photovoltaic panels, batteries and electrolyzers, showing that it is technically feasible. However, considering the current technical end economic challenges involved in using these technologies as primary power for on-site solutions, these are not included in the techno-economic analysis, prioritizing the assessment of more wide-spread solutions for the application.

3.1.2 Comparison of On-site Power Solutions

To better understand and compare the range of technologies available for off-grid Data Center power discussed previously, a qualitative benchmark of on-site power solutions is presented in Table 3.2. The table summarizes key characteristics, strengths, limitations, and economic indicators of the main alternatives, serving as a foundational reference for the subsequent techno-economic analysis, in which this qualitative pre-assessment will be complemented by a thorough and quantitative approach.

Gas Turbines are a widely adopted solution due to their scalability, high power density, and cost advantages. However, they require complex maintenance, and are currently subject to long lead times due the surge in their demand, making them more challenging to deploy rapidly. Fuel Cells, particularly SOFCs, offer high efficiency, low emissions, and modularity, making them suitable for stationary power generation. Despite these advantages, they often come with high capital costs and require strict fuel purity to maintain long-term performance. Reciprocating Engines provide fast load-following capabilities and are well-suited for backup and peaking applications, but they suffer from lower efficiency, higher emissions, and increased maintenance demands. Renewable systems, such as on-site solar PV and wind generation, finally, offer an environmentally friendly and cost-effective option for supplemental power. However, their reliance on proper sun and wind resources, low power density, and intermittent nature, make it a challenge to effectively implement them in some regions or spatially constraint places, and require the need of integration with energy storage or auxiliary systems to ensure reliable operation.

This benchmark serves as an initial comparison of the different on-site power systems to understand their characteristics, benefits and drawbacks. However, in chapter 4, a detailed analysis of these are presented for a 100 MW Data Center application.

Table 3.2: Qualitative comparison of on-site power solutions for Data Centers

Technology	Description	Strengths	Challenges	Main Application for Data Centers	Main Fuels for Data Centers	Reference Construction Cost	Reference LCOE
Gas Turbines	Turbo-machinery that converts chemical energy to mechanical energy through combustion.	Scalable, high power density, potential for waste heat recovery, relatively cost efficient, highly mature industry.	Sensitive to fuel prices, complex maintenance, long lead times.	Primary/secondary.	Natural Gas	722 $/kW (CCGT) - 1006 $/kW (SCGT) (EIA, 2024a)	109-181 $/MWh (CCGT), 154-327 $/MWh (GT) (Kost et al., 2024)
Fuel Cells	Electrochemical devices that convert chemical energy directly into electricity.	High efficiency and reliability, low emissions, modular design, quiet operation, low lead times.	High capital cost, sensitivity to fuel purity, temperature limitations affecting startup and durability (SOFCs).	Primary/secondary.	Natural Gas, Hydrogen	1907-1131 $/kW (PEM-CHP), 1194-787 $/kW (SOFC-CHP) (Battelle Memorial Institute, 2016)	220 $/MWh (SOFC CHP)(Roy et al., 2024)
Reciprocating Engines	Internal combustion engines that convert fuel energy to mechanical power for generators.	Fast load-following, rapid deployment, flexible operation, and well-proven technology.	Lower efficiency, higher emissions, maintenance intensive, noise and vibration challenges.	Backup and peaking power applications requiring rapid response.	Diesel, Natural Gas	1788 $/kw (EIA, 2024a)	212-281 $/MWh (Diesel), 68-101 (Gas) (Lazard, 2015)
Renewable Systems	Hybrid systems based on on-site Solar PV and Wind generation (often integrated with energy storage or auxiliary systems).	Environmentally friendly, low operating costs, scalable, and benefiting from decreasing LCOE.	Intermittent output, site resource dependent, low power density, and storage or balancing requirements.	Supplemental power to reduce environmental impact and operating costs.	Solar, Wind	758 $/kW (PV)- 1160 $/kw (IRENA, 2024)	44 $/MWh - 33 $/MWh (IRENA, 2024)

3.1.3 *Bloom Energy*'s SOFC System

Bloom's Energy Server (ES) is a SOFC module operating at temperatures of around 800°C that has been in the market since 2008 (Bloom Energy, 2024b). This system has an up-time of 99,998%[4], and an average lifetime electrical efficiency of 54%, positioning the company as an industry leader in this aspect[5]. Moreover, the exhaust of the system, at 350°C, can be channeled and integrated with CHP systems, increasing overall system efficiency to over 90% and improving economic results (Bloom Energy, 2024c). The Energy Server is fuel-flexible—capable of operating on natural gas, biogas, or hydrogen—and can be deployed in various configurations, including grid-parallel, microgrid, and off-grid setups (Bloom Energy, 2024b).

As illustrated in Figure 3.10, *Bloom Energy*'s ES is rated at 325 kW and it is comprised of various modules, all of which are typically factory-packaged and mounted on a pre-wired skid that includes all necessary interconnections—electrical cabling, piping, and auxiliary equipment—for simplified installation and deployment (Bloom Energy, 2024b).

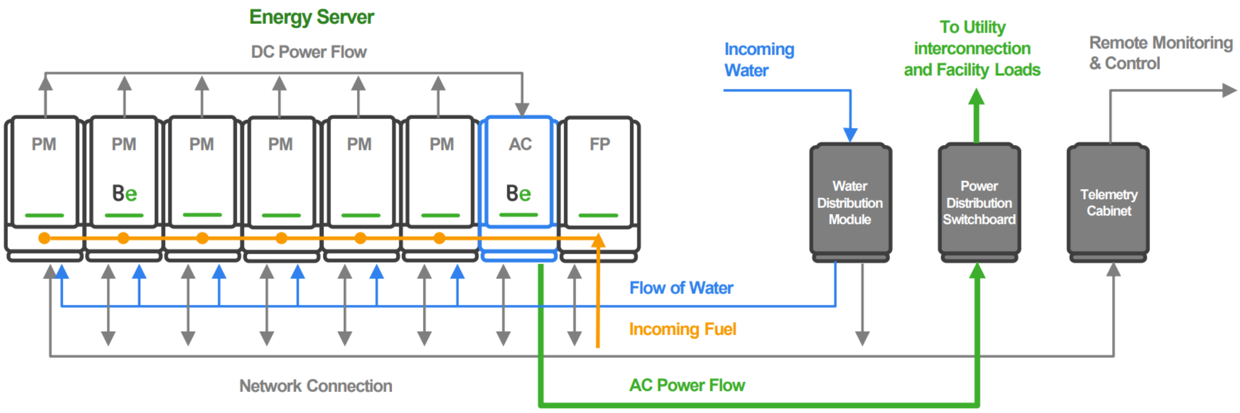


Figure 3.10: *Bloom Energy*'s 325 kW Energy Server Flow Diagram (Bloom Energy, 2024b).

ES Modules

- **The Power Module (PM):** This module contains the SOFC stacks that convert fuel into DC power, and the power conditioning units that regulate the output DC voltage.
- **The Fuel Processing module (FP):** Here, the fuel is fed, the impurities are removed, and the gas is distributed to the PMs.
- **The inverter module (AC):** The AC Converts the DC power from the PMs into AC power.

Additional auxiliary components that support system operation are:

- **Telemetry Cabinet (TC):** For remote monitoring of the Bloom Energy equipment.
- **Water Distribution Module (WDM):** To supply water to the PMs during start-up.
- **Power Distribution Switchboard (PDS):** To make electrical connections to the electrical services at the site.

As it was previously mentioned, SOFCs in general, and *Bloom Energy* systems in particular, offer great versatility to couple with complementary systems given the energy still contained in the exhaust gas. Bloom Energy (2024c) mentions typical applications being hot water production, steam generation, and chilled water production, while Gandiglio et al. (2013), as well as many other studies, demonstrate the feasibility of hybrid SOFC-GT systems that could even consider a bottoming steam cycle. Recent announcements, additionally, present a partnership between *Bloom Energy* and *Chart*

[4]Note that even if in specification sheets this is the reported availability, in the posterior analysis one of 99,9% is used based on existing company budgets analyzed for Data Center applications.

[5]The main specifications of *Bloom Energy*'s Energy Server 6.5 working with natural gas can be seen in Table A.1 in Appendix A.

Industries to couple *Bloom Energy*'s power systems with carbon capture solutions (Bloom Energy, 2025c).

3.2 Opportunities and Challenges for SOFC Integration

The tremendous capital deployment in the Data Center ecosystem, and close linkage with the power sector, present a significant market opportunity for power businesses (Sachdeva et al., 2025), and on-site sustainable power solution businesses are one of the key players benefiting from this depicted energy-constrained, sustainability-ambitious landscape. Fuel Cells, being a reliable on-site solution that can handle the dynamic workloads present and meet emission standards, are set as one of the most considered behind-the-meter power sources: as it was previously mentioned, 30% of Data Centers are expected to have on-site power generation by 2030, with 1,1 GW of Fuel Cells already announced from a total of 4,8 GW (Bloom Energy, 2025a), something partially motivated by the unprecedented lead times of Gas Turbines (Gas Turbine Hub, 2025). According to Bloom Energy (2025a), reliability, sustainability, time-to-power, cost, load flexibility and power density are the key features that Data Center developers seek in on-site power solutions, and Fuel Cells present a high degree of competitiveness in most of them. In particular, SOFCs due to their high-efficiency, fuel flexibility, and large scalability, stand out for the Data Center application (Benstead, 2024).

Overall, the global SOFC market size was valued at 3,60 billion in 2025 and it is expected to reach USD 37,21 billion by 2033, growing at a CAGR of 33,9% in the period (Straits, 2025), and largely driving the growth in the stationary Fuel Cells market with it (Benstead, 2024). In this segment, there are approximately 50 active players, with the top four accounting for 85,2% of total installed capacity (Modern Power Systems, 2023). *Bloom Energy* leads this pack with over 40% of global market share, followed by Doosan-HyAxiom, FuelCell Energy and Panasonic (Modern Power Systems, 2023). In 2023, around 40% of the market of SOFCs was Data Center power (Fortune, 2025), and this segment is expected to grow at the fastest rate until 2028, being one of the most lucrative end-use markets for SOFCs (Markets and Markets, 2025; Straits, 2025). Europe, in particular, is anticipated to exhibit a CAGR of 46,9% until 2033 in the SOFC sector, with Germany as one of the most important markets for this technology (Straits, 2025).

Despite these favorable conditions, there are challenges limiting the SOFC widespread on-site power solution for Data Centers. As noted by TechSci Research (2025), one of the key obstacles for these systems is their high upfront CAPEX, which makes it challenging to compete with other energy technologies such as Gas Turbines cost-wise. Additionally, scaling up production to meet growing market demand while maintaining consistent quality is a significant concern. Other critical challenges include ensuring long-term reliability and durability, securing reliable fuel sources, and establishing a resilient fuel supply infrastructure (TechSci Research, 2025). On a more technological level, a key challenge lies in developing high-performance, durable electrolyte materials capable of operating at lower temperatures, as lowering the operating temperature can enhance durability and reduce manufacturing costs (TechSci Research, 2025).

Bloom Energy is in a very good position regarding these challenges. The company develops top-tier systems already proven reliable in the sector, with a strong presence for more than 12 years (Bloom Energy, 2025b). Moreover, their systems present a uniquely low time-to-power, they are modular, completely scalable, and present high cost competitiveness while significantly lowering the environmental impact (Bloom Energy, 2025b). Given that the Data Center sector has demonstrated a strong willingness to invest in decarbonization solutions, driven by sustainability commitments, regulatory pressures, and corporate ESG goals, *Bloom Energy* SOFC's characteristics put the company in a potentially advantageous position.

In the next chapter, a detailed analysis of *Bloom Energy*'s SOFC systems and on-site power generation competitors is performed for a 100 MW Data Center application case. Here, it will be possible to assess the performance of Bloom against other power solutions and offer a quantitatively backed benchmark on technical, economic and environmental dimensions.

Chapter 4

Techno-economic Analysis

Chapter Description

This chapter introduces the techno-economic modeling of SOFC systems, describes the studied configurations of *Bloom Energy*'s systems to power a 100 MW Data Center, outlines the methodology used to model them and their on-site power generation competitors, and presents and discusses the obtained results.

Main Takeaways

1. Bloom's non-CHP configurations present electrical efficiencies only matched by CCGTs. These systems also offer highly competitive ramp rates and availabilities suitable for Data Center requirements.
2. Bloom's CHP systems achieve total efficiencies above 80%, including useful heat output. Carbon capture reduces net electrical efficiency from 54% to 49% but enhances heat recovery possibilities by over 5 MW.
3. Natural Gas SOFCs with CHP reduces fuel use significantly compared to Gas Turbines and Reciprocating Engines. Hydrogen and Carbon Capture variants further reduce or nearly eliminate direct CO_2 emissions.
4. SOFC systems emit substantially lower levels of NO_x, SO_x, CO, VOCs, and methane compared to conventional on-site generation and grid averages. Water and land use intensities are also lower than alternatives.
5. Although Bloom's CAPEX is high, the modular design supports predictable costs. Stable operational expenses and fast deployment contribute to competitive LCOEs, especially when considering opportunity costs related to time-to-power advantages.
6. The LCOE of Bloom's systems is less affected by fluctuations in fuel prices and carbon costs than on-site alternatives, but they are more exposed to interest rate fluctuations due to their higher share of CAPEX in the LCOE structure. Hydrogen-based configurations have higher fuel cost exposure but benefit from carbon pricing and policy mechanisms.
7. SOFC systems can be deployed in under 12 months, while Gas Turbines and grid connections often require multiple years. This reduces time-to-market risks and supports Data Center operational continuity.
8. Over the system lifetime, Natural Gas CHP configurations reduce CO_2 emissions by more than 50% compared to Gas Turbines and Reciprocating Engines. Hydrogen and Carbon Capture options approach net-zero or net-negative emissions.

Contents

4.1 Introduction to Techno-economic Analysis

Given the complexity of the techno-economic assessment of SOFCs, before jumping to the specific modeling methodology for the particular application cases described, a brief introduction to the the basis of it according to the scientific literature is presented.

4.1.1 Introduction to Physico-chemical Modeling of SOFC Systems

Fuel Cells convert chemical energy directly into electrical energy through redox reactions at the electrodes. Among them, SOFCs operate at high temperatures—typically between 700°C and 1000°C, which enables internal reforming of light hydrocarbons and efficient cogeneration of heat and power.

At the core of an SOFC is an electrochemical process where hydrogen reacts with oxygen ions at the anode, releasing electrons that travel through an external circuit, producing electric power. The oxygen ions are supplied through the electrolyte from the cathode side, where oxygen from air is reduced. The resulting product, water, is formed within the anode. The overall reaction is exothermic and supports high thermal efficiency, making SOFCs particularly attractive for CHP applications and distributed generation.

The performance of an SOFC stack is influenced by interconnected processes such as electrochemical reactions that dictate current and voltage, internal reforming of hydrocarbons into hydrogen-rich gases, thermal management to sustain optimal temperatures, and mass transport, which affects reactant availability and voltage through concentration polarization. These processes together influence key output parameters such as the cell voltage, power density, fuel utilization, and waste heat production. In this thesis, SOFC systems are modeled as functional black-boxes within a broader techno-economic analysis. The detailed physico-chemical behavior of the Fuel Cell is not explicitly simulated but is used to inform the performance parameters of the system.

To support transparency and scientific rigor, the key governing equations, including Faraday's law, Nernst potential, polarization losses, internal reforming chemistry, and energy balances, are summarized in Appendix B. These provide the theoretical foundation behind the black-box parameters used in the model and ensure consistency with literature and manufacturer-reported data.

4.1.2 Introduction to Economic Modeling of SOFC Systems

The methodology used to analyze the economic dimension of SOFC systems varies across studies but generally follows a common framework. While costs are typically divided into CAPEX and OPEX, the specific cost calculation methods and classifications within these categories differ between studies.

Napoli et al. (2015), calculate the CAPEX based on research done by Staffell and Green (2013), who estimate the future costs of Fuel Cell systems adjusting common academic projections with actual commercial data, and complement this information with percentage estimates for installation and operational costs (Napoli et al., 2015). C. Y. Chan et al. (2023) employ a similar approach by classifying costs total plant costs (TPC), annual fixed operating costs (AFOC), annual variable operating costs (AVOC), using Battelle Memorial Institute (2016) estimates for the SOFC subsystem and other literature estimates for the rest of the costs. Wang et al. (2023), on the other hand, employ the methodology developed by the US National Energy Technology Laboratory (NETL) approach for techno-economic analysis of power plants where CAPEX is classified into different categories[1], component costs are calculated separately using the chemical engineering plant cost index method and other costs calculated according to different methodologies proposed by the literature.

After considering all the costs involved and the revenue streams, taxes, incentives, different economic and financial indicators can be calculated to assess the project. Depending on the consideration of the time value of money, these economic evaluation indicators can be divided into static and dynamic. While the first ones present an advantage in the simplicity of the calculation and understanding, they do not accurately reflect the actual situation of the investment project (Yang et al., 2024). Dynamic indicators, considering the time value in the economy, are the most widely found tools in the literature regarding economic analyses of power plants, and the ones that are used within this category depends on the particular goal of the case.

Napoli et al. (2015) and Wang et al. (2023) make use of the Net Present Value (NPV) methodology in their studies. Roy et al. (2024) and Lai and Adams (2024), on the other hand, make use of the LCOE. Furthermore, Yang et al. (2024) add the Internal Rate of Return (IRR) and the Payback Period (PB) as additional key tools to assess projects. Given that LCOE, NPV, PB and IRR are the most widely used found assessment tools in the literature, these will be described briefly.

LCOE. The levelised cost of electricity is determined by the ratio of an energy asset's total lifetime costs by the asset's total energy generation over its life cycle, including a discount rate to account for the time value of money (Gomstyn & Jonker, 2024). This represents is the constant amount of a payment stream per unit of energy produced that has the same present value as the total cost of building and operating a power plant over its life (EF China, 2011), and can be calculated by (Kost et al., 2024):

$$\text{LCOE} = \frac{I_0 + \sum_{t=1}^{n} \dfrac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \dfrac{W_{\text{out},t}}{(1+i)^t}} \tag{4.1}$$

Being the total annual costs A_t composed of fixed and variable costs for the operation of the power plant, maintenance, servicing, repairs and insurance payments, where also end of life considerations can be made (Kost et al., 2024):

[1] These are: bare erected cost (BEC), engineering, procurement and construction cost (EPCC), total project cost (TPC), total overnight cost (TOC) and total as-spent cost (TASC) (Wang et al., 2023).

$$A_t = \text{OPEX}_t + \text{CAPEX}_t - R_t + D \tag{4.2}$$

Where:

- LCOE: Levelized Cost of Electricity.
- I_0: Initial capital expenditure for the energy storage system.
- A_t: Total annual cost in year t, comprising the following components:
  - OPEX$_t$: Annual operational and maintenance costs in year t.
  - CAPEX$_t$: capital costs in year t.
  - R_t: Residual value or recovery at the end of the system's lifetime in year t.
  - D: decommisioning costs.
- $W_{\text{out},t}$: Annual energy output from the system in year t.
- n: Lifetime of the storage system (in years).
- i: Discount rate applied to reflect the time value of money.

The LCOE is a powerful metric as it allows the comparison of different technologies of unequal life spans, project size, different capital cost, risk, return, and capacities (DOE, 2015).

Payback Period. the payback period is calculated by identifying the point at which cumulative revenue equals initial investment, considering discounted cash flows[2]. That is,

$$\sum_{t=0}^{PB} \frac{\text{NCF}_t}{(1+i)^t} = I_0 \tag{4.3}$$

Where

- PB: Payback period (the time at which cumulative discounted cash flows equal the initial investment).
- NCF$_t$: Net cash flow generated by the innovation project in year t.
- i: Discount rate.
- I_0: The initial amount invested in the project.

NPV. The NPV reflects the present value of expected cash flows on a project, measuring the surplus value on the project (Burkšaitienė, 2009). This can be calculated with the following formula (Žižlavskỳ, 2014):

$$\text{NPV} = \sum_{t=0}^{n} \frac{\text{NCF}_t}{(1+i)^t} \tag{4.4}$$

Where

- NPV: Net Present Value.
- NCF$_t$: Net cash flow generated by the innovation project in year t.
- i: Discount rate.
- n: Time horizon (total number of years).

IRR. The IRR represents the discount rate when the total present value of capital inflows is equal to the total present value of capital flows, making the NPV equal to zero (Yang et al., 2024). That is,

$$\text{NPV} = \sum_{t=0}^{n} \frac{\text{NCF}_t}{(1+IRR)^t} = 0 \tag{4.5}$$

[2]Note that this metric can be transformed into static if cashflows are not discounted

It is important to note that all of these show different angles of the project, complement each other, and are preferred on different circumstances. While the NPV gives a hint of the project's profitability, the Payback Period offers insights into the project's breakeven point and liquidity, the IRR a measure of capital efficiency, and the LCOE the actual cost of the electricity produced (Frykberg, 2023; Chathams, 2022).

Having laid out the basis of technical and economic analysis of SOFC systems according to the literature, now the specific systems studied along with their modeling methodologies are presented. First, the focus is placed on Bloom systems, whereas later both grids and competitor systems are described.

4.2 Bloom System Descriptions and Modeling Methodologies

To explore how *Bloom Energy* systems perform technically, environmentally and economically, these are studied under different configurations. These vary depending on waste heat re-purposing and carbon capture integration, and are modeled with two different fuels: natural gas and hydrogen (Table 4.1)[3]. Furthermore, different locations are considered for the analysis: Germany, the UK, Ireland and Italy. Additionally, an EU-average case is considered.

Table 4.1: Analyzed system configurations with fuel types and carbon capture options.

N	Configuration	Case	Subcase	Carbon Capture	Fuel
1	Wasted Heat	a	i	No	Natural Gas
			ii	No	Hydrogen
		b	i	Yes	Natural Gas
2	CHP - Hot Water Production	a	i	No	Natural Gas
			ii	No	Hydrogen
		b	i	Yes	Natural Gas

Even though different Bloom configurations are assessed, they share a common ground: they power the same Data Center and and have the same power topology. Following, before jumping to the description and modeling methodologies of each studied case, a description of the base system upon all cases are based on is presented.

4.2.1 General System Description and Methodology

System Overview

The modeled load consists of an off-grid 100 MW Data Center. In this type of configuration, to address redundancy and degradation throughout the lifespan of the SOFCs, extra capacity is added. That is, a total rated capacity of 125,125 MW is employed, requiring the installation of a total of 385 Bloom Energy servers[4] (Figure 4.1). Next, a basic description of the system is presented.

System Description

The system architecture is designed in a modular fashion, consisting of 35 different 3,575 MW stamps of 11-325 kW Bloom ES each. These stamps are self-contained electrical systems composed of both AC and DC distribution layers, with Bloom Servers as the generators.
AC power is tapped by inverting the DC SOFC generated power to 415 V and fed to the low voltage bus (415V PDS), serving local IT loads and interfaces with the local transformer. This

[3] Note that this is the same table as Table 1.1 and it is only repeated for clarity.
[4] This capacity redundancy decision is based on previous *Bloom Energy* projects and internal communications with the company.

transformer steps the voltage up from 415 V to 34,5 kV for either exporting to the facility's main bus or enabling interaction with the utility grid, in case there is one. At the same time, the native DC output of the Bloom ES is fed into a DC bus that is supported with fast-response energy management by the use of supercapacitor modules (SLs). Each server is coupled with one SL ancilliary module, which provides step load support in island mode and voltage smoothing. In this way, significant loads that exceed the ramp rate of the Bloom ES can be met by the almost instant power delivery of the supercapacitor systems.
The control structure within each stamp is hierarchical. A local control unit known as the Stamp MC monitors and manages the operation of the Bloom Servers and their associated supercapacitors. This unit ensures local voltage and power quality regulation, responds to internal anomalies, and communicates with a central Headend MC, which is the global control unit overseeing all the stamps connected to the bus[a]. This module coordinates processes such as load balancing, startup/shutdown sequences, and potential grid interaction, acting as the central brain of the power system. Furthermore, in the DC bus of each stamp, a Braking Module BM is placed. This consists of resistor banks and chopper circuits aimed to dissipate excess energy when the SL buffer's DC-bus voltage rises above safe thresholds, protecting both the power electronics and the fuel cells themselves from damaging over-voltage.
Additionally, water de-ionization and distribution modules are placed to supply pure water to the energy servers for balance of plant purposes (not shown in the figure). The specific number of modules needed varies according to the quality of water present in the location, but previous projects employ numbers in the order of 80 for the capacity involved. In this system, water is needed during start-up, shutdown, and low-power modes. According to *Bloom Energy*'s internal documents, during initial startup, the Energy Server takes on average about 16 to 36 hours from ambient temperature to get to full power, where it would require water input. However, once the Power Modules reach a level of sustained power output, the water needed by the SOFC is self-generated by the recirculation of the anode products of the reaction.
As a final note, telemetry cabinets are placed to collect real-time data from system, transmitting this information to the control center (and Bloom's remote monitoring service), enabling remote health checks, alarm notification, and performance optimization.

[a]Note that there can be different buses depending on the specific Data Center need. The analysis of this is outside the scope of the project.

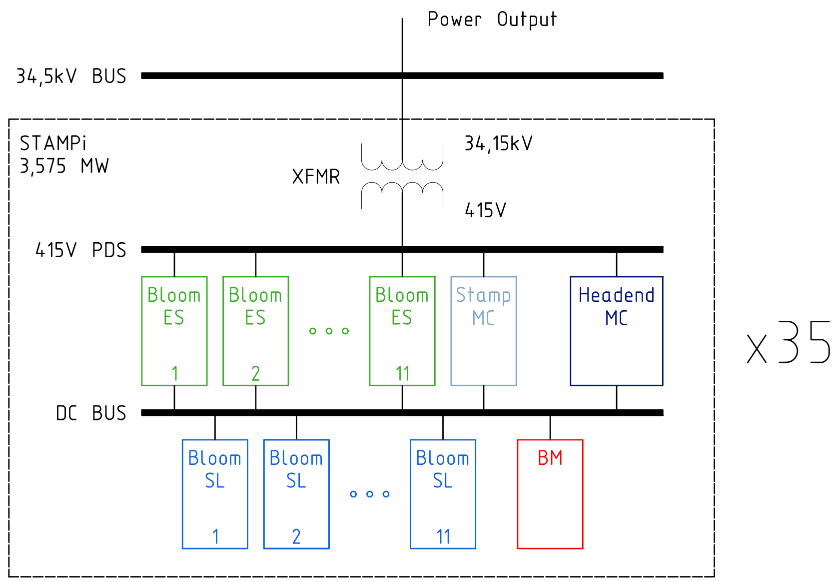


Figure 4.1: Basic power system structure modeled. Based on Bloom's past projects.

Having explained the overall design of the facility, now it is time to delve deeper into the process happening inside the Energy Servers. Earlier mentioned, Bloom Energy Servers are the main building blocks of the system. These consist of the basic modular power blocks commercialized by *Bloom Energy*, and include several key components (Figure 4.2). At their core, the Power Modules are found, consisting of the SOFC stacks responsible for the electrochemical conversion of the fuel fed into DC power. These are coupled with power conditioning units that regulate the output DC voltage and an Inverter Module to convert the DC output of the SOFCs into AC power to export to the 415V bus. Furthermore, the fuel fed to the PMs is handled by the Fuel Processing Module, which removes impurities and ensures the proper distribution of the processed gas to the Power Modules.

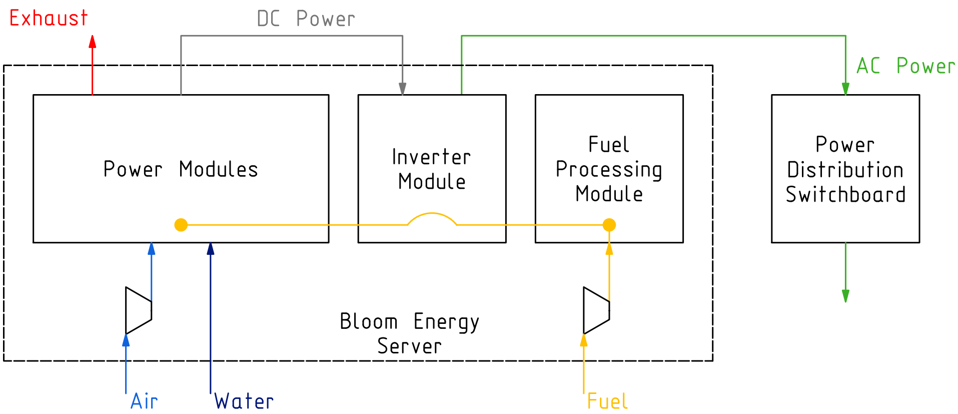


Figure 4.2: *Bloom Energy*'s SOFC system.

On a general level fuel, the process happening inside the Bloom ES can be described as the following: fuel is sent to the fuel processing module, where it is cleaned and distributed to the power modules, which consist of the SOFC stacks that convert the chemical energy stored in the fuel into DC power. In case of using hydrogen as fuel, this is the fuel directly consumed in the electrochemical cells. However, for the case of natural gas, a reforming process occurs at the anode of the ES. As it is described in Equation B.11 and Equation B.12 in Appendix B, the main reactions occurring are the reforming and the water gas shift, being the hydrogen produced the main fuel of the cell (Santarelli, 2014a):

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \;, \tag{4.6}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \;, \tag{4.7}$$

That is, the overall reaction could be considered as:

$$CH_4 + 2\,H_2O \rightleftharpoons CO_2 + 4\,H_2 \;, \tag{4.8}$$

The *REDOX* reaction produced between the H_2 generated and the O_2 in the incoming air to the cathode produce current that can be described using the Faraday law presented in Equation B.24 for the stack[5]:

$$I = \frac{\dot{n}_{H_2,consumed} \cdot 2F}{n_{cells}} \;, \tag{4.9}$$

And, on the other hand, the generated voltage in the SOFC depends on the current demanded by the load, given the polarization curve of the SOFC (Equation B.5).

This generated power is processed by conditioning units present in the PMs, and then is sent to the Inverter Module, where it is converted into AC and sent to the Power Distribution System to be distributed to the loads, with redundancies depending on the load criticality.

[5]Note that here the nomenclature x_3 was replaced by $\dot{n}_{H_2,consumed}$ for simplicity.

Additionally, the high quality exhaust gases from the system, which can reach up to 6,8 kg/h at over 350°C for a 1 MW installation, can be further put into use to enhance the overall efficiency. In the cases analyzed in this report, the only studied use is the hot water production.

Going deeper into the explanation makes the development of the physical-chemistry of the SOFCs necessary. In the box below, a load-to-fuel approach is used to explain the electricity generation process of Bloom ES for a Data Center application.

Technical Description

Load Demand. Given a characteristic Data Center load profile, there will be a given time dependent power demand by the load, which needs to be covered by the SOFC system:

$$P_{DC} = P_{load} = P_{load}(t) \tag{4.10}$$

Total System Power Supply. Since SOFCs have inherent response time limitations (ramp rate constraints), rapid power changes must be managed with the aid of another technology. In the case of *Bloom Energy* systems, this is done by supercapacitors. That is, at any time t, the total power demand consists of contributions from the SOFC and the supercapacitors:

$$P_{\text{load}}(t) = P_{\text{SOFC,net}}(t) + P_{\text{SC}}(t) \tag{4.11}$$

where:
- $P_{\text{SOFC,net}}(t) = P_{\text{SOFC}}(t) - P_{aux}(t)$ is the net power provided by the fuel cell when considering the power consumption of the auxiliary systems.
- $P_{\text{SC}}(t) = V_{\text{SC}}(t) \cdot I_{\text{SC}}(t)$ is the power delivered or absorbed by the supercapacitor.

SOFC System Power Supply. The SOFC voltage follows the polarization equation described in Equation B.5:

$$V_{\text{c}} = V_{\text{c}}(I) = V_{\text{oc}} - \eta_{\text{ohm}}(I) - \eta_{\text{act}}(I) - \eta_{\text{dif}}(I) \ , \tag{4.12}$$

from where a power dependence on the current can be established for the net power provided by the SOFC:

$$P_{\text{SOFC,net}} = P_{\text{SOFC}}(I) - P_{\text{aux}}(I) = V_{\text{SOFC}}(I) \cdot I_{\text{SOFC, total}} - P_{\text{aux}}(I) \tag{4.13}$$

That is, a $P_{\text{SOFC,net}}(I)$ curve could be built, from where power demanded by the load determines the current outputs and voltages. Note that this power is later conditioned by power electronics to match the requirements of the load.

Power Consumed by Auxiliaries. SOFCs, as all power generation technologies, have auxiliary systems that are essential to their functioning. For the case of SOFCs, one of the main sources of power consumption by auxiliary systems consists of the air and fuel compressors. These can be calculated according to the methodology presented by Saisirirat (2015) based on the perfect gas equations and polytropic transformations. The exhaust temperature can be calculated using

$$T_e = T_i \left(\frac{p_e}{p_i}\right)^{\frac{\gamma-1}{\gamma\eta_{\infty C}}} \tag{4.14}$$

where:
- T_i, T_e are the inlet and exit temperatures, respectively.
- p_i, p_e the Inlet and exit pressures, respectively.
- $\gamma = \frac{C_p}{C_v}$ the ratio of specific heats.
- $\eta_{\infty C}$ the polytropic efficiency of the compressor.

On the other hand, the isentropic enthalpy change Δh_C would be

$$\Delta h_C = C_p(T_e - T_i) \ , \tag{4.15}$$

he efficiency of the compressor η_C

$$\eta_C = \left(1 - \left(\frac{p_e}{p_i}\right)^{\frac{\gamma-1}{\gamma}}\right) \Big/ \left(1 - \left(\frac{p_e}{p_i}\right)^{\frac{\gamma-1}{\gamma\eta_{\infty C}}}\right) \ . \tag{4.16}$$

and finally the mechanical power consumed by the compressor P_C will depend on the flow rate to be compressed $\dot{m}$:

$$P_C = \frac{\dot{m}\Delta h_C}{\eta_C} \tag{4.17}$$

The total power consumed by the auxiliaries can be calculated by summing consumptions of the fuel and air compressors, as well as other auxiliaries systems present:

$$P_{\text{aux}} = P_{\text{C, fuel}} + P_{\text{C, air}} + P_{\text{aux+}} \tag{4.18}$$

SOFC Power Supply Limitations. As it was previously mentioned, given that SOFCs cannot change power instantaneously, a ramp rate limit is imposed. This electrical ramp rate m can be defined as the maximum electrical power variation ΔP_{load} in a given time interval, Δt, and it can be expressed as (Napoli et al., 2015):

$$m = \frac{\Delta P_{load}}{\Delta t} \tag{4.19}$$

For each moment, this load ramp rate m is contrasted to the ramp rate M of the Fuel Cell, representing its maximum capability to adapt its power output: if the ramp rate M is bigger than m, the Fuel Cell can exactly follow the load in that particular interval, while if the ramp rate M is lower than m, the fuel cell cannot exactly follow the load (Napoli et al., 2015). That means that to maintain this constraint, the following needs to occur:

$$P_{\text{SOFC}}(t + \Delta t) = P_{\text{SOFC}}(t) + \min\left(\Delta P_{\text{load}};\ M \cdot \Delta t\right) \tag{4.20}$$

where ΔP_{load} is the power change over Δt.

Supercapacitor function. This is where the supercapacitor plays a critical role. The power mismatch due to SOFC ramp limitations is exchanged with the supercapacitor, which discharges when $P_{\text{load}} > P_{\text{SOFC}}$ and charges when the opposite happens:

$$P_{\text{SC}}(t) = P_{\text{load}}(t) - P_{\text{SOFC}}(t) \tag{4.21}$$

Note that the supercapacitor should not overcharge, meaning that:

$$SOC_{SC} = \frac{E_{SC}}{E_{SC,\max}} \leq SOC_{SC,\max} \tag{4.22}$$

where E_{SC} is the stored energy, depending on its capacitance C_{SC} and its voltage V_{SC}:

$$E_{SC} = \frac{1}{2} C_{SC} V_{SC}^2 \tag{4.23}$$

The supercapacitor's voltage follows:

$$V_{\text{SC}}(t) = \frac{Q_{\text{SC}}(t)}{C_{\text{SC}}} \ , \tag{4.24}$$

where $Q_{\text{SC}}(t)$ is the charge stored.

And the current exchanged by the supercapacitor is:

$$I_{\text{SC}}(t) = \frac{dQ_{\text{SC}}}{dt} = \frac{P_{\text{SC}}(t)}{V_{\text{SC}}(t)} \tag{4.25}$$

Hydrogen Consumption The current demanded by the load determines the hydrogen consumption inside the SOFC. The hydrogen molar flow rate consumed in the anode[a] can be calculated using Faraday's law:

$$\dot{n}_{H_2,consumed} = \frac{n_{cells} \cdot I_{\text{SOFC, total}}}{2F} \tag{4.26}$$

Fuel Supply. However, the sources of this hydrogen consumed in the anode of the Fuel Cell vary. Two alternatives are analyzed for this case: hydrogen and natural gas.

- **Hydrogen:** Here, the amount of fuel that needs to be supplied can be calculated by the flow of hydrogen reacting at the anode and the consideration of the fuel utilization factor U_f:

$$\dot{n}_{H_2,supplied} = \frac{\dot{n}_{H_2,consumed}}{U_f} \tag{4.27}$$

- **Natural Gas:** In the case of natural gas, given $\dot{n}_{H_2,consumed}$ (named x_3 in B.16), the system of equations Equation B.16-Equation B.18 can be restructured to obtain the mole flow of fuel needed to suply the power.
  Considering
  - x_1 as the mol/s of CH_4 that reacts
  - x_2 as the mol/s of CO that reacts
  - x_3 as the mol/s of H_2 that reacts ($\dot{n}_{H_2,consumed}$)
  - $\dot{n}_i$ as the total mole flow into the stack.
  - CO_i, H_2O_i, CH_{4i}, H_{2i}, CO_{2i} as the inlet mole flows to the stack, calculated as the product of the molar fraction of these in the inlet flow y_i multiplied by the total mole flow into the stack $\dot{n}_i$.
  - U_f as the fuel utilization factor in the cell.

  The system of three nonlinear equations (Equation B.16 - Equation B.18) can be solved for the three unknowns $(x_1, x_2, \dot{n}_i)$, with K_p expressed in terms of molar fractions:

$$Kp_{\text{reforming}} = \left\{ \frac{\left(\frac{CO_i + x_1 - x_2}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{H_{2i} + 3 \cdot x_1 + x_2 - x_3}{\dot{n}_i + 2 \cdot x_1}\right)^3}{\left(\frac{CH_{4i} - x_1}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{H_2O_i - x_1 - x_2 + x_3}{\dot{n}_i + 2 \cdot x_1}\right)} \right\} p_{\text{cell}}^2 \tag{4.28}$$

$$Kp_{\text{shift}} = \left\{ \frac{\left(\frac{H_{2i} + 3 \cdot x_1 + x_2 - x_3}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{CO_{2i} + x_2}{\dot{n}_i + 2 \cdot x_1}\right)}{\left(\frac{CO_i + x_1 - x_2}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{H_2O_i - x_1 - x_2 + x_3}{\dot{n}_i + 2 \cdot x_1}\right)} \right\} \tag{4.29}$$

$$x_3 = U_f \cdot (3 \cdot x_1 + x_2 + H_{2i}) \tag{4.30}$$

  Having the set of solutions $x_1, x_2, \dot{n}_i$, the composition of the exit flow e of the anode can be calculated as shown before:

$$\dot{n}_{CH_4,e} = \dot{n}_{CH_4,i} - x_1 = \dot{n}_i \cdot y_{CH_4,i} - x_1 \tag{4.31}$$

$$\dot{n}_{CO,e} = \dot{n}_{CO,i} + x_1 - x_2 = \dot{n}_i \cdot y_{CO,i} + x_1 - x_2 \tag{4.32}$$

$$\dot{n}_{CO_2,e} = \dot{n}_{CO_2,i} + x_2 = \dot{n}_i \cdot y_{CO_2,i} + x_2 \tag{4.33}$$

$$\dot{n}_{H_2O,e} = \dot{n}_{H_2O,i} - x_1 - x_2 + x_3 = \dot{n}_i \cdot y_{H_2O,i} - x_1 - x_2 + x_3 \tag{4.34}$$

$$\dot{n}_{H_2,e} = \dot{n}_{H_2,i} + 3x_1 + x_2 - x_3 = \dot{n}_i \cdot y_{H_2,i} + 3x_1 + x_2 - x_3 \tag{4.35}$$

Air Supply. The stoichiometric O_2 supply needed to react with the fuel fed is simply given by

$$\dot{n}_{O_2,stoic} = \frac{\dot{n}_{H_2,consumed}}{2} \tag{4.36}$$

While the stoichiometric air flow needed can be estimated by considering a 21% V/V O_2 content in the air:

$$\dot{n}_{Air,stoic} = \frac{\dot{n}_{O_2,stoic}}{0,21} \tag{4.37}$$

The total air supply, on the other hand, can be calculated by the air excess ratio λ:

$$\dot{n}_{Air,total} = \lambda \cdot \dot{n}_{Air,stoic} \tag{4.38}$$

Even though the detailed technical description presented above lays a solid ground for the technical modeling methodology of the SOFC systems, presenting most of the elements required to develop concentrated parameters simulations at component level inside *Bloom Energy* systems, after discussions with the company it was decided that in the interest of time and IP information preservation, the models employed would consider Bloom ES as "black boxes". This means that in the following analysis, these are consider as a single component converting chemical energy into heat and power, not providing detailed analyses of the processes happening within them.

[a] That is, actually reacting.

General Methodology

Despite their specific characteristics, all cases share a common analytical framework. To avoid redundancy in the methodology descriptions, the shared elements across the different cases are summarized below, covering the technical, environmental, and economic assessments. Bloom data used in the analysis based on is directly company sourced, and it can be found in Table 4.2 for the Natural Gas case, along with extra data needed for the analysis which was sourced from additional sources. According to *Bloom Energy*, Hydrogen systems do not present any significant variations apart from the direct emissions, which in the Hydrogen case are negligible in all dimensions studied.

Table 4.2: Data used to model the Bloom Energy NG SOFC system.

Variable	Unit	Value	Note
Global			
Natural Gas Price	USD/MWh	Table 4.6	Location dependent
Hydrogen Price	USD/MWh	Table 4.7	Location dependent
Carbon Price	USD/Ton	70,1	EU-ETS 2024 average (ICAP, 2024)
Interest Rate	%	4%	Estimated EU average for 2025 (European Central Bank, 2025)
Conversion Rate	USD/EUR	1,1	Assumption based on historical data.
	USD/GBP	1,3	Assumption based on historical data.

Performance			
Electrical Efficiency	%	54%	Conservative 20-year guaranteed average efficiency according to internal documents
Part-Load Efficiency	%	53%	At 50% load
Ramp Rate	%	120%	(Bloom Energy, 2024a)
Operation			
Lifespan	years	5	Internal communications. Note that equipment changes are typically included in fixed rate agreements with clients for a total operation of 20 years.
Turn Down Limits	%	30%	Minimum viable operation due to technical reasons, not environmental needs.
Availability	%	99,9%	Guaranteed availability for 20 years. Based on internal documents.
Redundancy	-	25%	Based on internal documents for similar Data Center applications
Sustainability			
Direct Emissions			
CO_2e	kg/MWhe	308–378	(Bloom Energy, 2024a)
NO_x	kg/MWhe	0,001	(Bloom Energy, 2024a)
SO_x	kg/MWhe	4,6e-6	(Bloom Energy, 2024a)
CO	kg/MWh	0,005	(Bloom Energy, 2024a)
CH_4	kg/MWh	0	Internal documents
VOCs	kg/MWh	0,004	Internal documents
UHC	kg/MWh	0,004	Approximated as total hydrocarbon plus methane emissions
PM2.5	kg/MWh	0	Internal documents
Noise	dBA	<65	(Bloom Energy, 2024a)
Water Consumption	l/MWhe	3,83	Internal documents
Land Use Intensity	m^2/MW	47,29	Internal documents
Economics			
CAPEX	USD/kWe	4711,8	Internal documents
Fixed OPEX	USD/kWe year	265,3	Internal documents
Non-fuel Variable OPEX	USD/MWhe	0,0	Internal documents
Installation			
Delivery time	months	12	Internal documents
Installation and Commissioning	months	-	Included in the 12 months
Time-to-power	months	12	Internal documents

Technical. As it was previously mentioned, Bloom ES were considered as single electrochemical components, without directly analyzing their subsystems and the processes happening within them. Given the Data Center load and the loads demanded by auxiliaries to the power system, the net power demanded by the facility was obtained as:

$$P_{net} = P_{DC} + P_{aux} \tag{4.39}$$

The total annual energy consumed by the system, in turn, was calculated by integrating the power demanded by the Data Center and the power auxiliaries over the year:

$$W_{DC} = P_{DC} \cdot \lambda_{DC} \cdot 8760\ h \tag{4.40}$$

$$W_{net} = W_{DC} + W_{aux} \tag{4.41}$$

For this purpose, the load factor considered λ_{DC} was 85%, which lies in the middle of the 80-90% typical range reported by ICIS (2025).

Considering Bloom systems electrical efficiency η_{el}, the volume rate of fuel consumed $\dot{V}_{\text{fuel}}$ was calculated via the simple formula.

$$\dot{V}_{\text{fuel}} = \frac{P_{net}}{\eta_{el} \cdot LHV_{fuel}}\ , \tag{4.42}$$

where the heating value LHV_{fuel} varies depending on whether natural gas or hydrogen is used (Table A.2).

On the other hand, the annual fuel consumption of the system was calculated by the integration of the fuel rate $\dot{V}_{\text{fuel}}$ over the year :

$$V_{\text{fuel}}(t) = \int_0^t \dot{V}_{\text{fuel}}\ dt \Rightarrow V_{\text{fuel}}^{yr} = \bar{\dot{V}}_{\text{fuel}} \cdot \Delta t = \frac{\bar{P}_{net}}{\eta_{el} \cdot LHV_{fuel}} \cdot 8760h\ , \tag{4.43}$$

where $\bar{\dot{V}}_{\text{fuel}}$ and $\bar{P}_{net}$ are the average fuel mass flow rate and average load over the period Δt, respectively.

Furthermore, when considering global system efficiencies, several metrics were defined. The total electrical system efficiency corresponds directly to the electrical efficiency reported by *Bloom Energy* (η_{el}), since their systems are solely responsible for electricity production. Another valuable metric for characterizing the systems is the net useful electrical efficiency ($\eta_{el,use}$), which measures the proportion of energy actually utilized by the Data Center relative to the total fuel input.

$$\eta_{el,use} = \frac{P_{DC}}{\dot{V}_{\text{fuel}} \cdot LHV_{fuel}} \tag{4.44}$$

Following the same logic, two additional indicators were introduced: the total efficiency (η_{tot}), which accounts for the total energy output in the form of both electricity and useful heat, and the net useful total efficiency ($\eta_{tot,use}$), which considers only the directly useful electricity and heat produced.

$$\eta_{tot} = \frac{P_{net} + \dot{Q}_{\text{water}}}{\dot{V}_{\text{fuel}} \cdot LHV_{fuel}} \tag{4.45}$$

$$\eta_{tot,use} = \frac{P_{DC} + \dot{Q}_{\text{water}}}{\dot{V}_{\text{fuel}} \cdot LHV_{fuel}} \tag{4.46}$$

The data used for the technical analysis concerning *Bloom Energy* systems was provided by the company, either by internal communications and documents, or by publicly available specifications and company documents. On the other hand, fuel specifications are from EU data bases and scientific literature (Table A.2). These were country based for natural gas according to EU reports (Eurostat, 2025a), and general for the Hydrogen case according to TU Delft (2025).

Environmental. A bottom-up, scope-I environmental assessment of each system configuration was performed, quantifying direct emissions of CO_2, NO_x, SO_x, CO, $VOCs$, CH_4, UHC and $PM2.5$ for the Data Center as a whole, as well as Well-to-Energy (W2E) emissions by adding the upstream fuel cycle emissions, specifically for the CO_2 case. Next, the general methodology is presented, and later specific methodological adaptations for individual configurations are described separately in their respective sections.

- **Functional unit and system boundary.** The functional unit considered is the entire 100 MW Data Center operating continuously for one year (8760 hours) with a load factor λ_{DC} of 0,85, equivalent to a total annual energy output W_{net}[6]. The system boundary included only on-site emissions and resource consumptions for Scope I analysis, and adds upstream fuel emissions for the Well-to-Energy ones.
- **Scope I - Direct Emissions.** Scope I emissions considered here were the direct emissions of CO_2, NO_x, SO_x, CO, $VOCs$, CH_4, UHC and $PM2.5$. These were quantified using emission factors $f_{\mathrm{direct,i}}$ provided by Bloom Energy (2024a) and additional internal documents. For each pollutant i, the total annual direct emissions are calculated as:

$$E_{\mathrm{scope\ I,i}} = E_{\mathrm{direct,i}} = f_{\mathrm{direct,i}} \cdot W_{\mathrm{net}} \tag{4.47}$$

  where W_{net} is the total net electric energy output over the year.

  For the Hydrogen case, zero direct emissions were considered.
- **Scope I - Net Emissions.** In cases with CHP, net emissions were calculated by deducting the avoided emissions to the direct ones. Avoided emissions were considered the emissions a natural gas boiler would produce to achieve the same useful thermal output according to the emission factors presented in Table 4.3.

$$E_{\mathrm{Net\ scope\ I,i}} = E_{\mathrm{direct,i}} - E_{\mathrm{avoided,i}} \tag{4.48}$$

Table 4.3: Boiler emission factors

Pollutant	Unit	Value	Source
CO_2	kg/MWh	233,6	(Casasso et al., 2019)
NO_x	kg/MWh	0,237	(Casasso et al., 2019)
SO_x	kg/MWh	0,002	(Casasso et al., 2019)
VOCs	kg/MWh	0,0110	(Casasso et al., 2019)
CH_4	mg/kWh	10,7	(Casasso et al., 2019)
PM2,5	kg/MWh	0,00141	(EPA, 1998)
CO	kg/MWh	0,0620	(EPA, 1998)
TOC	kg/MWh	0,00816	(EPA, 1998)
UHC	kg/MWh	0,0188	Estimated as TOC + CH_4

On the other hand, the emissions of systems with CC systems were calculated using assumed capture efficiencies of 99% based on ranges reported by Chart Industries (2025).

$$E_{\mathrm{Net,i}} = (1 - \eta_{CC}) \cdot E_{\mathrm{direct,i}} \tag{4.49}$$

[6] Note that what W_{net} accounts for depends on the case.

For CHP cases with CC, both effects were considered.

$$E_{\text{Net,i}} = (1 - \eta_{CC}) \cdot E_{\text{direct,i}} - E_{\text{avoided,i}} \tag{4.50}$$

Furthermore, for the case of CO_2, net emissions were calculated by adding the Methane slip present in carbon dioxide equivalent terms using a GWP of 30.

- **Well-to-Energy Emissions.** Given that the on-site Data Center power generation employs fuels whose production cycles have emissions associated with them, these were accounted for. With this aim, CO_2e upstream lifecycle emissions f_{upstream} were considered both for natural gas and hydrogen. The natural gas upstream emission factor $f_{\text{upstream,NG}}$ for the systems studied was estimated from the world average value of 34,6 g/kWh NG reported by the IEA (2024b). On the other hand, for the hydrogen case, Arrigoni et al. (2024) developed a comprehensive study on emissions generated along the whole green fuel supply chain depending on different transport methods: on-site generation, off-site compressed hydrogen transported by pipeline (C-H2) and liquid hydrogen (L-H2) transported by ship. Values found in this were 0,6 kg $CO_2eq/kg\ H_2$ for on-site production, 2,3 kg $CO_2eq/kg\ H_2$ for C-H2 and 1,9 kg $CO_2eq/kg\ H_2$[7], respectively. Even though the emission factors present great variation within each other, the large difference existing between them and natural gas systems makes them insignificant in comparison. Therefore, to simplify the analysis, only pipeline transport (C-H2) was considered.

  With these upstream emission factors found, total upstream emissions triggered by the Data Center power consumption and the Well-to-Energy emissions for each of the j fuel cases depending on the fuel energy supplied W_{fuel} were obtained:

$$E_{\text{upstream,j}} = f_{\text{upstream,j}} \cdot W_{\text{fuel}} \tag{4.51}$$

$$E_{\text{W2E,j}} = E_{\text{Net CO2,j}} + E_{\text{upstream,j}} \tag{4.52}$$

- **Water consumption.** Water use associated with operation was quantified based on a water consumption factor k_w of 3,83 l/MWh, obtained from internal documents shared by *Bloom Energy*. The total annual water consumption W_{water} was computed as:

$$W_{\text{water}} = k_w \cdot W_{\text{net}} \tag{4.53}$$

- **Land footprint.** Land occupation was estimated by the calculation of the land occupation factor based on previous large scale *Bloom Energy* projects without vertical stacking:

$$k_{\text{land,MW}} = \frac{Area}{Power} = 47,2\ m^2/MW \tag{4.54}$$

  With this factor, the total land use for the 100 MW Data Center was calculated assuming a total capacity P_{total} of 125,125 MW deployed.

$$A_{\text{land}} = k_{\text{land}} \cdot P_{\text{total}} \tag{4.55}$$

  Furthermore, the land use factor per energy produced annually was calculated by considering the nominal Data Center power with a load factor f_{load} of 0,85:

$$k_{\text{land,MWh}} = \frac{k_{\text{land,MW}}}{8760\ h \cdot f_{\text{load}}} \tag{4.56}$$

[7] Note that here on-site production assumes wind energy in the Netherlands and the other two production in Portugal and consumption in the Netherlands (Arrigoni et al., 2024).

Economic. The scope of *Bloom Energy* supply reaches the provision of the Packaged Energy Servers, Water De-ionization Modules (WDM), Telemetry Cabinets Load Buffer Modules (SL), Controller Modules (MC), Braking Modules (BM), and Installation and Microgrid kits for Fuel Cells, as well as the commissioning of the system and the Operation and Maintenance (O&M) services to ensure the system performs on 24x7x365 basis including all anticipated future PM components replacements (Table 4.4). However, the company is not responsible for the installation of the systems, being site civil works, electrical infrastructure-switchgear, distribution boards, ATS, transformers, control rooms, external cablings, mechanical infrastructure, gas grid applications, connection, metering, pressure reducing stations, and other gas infrastructure.

Table 4.4: Scope of Supply – Bloom Energy vs. Client/Subcontractors

Within Bloom Energy's Scope	**Outside of Bloom Energy's Scope**
• Packaged Energy Servers (PES) • Water De-ionization Modules (WDM) • Telemetry Cabinets • Load Buffer Modules (SL) • Controller Modules (MC) • Braking Modules (BM) • Installation kits for fuel cells • Microgrid kits for fuel cells • System commissioning • 24x7x365 Operation and Maintenance (O&M) • Future power module replacements (included in O&M costs)	• Site civil works (foundations, enclosures, etc.) • Electrical infrastructure (switchgear, distribution boards, ATS, transformers, control rooms, cabling between fuel cells and site electrical infrastructure) • Mechanical infrastructure • Gas grid applications and connection • Gas metering and pressure reducing stations • Remaining gas infrastructure • Installation of all above site systems

The lifecycle CAPEX and OPEX related to Bloom's scope of supply was based on previous confidential budgets developed by *Bloom Energy* for similar applications. Considering these, the methodology employed for calculating all the extra costs not considered in *Bloom Energy*'s scope was based on Wang et al. (2023), which in turn base their analysis on NETL guidelines. Here, costs are separated into CAPEX and OPEX, and each of them is split into further categories: CAPEX is classified to bare erected cost (BEC), engineering, procurement and construction cost (EPCC), total project cost (TPC), total overnight cost (TOC) and total as-spent cost (TASC) (Equation 4.57 - Equation 4.61), while OPEX is done so to Variable and Fixed.

$$BEC = C_{eq} + \text{Installation Cost} \tag{4.57}$$

$$EPCC = BEC + \text{Indirect Cost} \tag{4.58}$$

$$TPC = EPCC + \text{Contingencies} \tag{4.59}$$

$$TOC = TPC + \text{Owners Cost} \tag{4.60}$$

$$TASC = (1 + f_{TASC}) \cdot TOC \tag{4.61}$$

Where C_{eq} represents total equipment cost and the TASC was estimated with the use of a factor f_{TASC} as an extra percentage of the TOC.

For all cases, apart from *Bloom Energy* systems, auxiliary electrical and mechanical components were considered in the analysis. These include pumps, tanks, switchgear, and transformers, among others, and were estimated from Aero-derivative Simple Cycle Turbine data reported by the EIA (2024b). Even if using these estimates induces an error, as it includes components not necessarily present in the case study, given that this component costs are in all cases less than 2% of the total costs, the incurred error is considered acceptable. On the other hand, gas connection costs are neglected.

Installation Costs, Owner's Costs, Contingencies, and Variable and Fixed OPEX were considered according to Table 4.5. Here, the different estimates presented follow the categories used by Wang et al. (2023) using estimates suggested by *Bloom Energy*.

Table 4.5: Summary of Capital and Operational Costs.

Cost Category	Item	Value
Installation Costs	**Direct Costs**	
	Erection, Steel Structures, Painting	5% of Equipment Cost
	Piping	≈0% of Equipment Cost
	Indirect Costs	
	Yard Improvement	2% of BEC
	Engineering/Consulting	3% of BEC
	Miscellaneous	2% of BEC
	Building	≈0% of BEC
	Owner's Cost	3% of EPC
Contingency	Contingency	5% of EPC
OPEX	**Variable**	
	Fuel Cost	Table 4.6
	Carbon Cost	70,1 \$/Ton CO_2eq
	Fixed	
	Labor Cost	1% of TOC
	Maintenance	3% of TOC

In the analysis, natural gas prices were based on average annual prices reported by governmental sources for each of the analyzed cases (Table 4.6), and hydrogen ones were calculated based on average values taken from the European Hydrogen Observatory (2023). Note that on-site hydrogen production values were taken as a benchmark and these will be varied on a later sensitivity analysis. On the other hand, the cost of GHG emission was estimated by the cost of Carbon in the European Union Emissions Trading System (EU-ETS), reported at an average of 70,1 \$/ton CO_2e by the International Carbon Action Partnership - ICAP (2024) for 2024.

Having defined the cost structure, the LCOE was employed as an indicator for results, using a methodology identical to the one presented in section 4.1.2. For this purpose, an interest rate of 4% was considered, given that this is the estimated EU average for 2025 (European Central Bank, 2025). Acknowledging that this value presents high variation among the analyzed locations, even reaching 5,7% in Ireland (European Central Bank, 2025), and that is very susceptible to macroeconomic changes, a posterior sensitivity analysis is done. Moreover, residual values and decommissioning costs were neglected, and a 20-year analysis horizon was adopted for all Bloom cases.

Given the time-sensitivity that high-revenue sectors such as the Data Center one present, time-to-power should be quantified in the analysis. Therefore, the above mentioned methodology was applied with two different assumptions within each case: considering opportunity costs of having a not operational Data Center due to lack of grid connection, and not doing so, assuming instant deployment.

Table 4.6: Natural gas prices considered.

Case	Price [$/MWh]	Note
EU-27	47,5	H1-2024 for large industrial consumers, includes all taxes (Eurostat, 2025c)
Germany	50,6	H1-2024 for large industrial consumers, includes all taxes (Eurostat, 2025c)
UK	58,9	H2-2024 for large industrial consumers, includes all taxes (UK Government, 2025b)
Ireland	34,8	H1-2024 for large industrial consumers, includes all taxes (Eurostat, 2025c)
Italy	47,4	H1-2024, includes all taxes (Eurostat, 2025c)

Table 4.7: Hydrogen price for selected countries and EU-27. Price per kg are average values taken from European Hydrogen Observatory (2023) for 2023 and LHV values are the ones reported by TU Delft (2025).

Region	H_2 Price [€/kg]	LHV [MJ/kg]	Cost [USD/MWh]
EU-27	6,61	120	218,1
Germany	8,89	120	293,4
UK	4,90	120	161,7
Ireland	4,10	120	135,3
Italy	6,58	120	217,1

If opportunity costs are not considered, no further modifications are to be done. However, taking into account the opportunity costs brings about other considerations.

As Table 2.2 shows, grid connection times highly vary depending on the location; and lease rates, the benchmark used for opportunity costs, also do so in a great deal. For this project, lead times used for the opportunity costs analysis were the average of the ranges reported in Table 2.2 (Table 4.8)[8]. To obtain the lead time value differential, these figures need to be compared with *Bloom Energy* lead times. These typically lie on the 12-18 months range for similar projects, but according to company sources the current delivery times are well below 12 months currently, so a reference value of 12 months was considered as total for time-to-power.

Conversely, monthly Data Center lease costs excluding energy costs were found directly for the Frankfurt and London, considered as country benchmarks, in CBRE (2024c). Values for Milan and Dublin were not found, but were estimated with the aid of the cost indexes presented by Turner & Townsend (2024b) and London and Frankfurt values. Finally, the value corresponding to EU-27 is reported by Savills (2024), but includes electricity costs. To adjust these values, a simplification using average grid costs of Frankfurt and London was used, given that these are the largest Data Center markets (Eurostat, 2025b). Given that many lease rates utilized rely on assumptions and simplifications, and that these are critical for the economic analysis, this is later considered in a sensitivity analysis.

Using the lead time differential and lease costs, the monthly opportunity cost was calculated and deducted from the monthly OPEX in which the system operates on *Bloom Energy* power but would otherwise not have been operational due to delayed grid connection. To exemplify using the German case, if the average Time-to-Power offered by *Bloom Energy* for the application is 12 months, and the average queue time for grid connection in the country is 48 months, then for the first 36 months of operation, Bloom systems' costs are deducted the Data Center lease revenues in their OPEX.

[8]Note that values for EU-27 were not found and the Italy figure was taken as an estimate

Table 4.8: Average connection times and lease rates in analyzed markets (without energy costs).

Location	Average Queue Time [months]	Lease Rate [$/kW month]	Source
EU-27	36	250	Assumption
Germany	48	225	(CBRE, 2024c; Milanesi et al., 2025)
United Kingdom	90	178	(CBRE, 2024c; Skidmore, 2025)
Ireland	60	171	(CBRE, 2024c; IEA, 2025a; Turner & Townsend, 2024b)
Italy	36	169	(CBRE, 2024c; IEA, 2025a; Turner & Townsend, 2024b)

As a final note, all the economic analysis was developed using USD. To convert between EUR and GBP to USD, reference exchange rates of 1,1 and 1,3 were used, respectively.

4.2.2 Case 1a: No Waste Heat Integration

System Description

This system consists of the base system presented in Figure 4.2, repeated in Figure 4.3 for clarity. Fuel, either natural gas or hydrogen, is electrochemically converted into electricity and heat through the process described in subsection 4.2.1. In this case, the energy contained in the hot exhaust is wasted, with no heat capture being present. At the same time, the CO_2 produced at the anode exhaust when working with natural gas is directly discharged to the atmosphere, as no carbon capture systems are in place.

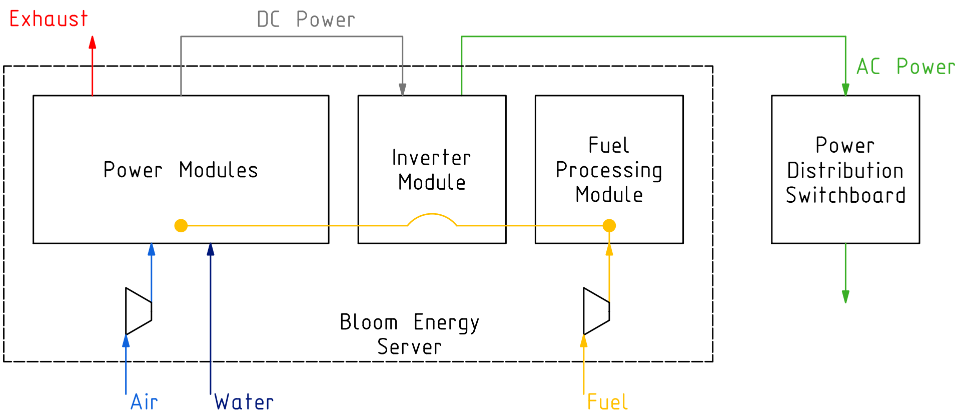


Figure 4.3: Case 1a: *Bloom Energy*'s SOFC system.

Technical Modeling Methodology

The methodology employed for this case does not differ from the one presented in section 4.2.1. Here, as neither carbon capture nor heat re-purposing are in place, $W_{net} = W_{DC}$, the total system efficiency $\eta_{el,use}$ was considered equal to the electrical one, as well as η_{tot} and $\eta_{tot,use}$:

$$\eta_{el} = \eta_{el,use} = \eta_{tot} = \eta_{tot,use} \tag{4.62}$$

Environmental Modeling Methodology

As with the technical methodology, the environmental methodology follows the same steps as the ones presented in section 4.2.1.

Economic Modeling Methodology

For Case 1a, in addition to *Bloom Energy* systems, the auxiliary electrical and mechanical components described in section 4.2.1 were included in the analysis. These include pumps, tanks, switchgear, and transformers, among others. That is, systems presented in Table 4.9 were considered, and the methodology described in section 4.2.1 was applied.

Table 4.9: Summary of Components considered for the BEC in Case 1a.

Component	Description
Bloom Energy equipment	PES, WDMs, Telemetry Cabinets, SLs, MCs, BMs, Installation kits for fuel cells, and Microgrid kits for fuel cells.
Auxiliaries	All major-non Bloom equipment: pumps, tanks, switchgear, transformers, etc.

4.2.3 Case 1b: No Waste Heat Integration + Carbon Capture

System Description

Building on Case 1a, this system consists of the coupling of *Bloom Energy* power generation platform fueled by natural gas with a carbon capture system (Figure 4.4). This variation upon the system presented in Case 1a signifies that the anode exhaust discharged from the Bloom Energy Servers is fed into a post-combustion CO_2 capture process consisting of the separation of the CO_2 from the stream. As a result, the reduction of 90-99% of the CO_2 emissions can be achieved[9]. *Bloom Energy* does not develop these systems but partners with different companies for the application. For projects of the size of the one in question, *Chart Industries* and *Honeywell* are the two possible options according to the company.

Technical Modeling Methodology

The technical modeling of this case builds on the general methodology presented in section 4.2.1, with the addition of the CC system, which affects both overall system efficiency and fuel consumption. Here, the power consumed by the CC system (P_{CC}) results in a net power reduction to the loads, and therefore the expressions developed in Equation 4.39-Equation 4.43 become:

$$P_{net} = P_{DC} + P_{CC} \tag{4.63}$$

$$W_{net} = P_{DC} \cdot \lambda_{DC} \cdot 8760\ h + W_{CC} \tag{4.64}$$

$$\dot{V}_{\text{fuel}} = \frac{P_{net}}{\eta_{el} \cdot LHV_{fuel}}\ , \tag{4.65}$$

$$V_{\text{fuel}}^{yr} = \bar{\dot{V}}_{\text{fuel}} \cdot \Delta t = \frac{W_{net}}{\eta_{el} \cdot LHV_{fuel}}, \tag{4.66}$$

where the same consideration of the load factor λ_{DC} being 0,85 applies.

[9] This considers ranges reported by Chart Industries (2025)

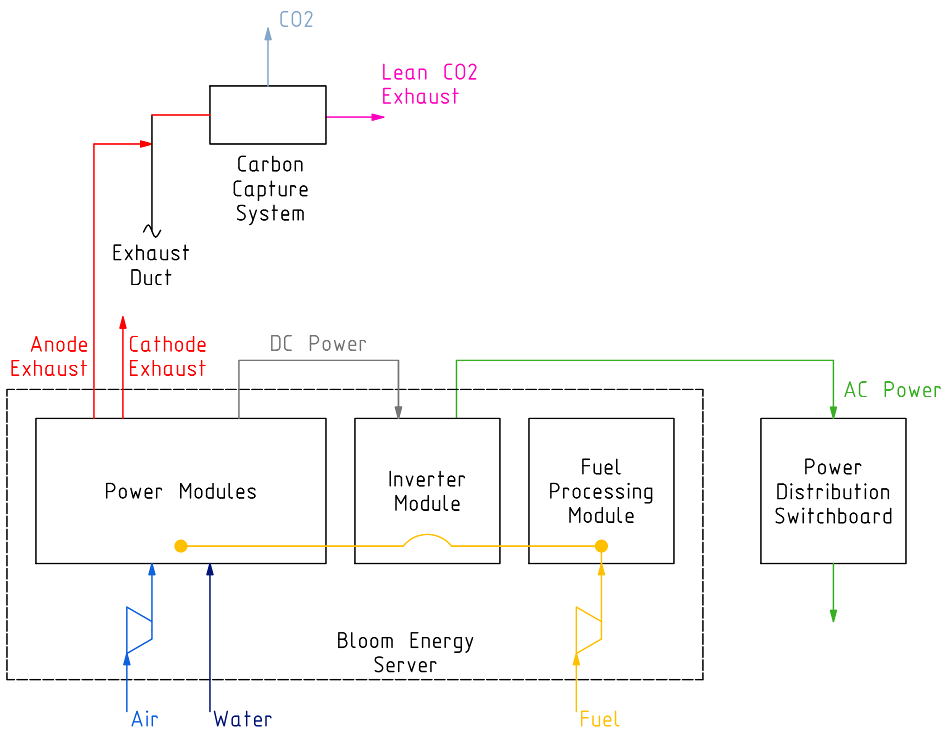


Figure 4.4: Case 1b: *Bloom Energy*'s SOFC system coupled with carbon capture.

Accordingly, the system efficiencies were calculated as:

$$\eta_{el,use} = \frac{P_{DC}}{\dot{V}_{\text{fuel}} \cdot LHV_{fuel}} \tag{4.67}$$

$$\eta_{tot} = \frac{P_{net}}{\dot{V}_{\text{fuel}} \cdot LHV_{fuel}} \tag{4.68}$$

$$\eta_{tot,use} = \eta_{el,use} \tag{4.69}$$

According to Bloom representatives, parasitic loads for the CC systems employed lie around the 10% figure, so that was the considered value. General data used for the analysis, on the other hand, follows the same considerations as for Case 1a.

Environmental Modeling Methodology

The environmental assessment methodology applied to Case 1b uses the approach detailed in Section 4.2.1, incorporating the additional consideration of the CC system. In this case, the net direct annual CO_2 emissions were calculated by accounting for the fraction of emissions captured:

$$E_{CO_2,\text{net}} = (1 - \eta_{CO_2}) \cdot E_{CO_2,\text{gross}} = E_{CO_2,\text{gross}} - E_{CO_2,\text{captured}} \tag{4.70}$$

where the captured CO_2 emissions are given by:

$$E_{CO_2,\text{captured}} = \eta_{CO_2} \cdot E_{CO_2,\text{gross}} \tag{4.71}$$

A capture efficiency η_{CO_2} of 99% was assumed. Moreover, it was further assumed that the CC system was exclusively dedicated to CO_2 capture, with no additional pollutants captured.

Economic Modeling Methodology

As for the technical analysis presented before, the same considerations regarding Case 1a apply. The general economic model developed remains the same as the one described (Table 4.5), but for Case 1b, the addition of the CC system in the economic structure of the project was considered (Table 4.10).

Table 4.10: Summary of Components considered for the BEC in Case 1b.

Component	Description
Bloom Energy equipment	PES, WDMs, Telemetry Cabinets, SLs, MCs, BMs, Installation kits for fuel cells, and Microgrid kits for fuel cells.
CC System	Full Carbon Capture system
Auxiliaries	All major non-Bloom equipment: pumps, tanks, switchgear, transformers, etc.

For the Carbon Capture system, CAPEX and OPEX figures stemming from previous Bloom projects for similar applications were employed. The CAPEX of the system was considered 700 \$/kW while the fixed annual OPEX 25 \$/kW.

4.2.4 Case 2a: CHP - Hot Water Production

System Description

In this case, the energy contained in the Bloom ES exhaust gases is leveraged through the use of Heat Exchangers to heat up water (Figure 4.5). After the SOFC power generation, the exhaust from the Energy Servers, at over 350°C, is collected in ducts and routed to a heat exchanger network, where the thermal energy contained in the hot gases is recovered for building heating or other industrial processes in the form of hot water. Note that before reaching the Heat Exchanger network, there is a bypass damper. This is because this approach offers control over whether waste heat is recovered or discarded, allowing the system to adapt to operational and maintenance needs efficiently: when heat recovery is not required, the exhaust can be bypassed to avoid overheating the heat exchanger or downstream equipment, enabling the management of varying thermal loads or fluid temperature requirements downstream. At the same time, this component is leveraged for maintenance and protection, allowing the heat exchanger to be isolated.

Technical Modeling Methodology

Building on the global methodology presented in section 4.2.1, this case involves the use of the heat exchanger network. Here, part of the energy contained in the exhaust is leveraged for hot water production. Thus, to calculate the benefits of this addition, some considerations were made.

Considering the exhaust gas mass flow rate $\dot{m}_{\text{gas}}$, the specific heat of exhaust gas $c_{p,\text{gas}}$, the inlet temperature as T_{in} and the outlet temperature as T_{out}, the heat available for recovery from the exhaust gas was calculated as:

$$\dot{Q} = \dot{m}_{\text{gas}} \cdot c_{p,\text{gas}} \cdot (T_{\text{in}} - T_{\text{out}}) \tag{4.72}$$

On the other hand, the heat effectively transferred to the water depends on the effectiveness of the Heat Exchangers η_{HX}. If the water fed is at a temperature T_{in} , and it needs to be heated by a ΔT_{water} amount, this means that the mass flow rate of water produced is given by:

$$\dot{Q}_{\text{water}} = \eta_{HX} \cdot \dot{Q} \tag{4.73}$$

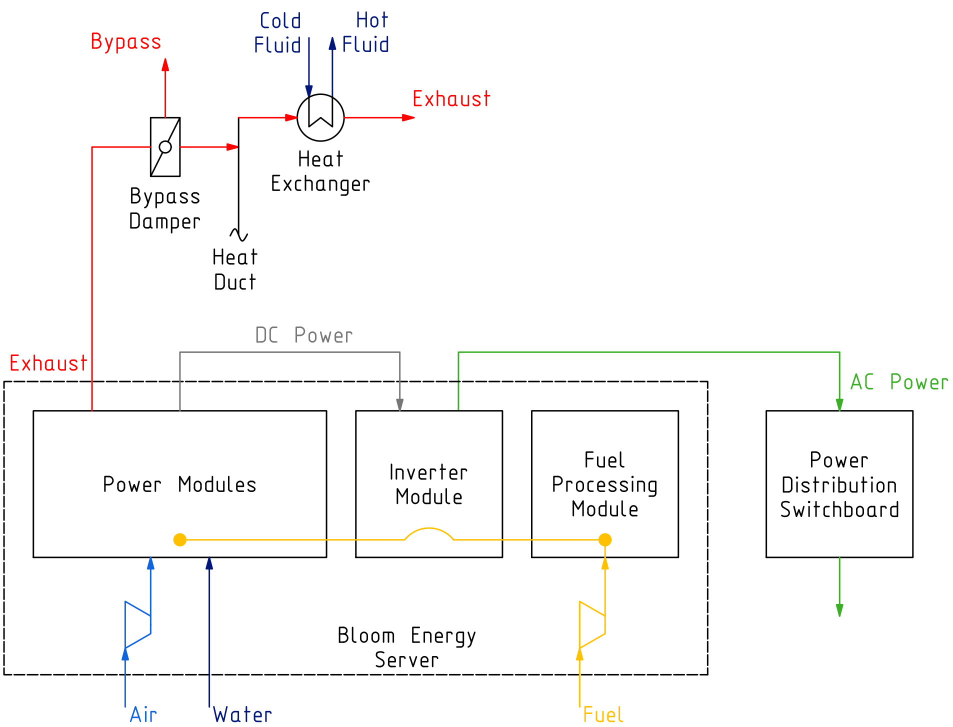


Figure 4.5: Case 2a: *Bloom Energy*'s system coupled with hot water production.

$$\dot{m}_{\text{water}} = \frac{\dot{Q}_{\text{water}}}{c_{p,\text{water}} \cdot \Delta T_{\text{water}}} \tag{4.74}$$

To compute these values, first some considerations and assumptions were made. As shown in Table 4.11, exhaust temperatures and mass flows from *Bloom Energy* systems vary significantly depending on the time after commissioning. Following the approach by Bloom Energy (2024c), three cases were defined: minimum, average, and maximum (Table 4.11). For the purpose of simplification, only the average case was considered for the analysis. On the other hand, Cp values were calculated by reverse-engineering the results presented by Bloom Energy (2024c) to make sure that the value matches the exact compositions and temperatures found in *Bloom Energy*'s SOFCs. Regarding water, the analysis assumed an inlet temperature of 0°C (liquid) and an outlet of 90°C, with a Cp value consisting of an average in the range.

Table 4.11: Heat recovery parameters for minimum, average and maximum cases depending on the number of years past commissioning.

	Unit	Min	Average	Max	Comment
Exahust Gas					
Mass Flow	kg/s	127,6	165,8	190,3	Adapted from Bloom Energy (2024c)
T_{in}	°C	356	367	384	Taken from Bloom Energy (2024c)
T_{out}	°C	100	100	100	Assumed based on Bloom Energy (2024c)
Cp	J/kg°C	1483,6	1311,1	1138,6	Calculated based on Bloom Energy (2024c)
Water					
T_{in}	°C	0	0	0	Assumed
T_{out}	°C	90	90	90	Assumed
Cp	J/kg°C	4190,9	4190,9	4190,9	Average in the T range

On the other hand, data presented by IPIECA (2022) show that heat exchanger effectiveness values, defined as the ratio of actual heat transfer over the maximum theoretical heat transfer, lie in the 80-95% range. A conservative average estimate of 87,5% was used for the heat exchanger [10], and no heat losses are considered for the purpose of analysis simplification.

Furthermore, a calculation of the fuel savings stemming from this heat repurposed was developed. For this, the natural gas consumption avoided for each of the 3 cases and natural gas properties presented in Table A.2 was calculated by considering that, otherwise, a natural gas boiler with an efficiency of $\eta_{\text{boil}} = 90\%$ would have been employed:

$$\dot{V}_{NG}^{\text{avoided}} = \frac{\dot{m}_{\text{water}} \cdot c_{p,\text{water}} \cdot \Delta T_{\text{water}}}{\eta_{\text{boil}} \cdot LHV_{NG}} \tag{4.75}$$

$$V_{NG}^{\text{avoided}} = \dot{V}_{NG}^{\text{avoided}} \cdot \lambda_{DC} \cdot 8760h \tag{4.76}$$

Environmental Modeling Methodology

To model the environmental dimension of Case 2a, the same base methodology laid out in section 4.2.1 was used. To account for the impact of the heat exchanger system, emissions avoided by it were deducted from the system emissions, considering a natural gas boiler with 90% efficiency (η_{boiler}) and a the emission factors f_{boiler} detailed in Table 4.3

$$E_{CO_2,net} = E_{CO_2,gross} - \frac{Q_{\text{water}}}{\eta_{\text{boiler}}} \cdot f_{\text{boiler}} \tag{4.77}$$

Following the same approach for the direct emissions, the upstream Carbon emissions saved by the avoidance of natural gas consumption were deducted from the gross system emissions in each fuel type case and exhaust conditions considered before calculating the net Well-to-Energy emissions:

$$E_{\text{upstream}} = f_{\text{upstream}} \cdot W_{\text{fuel}} - f_{NG} \cdot \left(\frac{Q_{\text{water}}}{\eta_{\text{boiler}}}\right) \tag{4.78}$$

Economic Modeling Methodology

Expanding on the global methodology presented previously, this case accounts for the procurement and installation of the heat exchanger system (Table 4.12). With this aim, cost estimation functions synthesized by Wang et al. (2023) were used, simplifying the analysis by considering only the heat exchanger and the pump used as additional components.

Table 4.12: Summary of Components considered for the BEC in Case 2a.

Component	Description
Bloom Energy equipment	PES, WDMs, Telemetry Cabinets, SLs, MCs, BMs, Installation kits for fuel cells, and Microgrid kits for fuel cells.
Heat Exchangers	Equipment to transfer exhaust heat to water.
Pump	Component used to pump water through the heat exchanger
Auxiliaries	All major-non Bloom equipment: pumps, tanks, switchgear, transformers, etc.

Given that these formulas were developed in past years, they need to be updated to current costs. For this purpose, a correction factor based on the variation of the chemical engineering plant cost

[10] Note that previous analysis presented by Bloom Energy (2024c) use CHP equipment efficiencies of 93,5%, so this represents a conservative estimate.

index (CEPCI) was used. Current CEPCI values were not found, but The University of Manchester (2025) reports one of 800,8 for 2023, which is the value employed in this project.

For the heat exchanger equipment costs, the cost function presented by Wang et al. (2023) parametrizes capital costs as a function of the heat transfer capacity of the component $\dot{Q}$. This formula was developed in 2005, when the CECPI ($CEPCI_0$) was 468,2.

$$Z_{HX} \approx 6,534 \cdot \dot{Q} \cdot \frac{CEPCI}{CEPCI_0} \tag{4.79}$$

On the other hand, the formula for pump costs presented in the same study parametrizes it based on pump power $\dot{W}$ and efficiency η_{pump}. This equation was developed in 2017, when the index $CEPCI_0$ was 567,5.

$$Z_{\text{pump}} = 800 \left(\frac{\dot{W}_{\text{pump}}}{10}\right)^{0,26} \cdot \left(\frac{1-\eta_{\text{pump}}}{\eta_{\text{pump}}}\right)^{0,5} \frac{CEPCI}{CEPCI_0} \tag{4.80}$$

Pump power demand, conversely, was calculated through the simple relation

$$\dot{W}_{\text{pump}} = \frac{\dot{V}_{\text{water}} \cdot \Delta P}{\eta_{\text{pump}}} \ , \tag{4.81}$$

where the total pressure drop was assumed at 1 bar, given that pressure drops at the tube side-where the water flows- normally lie on the range 0,1-1 bar (Vrcoolertech, 2024).

Cost savings from the natural gas consumption avoidance to heat up an equivalent mass flow of water using a boiler with a 90% efficiency were considered as OPEX reductions. For these, carbon emissions costs applicable were also included. These, as well as natural gas and hydrogen prices, followed the same considerations outlined in section 4.2.1.

4.2.5 Case 2b: CHP - Hot Water Production + Carbon Capture

System Description

Apart from the waste heat leveraging developed in Case 2a, this case includes a carbon capture process such as the one described in Case 1b (Figure 4.6). Here, anode and cathode exhausts are treated independently. While both cathode and anode exhausts' energy is leveraged by the use of heat exchangers to heat up water, cathode exhaust flows are directly released after the heat exchanger systems, while anode exhaust flows are fed to the CC system. As a result, colder streams of air (cathode side), CO_2 lean exhaust (anode side) and pure CO_2 are obtained.

Descriptions of the heat exchanger and carbon capture systems, developed in Cases 2a and Case 1b, respectively, largely apply. Note that, as here the focus is placed on basic overall system values, the actual configuration and specific designs do not matter as they do not affect the global values for the purpose of this project to a great extent.

Technical Modeling Methodology

To model this system, the case is largely based on Cases 1b and 2a. Considerations developed for Case 2a regarding exhaust temperatures and exhaust flows (Table 4.11), heat transfer (Equation 4.72), mass of water processed (Equation 4.74), and avoided natural gas consumption (Equation 4.76), apply. Note that even if actually the system changed from Case 2a, given that now anode and cathode exhaust flows are treated independently, in what refers to the global calculations used in the project, the overall values remain unchanged. As for Case 1b, a parasitic load of 10% was considered for the CC system.

Environmental Modeling Methodology

The environmental methodology to model this case comprises considerations of both Case 1b and Case 2a: Carbon Capture reduces direct emissions on-site at the same time that there is a virtual

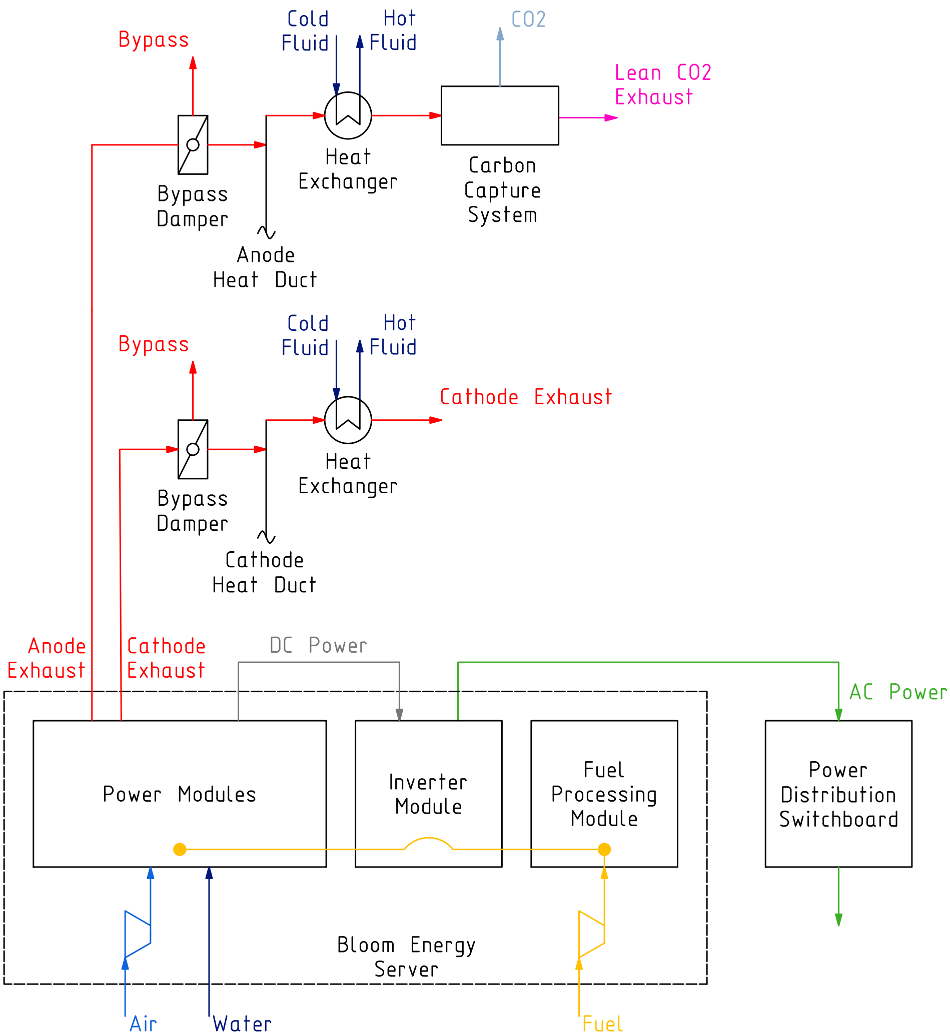


Figure 4.6: Case 2b: Bloom Energy's system coupled with hot water production and CC.

emission reduction due to the avoidance of natural gas consumption.

$$E_{CO_2,net} = (1 - \eta_{CO_2}) \cdot E_{CO_2,gross} - \frac{\dot{Q}_{\text{water}}}{\eta_{\text{boiler}}} \cdot f_{\text{boiler}} \tag{4.82}$$

Conversely, upstream emissions are reduced in the same fashion as Case 2a, as the CC system's change is already manifested in the change in the gross emissions by the modification of the total energy demanded by the system:

$$E_{\text{upstream}} = f_{\text{upstream}} \cdot W_{\text{fuel}} - f_{NG} \cdot \left(\frac{Q_{\text{water}}}{\eta_{\text{boiler}}} \right) \tag{4.83}$$

Following the approach presented in Case 2a, a natural gas boiler with 90% efficiency (η_{boiler}) and a CO_2 emission factor f_{boiler} of 233,6 g/kWh (Casasso et al., 2019) were considered.

For the rest of the pollutants, the methodology applied is equal to the one presented for Case 2a, considering that no additional pollutants are captured by the CC system.

Economic Modeling Methodology

As for the analyses presented before, the same considerations regarding Case 2a are valid. The general economic model developed remained the same as the one described apply, but for Case 2b, the addition of the CC system in the economic structure of the project was included with the same values employed for Case 1b (Table 4.13).

Table 4.13: Summary of Components considered for the BEC in Case 1a.

Component	Description
Bloom Energy equipment	PES, WDMs, Telemetry Cabinets, SLs, MCs, BMs, Installation kits for fuel cells, and Microgrid kits for fuel cells.
Heat Exchangers	Equipment to transfer exhaust heat to water.
Pump	Component used to pump water through the heat exchanger.
CC System	Full Carbon Capture system.
Auxiliaries	All major-non Bloom equipment: pumps, tanks, switchgear, transformers, etc.

4.3 Competitors' System Descriptions and Modeling Methodologies

Following the modeling framework established for *Bloom Energy* systems, the methodology used to assess the performance of competing grids and on-site generation solutions for Data Center applications is presented. The modeling approach for each alternative follows the technical, economic and environmental base parameters described for the Bloom cases to enable a robust benchmarking against them. These include fuel and carbon prices, fuel properties, interest and exchange rates, and opportunity costs. Next, each technology pathway is analyzed individually, beginning with the regional characteristics of the electricity grid, and following with on-site power solutions.

4.3.1 Grid

Five different Grid locations were considered for benchmarking: the EU-average case, Germany, the UK, Ireland and Italy. Table 4.14 presents a comparative overview of key parameters relevant to grid-based electricity supply across these selected European regions. It includes both infrastructure and environmental dimensions critical for the modeling. Specifically, the table details queue times for grid connection, modeled time-to-power , electricity prices in the first half of 2024, emissions intensity, and availability metrics.

The data highlights notable regional disparities in both cost and environmental performance. Electricity prices vary widely, with the UK showing the highest rate at 287,2 $/MWh, nearly double that of the EU-27 average. Germany faces longer queue times, while Ireland's grid access is effectively paused until 2030. Emission intensities for CO_2e and air pollutants such as NO_x and SO_x are also unevenly distributed, with Germany exhibiting the highest CO_2e output, while Italy shows relatively low emissions across all categories. Grid availability remains consistently high across all countries, exceeding 99,99%, indicating a generally reliable supply once access is granted.

4.3.2 Gas Turbines

The modeled system is based on an aero-derivative Gas Turbine operating in a simple cycle configuration, incorporating a 2N redundancy design—standard in the industry for on-site Gas Turbine power supply, according to *Bloom Energy*.

A wide array of Gas Turbines is available on the market, but not all are well-suited to Data Center applications. *Bloom Energy* has identified the specific models present in Table 4.15 as the main competitors, and the resulting average values found for these models regarding efficiencies, ramp rates and turn down limits were used for the benchmarking. While the power outputs and ramp rates vary significantly among the models, their efficiencies fall within a narrow range, from 35% to 41,3%.

Table 4.14: Parameters for Grid modeling by location. M. T-to-P refers to Modeled Time-to-Power.

Parameter	Unit	EU-27	Germany	UK	Ireland	Italy
Queue Time	years	-	Up to 7[1]; 3–5 in Frankfurt[2]	5–7[1]; 5–10[3]	Paused until 2030[1]	< 3[1]
M. T-to-P	months	36	48	90	60	36
Price	$/MWh	146,1[4]	203,6[4]	287,2[5]	207,7[4]	157,9[4]
Emissions						
CO_2e	kg/MWh	210[6]	329[6]	207[7]	260[6]	225[6]
NO_x	kg/MWh	0,27[8]	0,41[8]	0,23[9]	0,24[8]	0,103[8]
SO_x	kg/MWh	0,16[8]	0,20[8]	0,10[9]	0,059[8]	0,026[8]
VOCs	kg/MWh	0,020[8]	0,014[8]	0,013[9]	0,010[8]	0,010[8]
CO	kg/MWh	0,206[8]	0,182[8]	0,113[10]	0,371[8]	0,078[8]
PM2.5	kg/MWh	0,011[11]	0,008[11]	0,004[9]	0,014[11]	0,001[11]
Water Consumption	kg/MWh	5610[12]	2124[12]	1301[12]	1578[12]	5523[12]
Availability	%	-	99,9976[13]	99,9945[13]	99,9992[13]	99,9999[13]

[1] IEA (2025a).
[2] Milanesi et al. (2025).
[3] Skidmore (2025).
[4] Prices are H1-2024 for large industrial consumers and include all taxes according to Eurostat (2025b).
[5] Prices are H1-2024 for large industrial consumers and include all taxes according to UK Government (2025b).
[6] EEA (2025a).
[7] ITP (2025).
[8] Calculated using the total emissions of the energy sector of the country according to EEA (2024a) and its total energy supply (IEA, 2025f).
[9] Same approach as 8 but using emissions data from NAEI (2023).
[10] Same approach as 8 but using emissions from ONS (2024).
[11] Same approach as 8 but using emissions from EEA (2024b).
[12] Approximated from water consumption factors reported by Vanham et al. (2019) and respective electricity mixes reported by IEA (2025f).
[13] Calculated using the average annual interruption duration per customer (SAIDI). Data taken from Bundesnetzagentur (2023), UK Power Networks (2023), EirGrid (2023) and Terna (2022) for Germany, UK, Ireland and Italy, respectively.

Moreover, most models have relatively high turn-down limits driven by emissions compliance, making operation below 50% capacity infeasible in many cases.

Table 4.15: Main Gas Turbine competitors identified.

OEM	Model	ISO Gross Output [MW]	Efficiency (LHV)	Ramp Rate [%/min]	Emissions Turn Down Limits	Source
GE	9F.04	288	38,7%	8%	35%	(GE Vernova, 2025c)
GE	6F.03	88	36,8%	17%	-	(GE Vernova, 2025a)
GE	7F.05	239	38,5%	25%	35%	(GE Vernova, 2025b)
GE	LM2500+G4DLE	33,6	38,4%	15%	30%	(GE Vernova, 2019a)
GE	LM6000PF+	58	41,3%	6%	-	(GE Vernova, 2019b)
MHI	M501F	185,4	37,0%	86%	75%	(Mitsubishi, 2025)
Siemens	SGT6-5000F	260	40,0%	60%	30%	(Siemens Energy, 2025)
Solar Turbines	SMT130	16	35,4%	-	-	(Caterpillar, 2025)

Additional technical, environmental, and economic modeling parameters are detailed in Table 4.16. For the environmental impact of the systems, the same pollutants as for Bloom systems were considered, with the GT system presenting no emission abatement technologies. Emission factors were derived from EPA (2025), based on a heat rate assumption for aero-derivative turbines reported by EIA (2024b).

The economic modeling of the system was developed employing values outlined by Kost et al. (2024), using the same fuel and carbon prices considered for the *Bloom Energy* cases. As for the rest of the cases, two types of levelised costs were considered: one considering an instant deployment and another one considering the opportunity costs stemming from the lease of the Data Center during the time-to-power differential with the grid. A reference delivery time of 7,5 years was adopted, corresponding to the midpoint of the 7–8 year range reported by Dale (2025). An additional 5 months for installation and commissioning, as noted by (GE Vernova, 2025f) for a GE LM6000 GT, was included to estimate the total system time-to-power.

Table 4.16: Data used to model the GT system.

Variable	Unit	Value	Note
Global			
Natural Gas Price	USD/MWh	Table 4.6	Location dependent
Hydrogen Price	USD/MWh	Table 4.7	Location dependent
Carbon Price	USD/Ton	70,1	2024 average (ICAP, 2024)
Interest Rate	%	4%	Estimated EU average for 2025 (European Central Bank, 2025)
Conversion Rate	USD/EUR	1,1	Assumption based on historical data.
	USD/GBP	1,3	Assumption based on historical data.
Performance			
Electrical Efficiency	-	38%	Identified competitors average.
Total Efficiency	-		Identified competitors average.
Part-Load Efficiency	-	29%	Bloom energy's internal assessments
Ramp Rate	%	31%	Identified competitors average.
Operation			
Lifespan	years	30	(Kost et al., 2024)
Turn Down Limits	%	31%	Identified competitors average.
Availability	%	98,2%	(Gas Turbine World, 2023)
Redundancy	-	2N	Typical requirement for Data Center applications as suggested by Bloom.
Sustainability			
Direct Emissions			
CO2e	kg /MWhe	471,4	Uncontrolled emission factors reported by EPA (2025) assuming 9447 MMBTU/kWh based on EIA (2024b).
NO_x	kg /MWhe	1,37	Uncontrolled emission factors reported by EPA (2025) assuming 9447 MMBTU/kWh based on EIA (2024b).
SO_x	kg /MWhe	0,015	Idem NO_x.
CO	kg/MWh	0,351	Idem NO_x

CH_4	kg/MWh	1,106	Idem NO_x
VOCs	kg /MWhe	0,009	Idem NO_x.
UHC	kg/MWh	0,084	Approximated as total hydrocarbon plus methane emissions according to EPA (2025)
PM2.5	kg/MWh	0,0017	Idem NO_x
Noise	dBA	85	(GE Vernova, 2019a)
Water Consumption	l/MWhe	138,2	Maximum considering NO_x Water Control according to GE Vernova (2025g)
Land Use Intensity	m^2/MW	46,9	(Gas Turbine World, 2023)
Economics			
CAPEX	USD/kWe	770	(Kost et al., 2024)
Fixed OPEX	USD/kWe year	25,3	(Kost et al., 2024)
Non-fuel Variable OPEX	USD/MWhe	4,4	(Kost et al., 2024)
Installation			
Delivery time	months	84-96	(Dale, 2025)
Installation and Commissioning	months	5	Based on GE Vernova (2025f) for a GE LM6000
Time-to-power	months	89-101	

4.3.3 Combined Cycle Power Plants

This case involves a combined-cycle power plant, where natural gas is combusted in a Gas Turbine to generate electricity. Instead of being vented, the hot exhaust gases are utilized to produce steam, which drives a steam turbine to generate additional power. While post-steam-cycle heat recovery for non-electrical uses is technically feasible, it was excluded from the scope of this project.

Table 4.17 summarizes the parameters used to model the CCGT system. Electrical efficiency values were sourced from Kost et al. (2024), with total and part-load efficiencies derived from Diezinger et al. (2024) and Li et al. (2020), respectively. On the other hand, the ramp rate was considered equal to the identified competitors average[11].

Operationally, a 30-year lifespan was assumed based on Kost et al. (2024), along with an availability of 95% (Najjar & Abu-Shamleh, 2020). A 2N redundancy configuration was used, following recommendations from *Bloom Energy* based on common industry practices.

Emission parameters, conversely, were calculated from EPA (2025) employing the reference heat rate reported by EIA (2024b), while water consumption and land use intensity were obtained from EIA (2023) and Nøland et al. (2022), respectively.

Finally, delivery time was assumed to be equivalent to that of Gas Turbines, recognizing the Gas Turbine component as the primary bottleneck in the CCGT system. The only difference between these two cases regarding Time-to-Power is the installation and commissioning period. For the CCGT, one of 18 months was assumed based on typical industry timelines suggested by *Bloom Energy*.

[11] That is, turbines presented in Table 4.15 operating in a combined cycle.

Table 4.17: Data used to model the CCGT system.

Variable	Unit	Value	Note
Global			
Natural Gas Price	USD/MWh	Table 4.6	Location dependent
Hydrogen Price	USD/MWh	Table 4.7	Location dependent
Carbon Price	USD/Ton	70,1	2024 average (ICAP, 2024)
Interest Rate	%	4%	Estimated EU average for 2025 (European Central Bank, 2025)
Conversion Rate	USD/EUR	1,1	Assumption based on historical data.
	USD/GBP	1,3	Assumption based on historical data.
Performance			
Electrical Efficiency	-	60%	(Kost et al., 2024)
Total Efficiency	%	75–85%	(Diezinger et al., 2024)
Part-Load Efficiency	-	51%	(Li et al., 2020)
Ramp Rate	%	30%	Identified competitors average in Combined Cycle application
Operation			
Lifespan	years	30	(Kost et al., 2024)
Turn Down Limits	%	48%	Identified competitors average in Combined Cycle application
Availability	%	95%	(Najjar & Abu-Shamleh, 2020)
Redundancy	-	2N	Typical requirement for Data Center applications as suggested by Bloom
Sustainability			
Direct Emissions			
CO2e	kg/MWhe	312,7	Uncontrolled emission factors reported by EPA (2025) assuming 6266 MMBTU/kWh based on EIA (2024b)
NO_x	kg/MWhe	0,91	Uncontrolled emission factors reported by EPA (2025) assuming 6266 MMBTU/kWh based on EIA (2024b)
SO_x	kg/MWhe	0,01	Idem NO_x
CO	kg/MWh	0,233	Idem NO_x
CH_4	kg/MWh	0,733	Idem NO_x
VOCs	kg /MWhe	0,006	Idem NO_x
UHC	kg/MWh	0,1	Approximated as total hydrocarbon plus methane emissions according to EPA (2025)
PM2.5	kg/MWh	0,0011	Idem NO_x
Noise	dBA	85	Assumed as GT noise (GE Vernova, 2019a)
Water Consumption	l/MWhe	10595	(EIA, 2023)
Land Use Intensity	m^2/MW	370,9	(Nøland et al., 2022)
Economics			
CAPEX	USD/kWe	1430	(Kost et al., 2024)
Fixed OPEX	USD/kWe year	5,5	(Kost et al., 2024)

Non-fuel Variable OPEX	USD/MWhe	22	(Kost et al., 2024)
Installation			
Delivery time	months	84-96	Considered same as GT (Dale, 2025)
Installation and Commissioning	months	18	Assumption based on industry standards
Time-to-power	months	102-114	

4.3.4 Gas Reciprocating Internal Combustion Engines

Finally, gas-fueled Reciprocating Internal Combustion Engines were considered as the last on-site power solution for the application. As for the Gas Turbine case, the efficiency, ramp rate and turn down limits to comply with emissions were taken from some of the main RICE competitors identified by *Bloom Energy* (Table 4.18).

Table 4.18: Main Gas Reciprocating Engine competitors identified.

OEM	Model	ISO Gross Output [MW]	Efficiency (LHV)	Ramp Rate [% /min]	Emissions Turndown Limits	Source
Jenbacher	J620	3,3	43,1%	200%	10%	(Jenbacher, 2025)
Wärtsilä	18V50SG	18,434	50,2%	100%	10%	(Wartsila, 2022)
Wärtsilä	34SG	9,795	48,9%	100%	10%	(Wartsila, 2025a)

The parameters used for modeling the engines are presented in Table 4.19. Here, apart from efficiency, ramp rate and turn down limits, which are competitors' averages, the rest of the values are literature based or assumed. That is the case for lifespan and availability, which were taken from Lazard (2015) and GE Vernova (2025d), and for the 2N redundancy considered, a suggestion by *Bloom Energy* based on industry standards. As for Gas Turbines, the emission factors were calculated based on EPA (2025) using a heat rate of 8000 MMBTU/kWh as reported by Lazard (2015).

For the economic parameters, some adjustments had to be made. Given that the used values for CAPEX and OPEX were for 2015, an adaptation to current prices had to be done. Thus, the Harmonized Index of Consumer Prices (HICP) was used taken the EU-27 averages for simplification for all cases (Eurostat, 2025d):

$$\mathrm{COST}_{i.2025} = \mathrm{COST}_{i.2015} \cdot \frac{\mathrm{HICP}_{2025}}{\mathrm{HICP}_{2015}} = 129,7 \cdot \mathrm{COST}_{i.2015} \tag{4.84}$$

For the inclusion of the Time-to-Power consideration on the LCOE, a total of 13-20 months for delivery, installation and commissioning was considered based on Larson (2020).

Table 4.19: Data used to model the RICE system.

Variable	Unit	Value	Note
Global			
Natural Gas Price	USD/MWh	Table 4.6	Location dependent
Hydrogen Price	USD/MWh	Table 4.7	Location dependent
Carbon Price	USD/Ton	70,1	2024 average (ICAP, 2024)
Interest Rate	%	4%	Estimated EU average for 2025 (European Central Bank, 2025)
Conversion Rate	USD/EUR	1,1	Assumption based on historical data.

	USD/GBP	1,3	Assumption based on historical data.
Performance			
Electrical Efficiency	-	47%	Identified competitors average
Total Efficiency	%	47%	Identified competitors average
Part-Load Efficiency	-	41%	Bloom energy's internal assessments
Ramp Rate	%	133%	Identified competitors average
Operation			
Lifespan	years	20	(Lazard, 2015)
Turn Down Limits	%	10%	Identified competitors average.
Availability	%	93%	(GE Vernova, 2025d)
Redundancy	-	2N	Typical requirement for Data Center applications as suggested by Bloom.
Sustainability			
Direct Emissions			
CO2e	kg /MWhe	399,2	Uncontrolled emission factors reported by EPA (2025) assuming 8000 MMBTU/kWh based on Lazard (2015).
NO_x	kg /MWhe	11,5	Uncontrolled emission factors reported by EPA (2025) assuming 8000 MMBTU/kWh based on Lazard (2015).
SO_x	kg /MWhe	0,002	Idem NO_x.
CO	kg/MWh	1,150	Idem NO_x
CH_4	kg/MWh	136,080	Idem NO_x
VOCs	kg /MWhe	0,4	Idem NO_x.
UHC	kg/MWh	9,870	Approximated as total hydrocarbon plus methane emissions according to EPA (2025)
PM2.5	kg/MWh	0,0003	Idem NO_x
Noise	dBA	101	(GE Jenbacher, 2025)
Water Consumption	l/MWhe	0,39	(Wartsila, 2025b)
Land Use Intensity	m^2/MW	52,6	(Wartsila, 2014)
Economics			
CAPEX	USD/kWe	2013,1	(Lazard, 2015)
Fixed OPEX	USD/kWe year	22,7	(Lazard, 2015)
Non-fuel Variable OPEX	USD/MWhe	16,2	(Lazard, 2015)
Installation			
Delivery time	months	12-18	(Larson, 2020)
Installation and Commissioning	months	1-2	(Larson, 2020)
Time-to-power	months	13-20	

4.4 Results and Discussion

Next, the performance of the proposed Bloom SOFC configurations is evaluated across three complementary dimensions—technical, environmental, and economic—following the methodology outlined above, and compared with the identified competitors. For conciseness, only representative graphs are sometimes shown when multiple locations are compared. However, all plotted outputs and detailed numerical results are provided in Appendix D. Each of the three dimensions opens with a concise set of key takeaways, and is followed by a full discussion of results. A sensitivity and scenario analysis is then developed to assess robustness and explore how results evolve under varying assumptions. Finally, a comparative summary brings together the technical, environmental, and economic findings, while a comprehensive table of every numerical outcome is available in the annex Appendix C.

4.4.1 Technical Results

Main Takeaways

1. Powering a 100 MW Data Center can result in over 50 MW of Heat Power surplus in Bloom CHP cases without Carbon Capture. Adding Carbon Capture results in parasitic losses in the order of 10%, but this also represents 5,1 MW of extra heat power available.
2. *Bloom Energy*'s electrical efficiencies of 54% are superior to competitor's except for CCGTs, whose efficiencies are a close match to Bloom's.
3. CHP cases drive the total efficiency to over 80%, while Carbon Capture diminishes the net electrical efficiency to around 49%. The combination of the two yields a total efficiency of 77%.
4. Bloom's SOFC systems result in 41% fuel savings vs Gas Turbines and 14% vs RICE, while CCGTs were found to consume 11% less. Bloom's CHP systems result in fuel savings in the order of 13-24% when compared to CCGT systems dedicated only to electricity generation, depending on the presence of carbon capture.
5. *Bloom Energy* has a significantly strong ramp rate advantage against competitors, with only some RICE models matching their 120% offering.
6. Bloom's 20-year guaranteed availability of 99,9% largely outcompetes alternative on-site solutions, but stands below the grid availabilities found through reported SAIDI values.
7. Turndown limits for emissions compliance among Bloom's identified competitors typically lie in the range of 30-50% for Gas Turbines, with some models even reaching 75%, and 10% for RICE. Bloom does not present an emissions turndown limit. However, operation below 30% for these systems is not possible due to operational reasons.

Power Output

The power output of the different systems is dependent on the configuration. Cases without carbon capture present net electric power consumptions equal to the power demand of the Data Center under the developed models, independently of the fuel. Moreover, if no heat capture is present, the total power output matches the net electric power output. However, this changes in CHP cases.

Powering a 100 MW Data Center load can result in over 50 MW of Heat Power surplus in Bloom CHP cases without Carbon Capture (Figure 4.7). This translates in 112,5-142,7 kg/s of 90 °C water produced assuming an initial temperature of 0°C and a heat exchanger efficiency of 90%. Considering carbon capture, power demand increases by 10 MW due to the requirements of the additional systems, resulting also in extra 5,1 MW heat available when CHP is present. That is, up to 148 kg/s of hot water with the previously stated assumptions can be produced on an average scenario.

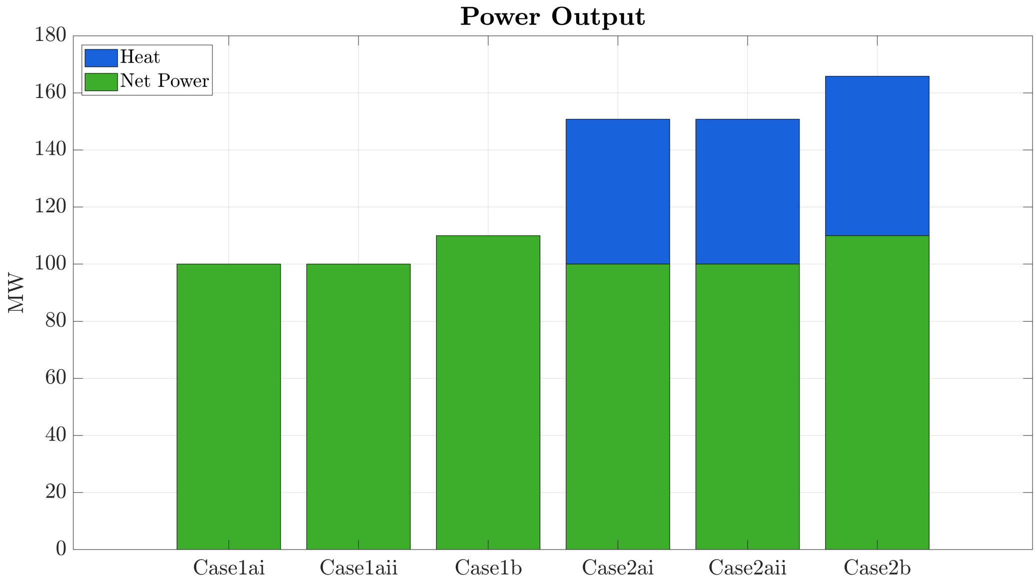


Figure 4.7: Heat and electric power outputs of the different configurations.

System Efficiencies

The above mentioned power consumption profiles for the different systems generate differences in the efficiencies observed. While the electrical efficiencies are equal 54% for all of Bloom systems, net electrical ones are not. The strong energy penalty present in the cases with CC case a decrease in the net-electric efficiencies of those systems. While for cases without it the electric and net-electric efficiencies are equal to 54%, with the addition of carbon capture the electric efficiencies of the systems go down to 49%. It is observed that electrical efficiencies notably surpass those of GT and RICE and are a close match to CCGT. This represents a conservative scenario, as it is making use of the minimum guaranteed average 20-year efficiency for Bloom systems. Considering Bloom's maximum efficiency of 65% (Bloom Energy, 2024a), electrical efficiencies almost surpass most CCGT plants.

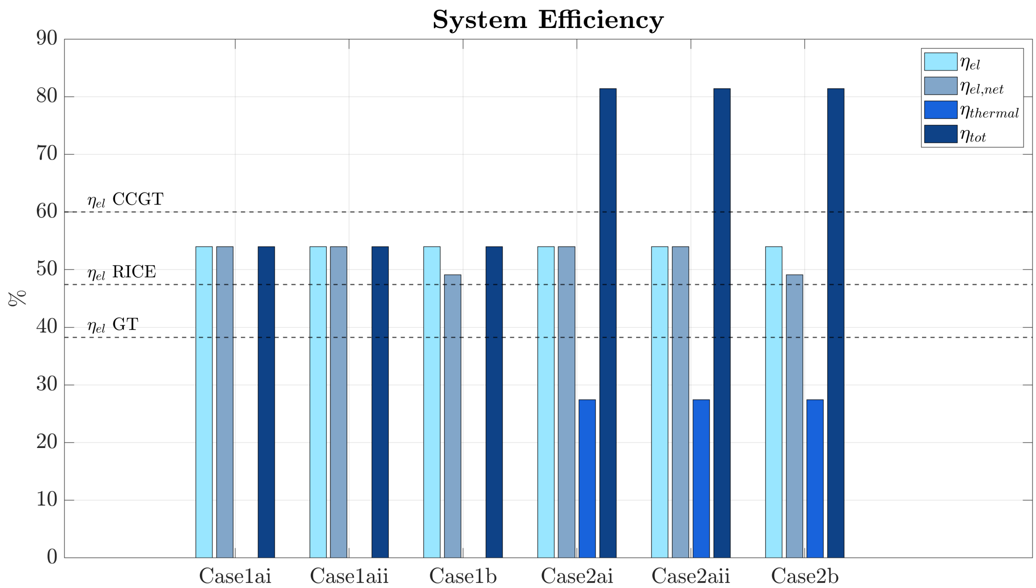


Figure 4.8: Resulting efficiencies for the different configurations.

On the other hand, thermal efficiencies scratch the 30% values for CHP systems, giving these systems a total efficiency of over 80%. That means an increase in total efficiency of over 50%, translating into fuel savings for other processes.

It is worth noticing that the analysis developed are static and considered at nominal power outputs. If dynamic simulations based on real Data Center load profiles or even static simulations outside of the nominal operation point were to be developed, it is expected that these results would change significantly. Under these scenarios, Bloom's systems could present an advantage due to their flatter efficiency curves when compared to the traditional fossil fuel generators analyzed. While Bloom presents a part-load efficiency of 53% at 50% load, according to *Bloom Energy*'s internal assessments, for RICE this number goes down to 51% and for Gas Turbines to 29%. CCGTs, on the other hand, also show efficiencies as low as 51% as well, according to Li et al. (2020).

Fuel Consumption

The different efficiencies bring about different fuel consumption patterns. As Figure 4.9 illustrates, for Bloom Natural Gas systems without CHP, fuel consumption is significantly lower than for Gas Turbines and Reciprocating Engines, being a close match to CCGTs. While the SOFC systems result in 41% fuel savings vs Gas Turbines and 14% vs RICE, CCGTs were found to consume 11% less than Bloom. CHP cases bring about a significant net fuel consumption reduction, reaching annual avoidance values of 100 Mm^3 for Natural Gas and 130 Mm^3 for Hydrogen, now being the fuel consumption of this systems significantly inferior to competitors running on the same fuels. On these cases, Bloom's CHP systems result in fuel saving in the order of 11-19% when compared to CCGT systems dedicated only to electricity generation, depending on the presence of Carbon Capture. The energy penalty induced by these systems increases overall fuel consumption by around 10%.

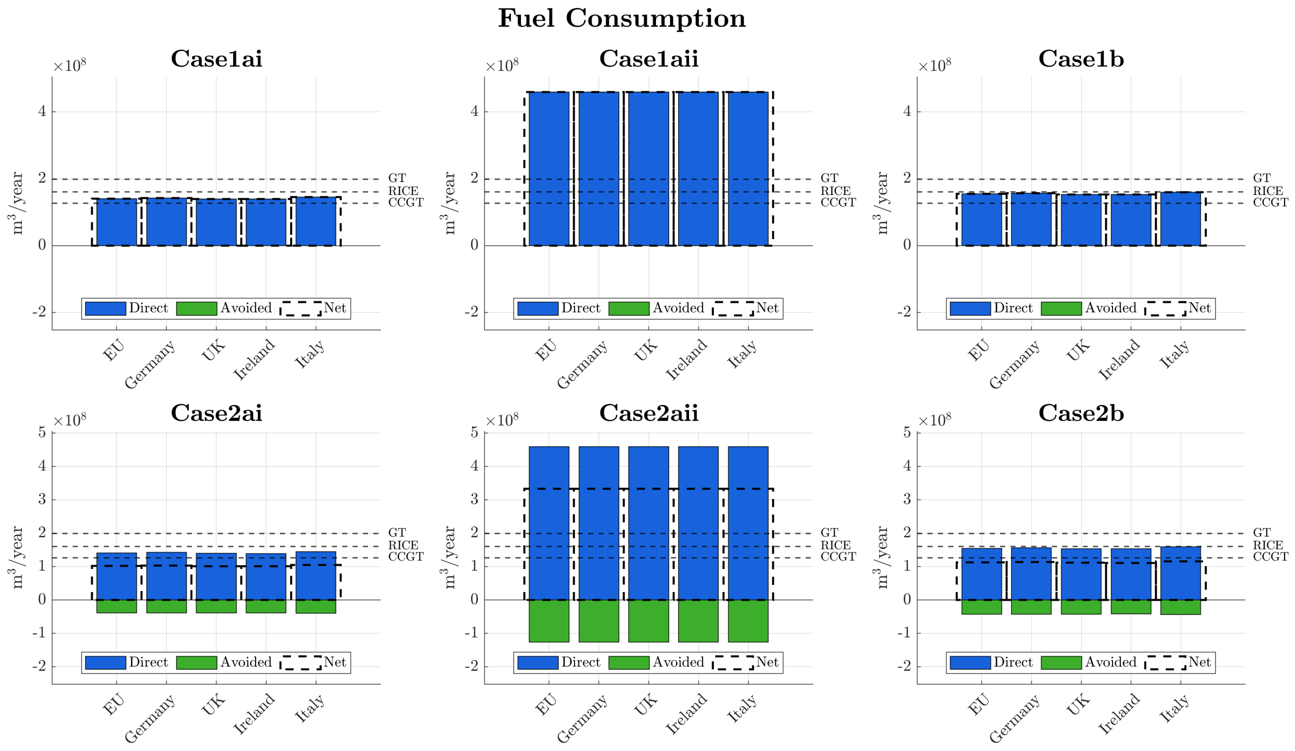


Figure 4.9: Volumetric fuel consumption of the different configurations.

It is important to note that the considerable increase in volumetric fuel consumption observed in Hydrogen cases when compared to Natural Gas ones is due to the differences in volumetric energy density of the fuels, and not to a difference in the efficiency of the systems.

Ramp Rate

Ramp rate is becoming an increasingly essential parameter for AI Data Center applications given the rapid load variations these can present. In this category, *Bloom Energy* has a very strong advantage against competitors (Figure 4.10). Bloom's ramp rate quadruples the average of the main Gas Turbines competitors identified both on simple and combined cycles, and is bigger than most RICE competitors. While competitor GTs present ramp rates of 8-86% and 5-65% for simple and combined cycles, Bloom presents one of of 120 %/min. Moreover, out of the main RICE competitors, the *Jenbacher J620* is the only one surpassing Bloom in ramp rate, with a value of 200%. All the other competitors analyzed stand at or below 100%, being considerably below Bloom's capabilities.

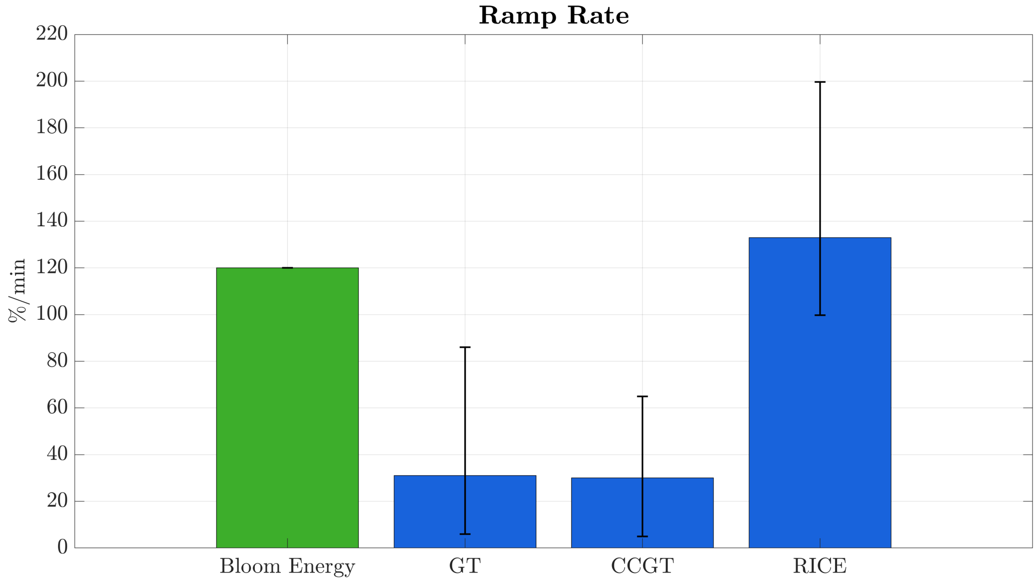


Figure 4.10: Ramp rates of Bloom and competitor power systems.

Turndown Limits

Regarding the turndown limits, it was found that competitor Gas Turbines have a typical maximum turndown limit to comply with emission regulations in the low 30-50% range operating in simple cycle and in the high 35-50% in combined one for the models analyzed[12], while RICE have one of 10%. Bloom does not have an emissions turndown limit, being able to operate until 0% in that regard. However, due to operational reasons, operation below 30% of nominal load is not possible.

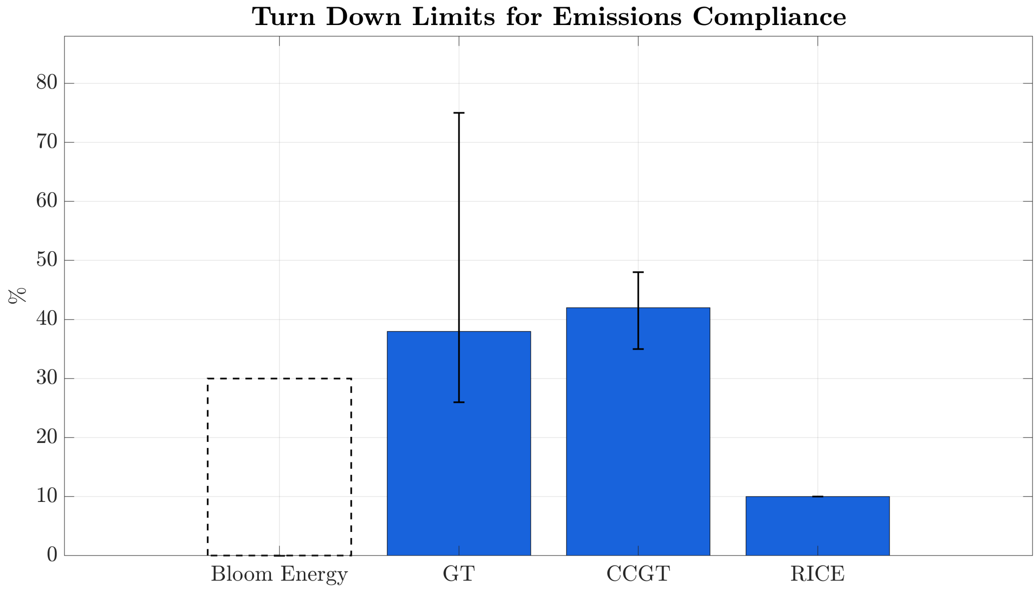


Figure 4.11: Turndown limits for Bloom and competitor power systems. Simple Cycle Gas Turbines' average does not considered the 75% value for the Mitsubishi M501F.

Surprisingly, finding turndown limits for Gas Turbines was not as simple and straightforward as expected, even failing to find values for some models in online specifications. A more thorough study in this regard could benefit from a more detailed search and/or a direct contact with the manufacturers.

[12]Note that the Mitsubishi M501F has a turndown limit of 75% operating in simple cycle, being the only one outside the mentioned range.

Availability

The availability of Bloom systems is highly superior to that of on-site competitors: while RICE presents one of 93%, CCGTs one of 95% and GTs one of around 98%[13], Bloom's guaranteed availability over a 20-year period stands above 99,9%. However, all these values stand below of those presented by all grids studied: the German, British, Irish and Italian grids present availabilities of over 99,99% when calculated using reported SAIDI values.

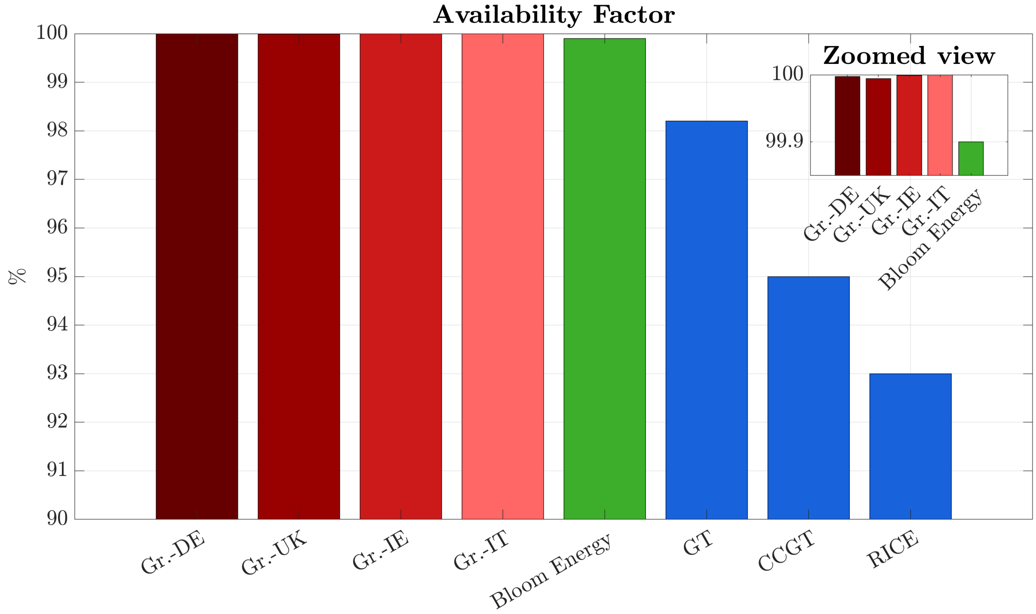


Figure 4.12: Availability for Bloom and competitor power systems.

4.4.2 Environmental Results

Main Takeaways

1. Bloom's baseline Natural Gas systems emit up to 255,4 kTon CO_2/year without CC, while CHP + CC cases reach -117,1 kTon/year of net direct emissions.
2. Conventional on-site systems emit 351–398 kTon CO_2/year, while EU grids range from 154–245 kTon/year depending on the country.
3. All Bloom configurations presents non-carbon emissions such as NOx, SOx, CO, CH_4, VOCs and UHC orders of magnitude below of all power alternatives studied.
4. Water intensity for Bloom is under 4 l/MWh, far below CCGTs (>10.000 l/MWh) and grid averages (1.500–5.600 l/MWh).
5. Land intensity per MWh is lowest for Bloom, especially with system stacking, outperforming all competitors even at single-level deployment.

CO_2 Emissions

The carbon emissions analysis shows that in Bloom cases without carbon capture, the direct CO_2 emissions are substantial for Natural Gas, reaching 255,4 kTon/year, whereas for Hydrogen it results in negligible direct emissions due to its carbon-free electro-chemical conversion. The introduction of carbon capture dramatically reduces net direct emissions, as reflected by the net direct values approaching zero or becoming negative in CHP cases: in Case 2b, the combined effects of CHP and

[13]Note that experts in the Gas Turbine field commented that this is a highly optimistic value.

carbon capture yield a net direct emission of -117,1 kTon/year, highlighting the system's potential for net negative carbon footprint when having current heating practices as a baseline.

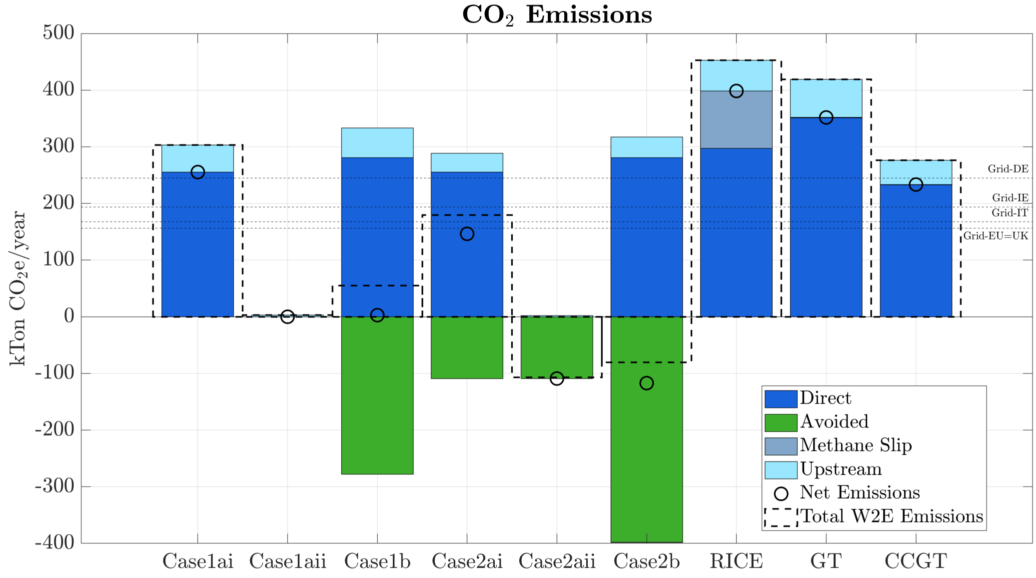


Figure 4.13: Carbon emissions of Bloom and competitor power systems.

Table 4.20: Carbon Emissions Summary for Bloom cases. All values expressed in kTon/year.

Bloom's CO_2 Emissions						
Type	**Case 1**			**Case 2**		
	i	ii	b	i	ii	b
Direct	255,4	0	280,9	255,4	0	280,9
Avoided	0	0	278,1	109,0	109,0	398,1
Net Direct	255,4	0	2,809	146,4	-109,0	-117,1
Upstream	47,65	3,171	52,42	33,14	2,205	36,45
Well-to-Energy	303,1	3,171	55,23	179,5	-106,8	-80,69

Table 4.21: Carbon Emissions Summary for Grid and On-site Emissions. All values expressed in kTon/year.

Competitors' CO_2 Emissions — Grid and On-site								
Type	**Grid**					**On-site**		
	EU	DE	UK	IE	IT	GT	CCGT	RICE
Direct	156,4	244,9	154,2	193,6	167,5	351,0	232,8	297,2
Avoided						0	0	0
Net Direct	156,4	244,9	154,2	193,6	167,5	351,8	233,3	398,5
Upstream						67,3	42,9	54,3
Well-to-Energy						419,1	276,2	452,8

Upstream emissions remain significant for natural gas-fueled cases, reaching over 67 kTon/year for Gas Turbines. The Well-to-Energy emissions, aggregating net direct and upstream contributions, further illustrate the impact of fuel and system configuration, with hydrogen-fueled cases showing markedly lower values (3,2 kTon/year in Case 1aii) compared to Natural Gas counterparts (303,1 kTon/year in Case 1ai). The avoided emissions component in Bloom's system configurations with CC emphasizes the role of CO_2 sequestration, which compensates for a large fraction of direct emissions and contributes to the overall emissions reduction.

In contrast, competitor grids and on-site generation technologies exhibit consistently higher direct and well-to-energy emissions. Grid emissions vary widely, reflecting regional grid carbon intensity, with Germany's grid showing direct emissions as high as 244,9 kTon/year, while Ireland's grid stands at 193,6 kTon/year. On-site fossil fuel technologies demonstrate the highest CO_2 emissions, with direct emissions peaking at 351 kTon/year for GT. The RICE case, while presenting less direct CO_2 emissions, the contribution of the substantial methane slip present, makes it the biggest polluter in CO_2e terms by a large margin.

A key insight from this comparison is the clear environmental advantage of Bloom when integrated with Carbon Capture, particularly in CHP configurations. These systems offer the potential not only to substantially reduce direct CO_2 emissions but also to mitigate upstream impacts through cleaner fuel use and improved system efficiency. However, it is crucial to acknowledge that hydrogen-fueled SOFC configurations already exhibit near-zero direct emissions, presenting a pathway for decarbonization that is less reliant on carbon capture infrastructure and minimizes upstream emissions as well. Moreover, the posterior uses and/or storage methods for the captured carbon dioxide highly determines the net-environmental effect that this technology has, requiring a specific analysis for each application case to evaluate the overall impact of the power systems.

Conversely, conventional fossil-fueled on-site power generation remains a significant source of CO_2 emissions, reinforcing the imperative for Data Centers to transition towards cleaner technologies such as SOFCs or renewable-based grid supply to meet sustainability goals.

Other Pollutants

Beyond CO_2 emissions, a thorough evaluation of local air pollutants provides further insight into the environmental performance of Bloom Energy's SOFC systems compared to conventional fossil-based technologies. The pollutants analyzed include NO_x, SO_x, CO, CH_4 (expressed in CO_2e), VOCs, UHCs, and $PM_{2.5}$, and are critical from a public health and air quality standpoint.

The results demonstrate that Bloom's SOFC systems, emit negligible amounts of air pollutants (Table 4.22). For example, NO_x emissions drop to zero in the Hydrogen cases and are already extremely low (around 745–801 kg/year) for natural gas-fueled SOFCs without carbon capture. Remarkably, cases with heat recovery exhibit negative NO_x, SO_x, CO, and VOC emissions, indicating a net avoidance effect.

Table 4.22: Air Pollutant Emissions for Bloom Cases. All values expressed in Ton/year, except CH_4 in kTon CO$_2$e/year.

Bloom's Pollutant Emissions						
Pollutant	**Case 1**			**Case 2**		
	ai	aii	b	ai	aii	b
NO_x	0,7446	0	0,8009	-98,86	-99,60	-106,3
SO_x	0,003425	0	0,003684	-0,7578	-0,7612	-0,8151
CO	3,723	0	4,004	-22,45	-26,17	-24,15
CH_4	0	0	0	-0,1345	-0,1345	-0,1445
VOCs	2,978	0	3,204	-1,504	-4,482	-1,618
UHC	2,978	0	3,204	-4,931	-7,909	-5,304
$PM_{2.5}$	0	0	0	-0,5919	-0,5919	-0,6367

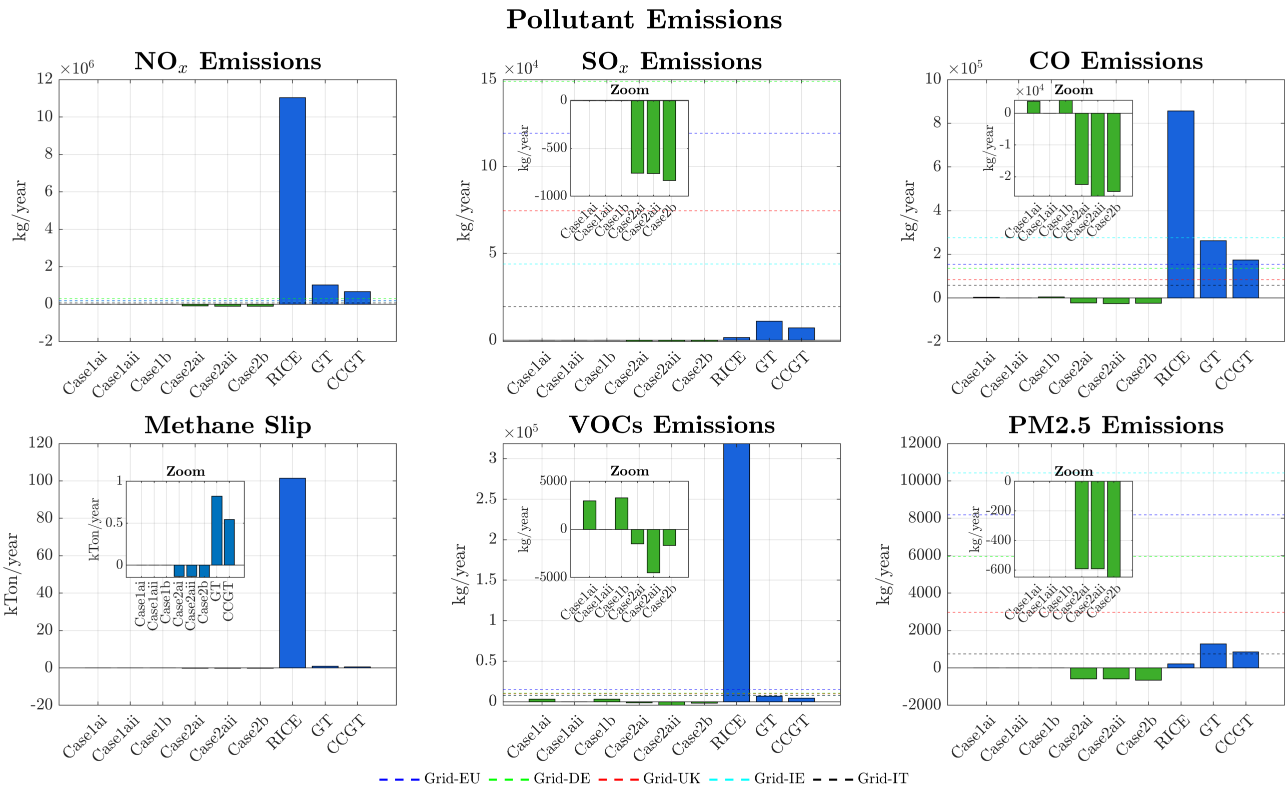


Figure 4.14: Non-CO2 pollutant emissions of Bloom and competitor power systems. Note that detailed graphs for each pollutant can be found in Appendix D.

In contrast, on-site competitors emit orders of magnitude more of every pollutant when no abatement systems are present (Table 4.23). RICE systems are particularly concerning, with emissions reaching over 11 million kg/year of NO_x, over 850.000 kg/year of CO, 7400 tons/year of UHCs, and almost 320.000 kg/year of VOCs. These figures illustrate the high environmental and health burden associated with combustion-based power generation in the Data Center context.

Table 4.23: Air Pollutant Emissions for Grid and On-site Sources. All values expressed in Ton/year except for methane, which is in kTon CO_2e/year.

Competitors' Pollutant Emissions — Grid and On-site Generators								
Pollutant	**Grid**					**On-site**		
	EU	DE	UK	IE	IT	GT	CCGT	RICE
NO_x	202,3	305,5	168,7	177,3	76,75	1.021	677,2	11.024
SO_x	121,9	146,9	74,04	43,66	19,66	10,85	7,196	1,589
CO	153,4	135,5	84,07	276,5	58,38	261,6	173,5	856,5
CH_4						0,823	0,546	101,3
VOCs	14,83	10,46	9,96	7,54	7,36	6,70	4,44	318,8
UHC						62,54	41,22	7.350
$PM_{2.5}$	8,364	5,877	2,771	10,37	0,88	1,28	0,847	0,21

CH_4 emissions, while negligible in all Bloom configurations, are considerable in conventional systems—especially RICE, which contributes over 100 kton CO_2e/year. This indicates not only significant climate impact but also suggests high inefficiencies within those systems.

Unburned hydrocarbons and fine particulate matter follow similar patterns. UHC and VOC emissions are nearly eliminated in SOFC configurations, while RICE once again emerges as a major emitter. $PM_{2.5}$ emissions are either null or net negative in Bloom cases, while on-site competitors contribute up to 1275 kg/year, further amplifying their environmental footprint.

Water Intensity

Water consumption for Bloom Systems is negligible compared to CCGT and grids considered: while this systems present water consumption levels at below 4 l/MWh, CCGTs require over 10.000 l/MWh and grids studied present consumption factors of between 1.500-5.600 l/MWh. When compared to simple Gas Turbines and Reciprocating Engines, some achieve comparable water consumption results depending on the specific pollutant control technologies used. Gas Turbines that use steam injection for NO_x control require around 140 l/MWh, while RICE with closed loop cooling systems values below 1 l/MWh.

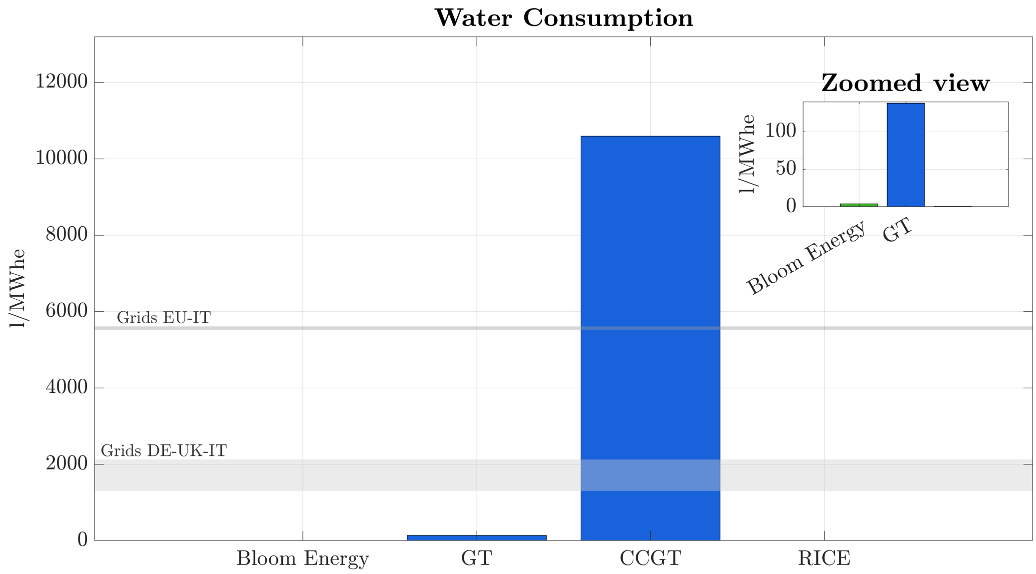


Figure 4.15: Water intensities of Bloom and competitor power systems.

Considering how water intensive the Data Center sector is, the major local water impact these facilities tend to have, and how scrutinized they are for this, low water consumption technologies present a notable advantage, and *Bloom Energy* presents an important edge in this regard.

Land Intensity

Bloom's land intensity per MW of capacity for no-stacked systems is comparable to those of GT and RICE and largely superior to CCGT, which requires significantly more land than competitors for an equal power capacity. However, with double or triple stacking, Bloom clearly outperforms all competitors.

Furthermore, when considering land intensity in energy terms, thus reflecting the differences in redundancy requirements for each, this becomes more evident: Bloom clearly outperform all competitors even with no-stacking. This is attributed to the higher reliability of these systems, which can operate with an extra capacity of 25% that fades in comparison with the 100% redundancy often used for competitor systems. Logically, considering stacking only magnifies this observed competitive advantage.

In an industry landscape where land availability and its costs represent a critical challenge, compact power solutions such as Bloom's stand in a very favorable position, especially in highly demanded markets such as FLAPD.

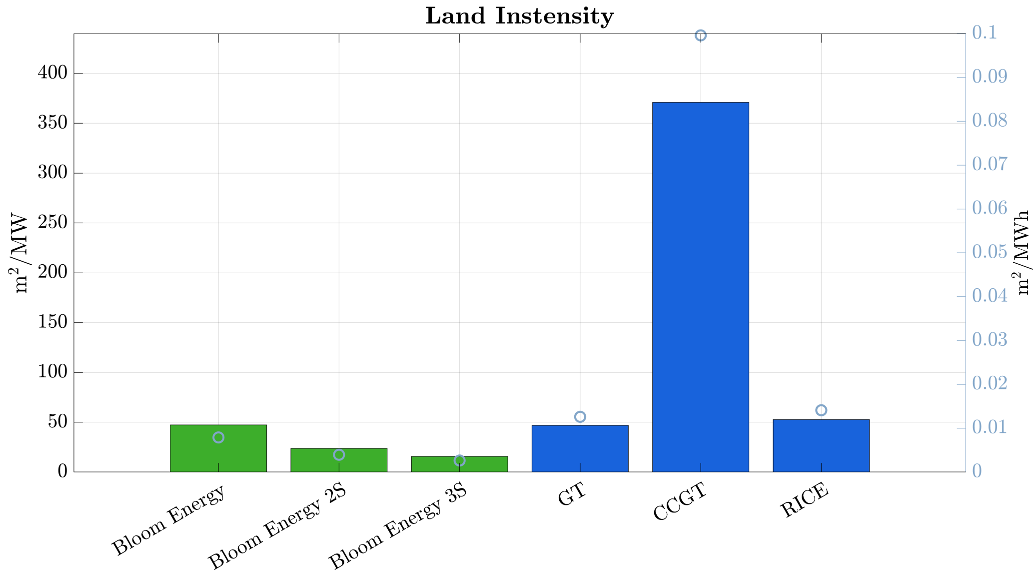


Figure 4.16: Land intensities of Bloom and competitor power systems. Note that this metric only encompasses electric power generation, not extra systems such as carbon or heat capture.

4.4.3 Economic Results

Main Takeaways

1. Bloom systems show high CAPEX, often representing over 80% of TASC, but offer predictable costs due to modular factory-built design.
2. OPEX is more stable and predictable for Bloom due to high fixed-cost share (30–60%), making it less sensitive to fuel price volatility.
3. NG-fueled Bloom systems have LCOEs of 215–260 $/MWh, which decrease by up to 45 $/MWh in CHP mode and remain competitive with most on-site options.
4. Hydrogen configurations nearly double the LCOE of Natural Gas ones.
5. Bloom's LCOE outcompetes RICE for virtualy all locations but remain more expensive than GTs and CCGTs. CCGT represent the cheapest on-site option (110–157 $/MWh), but it is only suitable for large-scale projects.
6. LCOE composition differs significantly: CAPEX dominates for Bloom in Natural Gas configurations (up to 40%), while OPEX leads in competitors.
7. Rapid deployment (<12 months) gives Bloom an edge in revenue-sensitive sectors like Data Centers, where grid delays and Gas Turbine lead times stretch into years.
8. When accounting for opportunity costs in time-to-power, Bloom's LCOE drops by up to 45%, undercutting RICE, GTs and CCGTs in all studied markets. Under this consideration Bloom's Natural Gas CHP options outperform the grid in the UK, Ireland, and Germany.

CAPEX

Bloom systems are significantly more expensive than competitors, even considering the significant advantage in redundancy requirements. Moreover, the CAPEX of Bloom systems represents a considerably large share of the total installation costs, as a major percentage of all the installation comes pre-mounted from the factory: according to the estimates developed in collaboration with the company, Bloom systems represent around 80% of the TASC (Figure 4.17). Even if initial investments in Bloom equipment are more significant, this also means that costs for these systems are more predictable, as most on-site requirements are avoided, along with all the cost uncertainties that comes with them. Furthermore, the company offers PPA schemes in which initial investment is minimized, building long term contracts for energy purchasing that avoid the large initial CAPEX requirements.

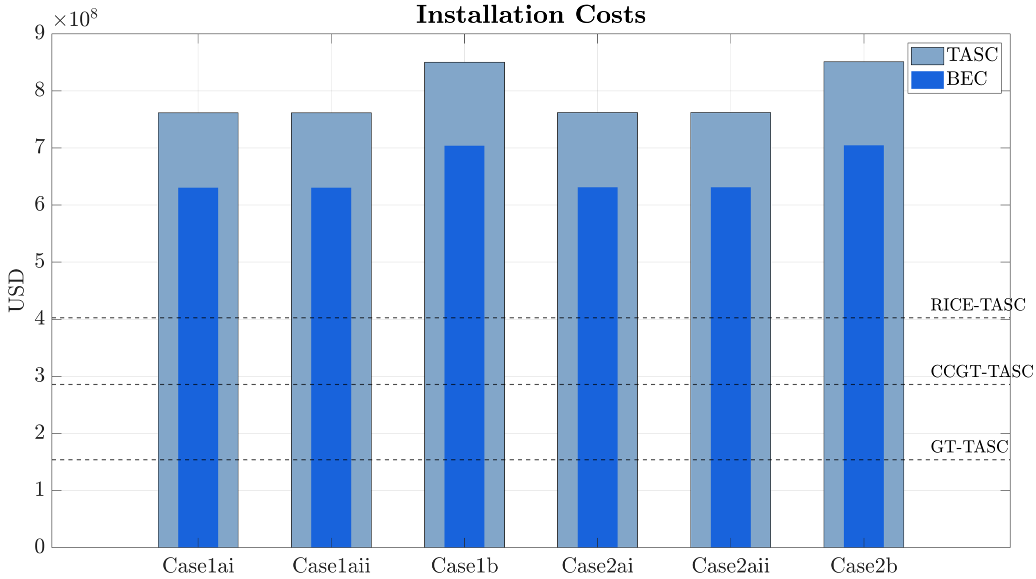


Figure 4.17: CAPEX for Bloom and competitor power systems.

OPEX

OPEX presents significantly different characteristics among the power systems. While for Bloom Natural Gas configurations, fixed OPEX represents a significant share of total OPEX (30-60%), for competitors, variable OPEX plays a bigger role due to the higher impact of fuel costs on the cost structure. This represents a significant advantage for Bloom's clients, offering greater predictability—an asset that becomes particularly valuable during fuel supply shocks, as will be explored later.

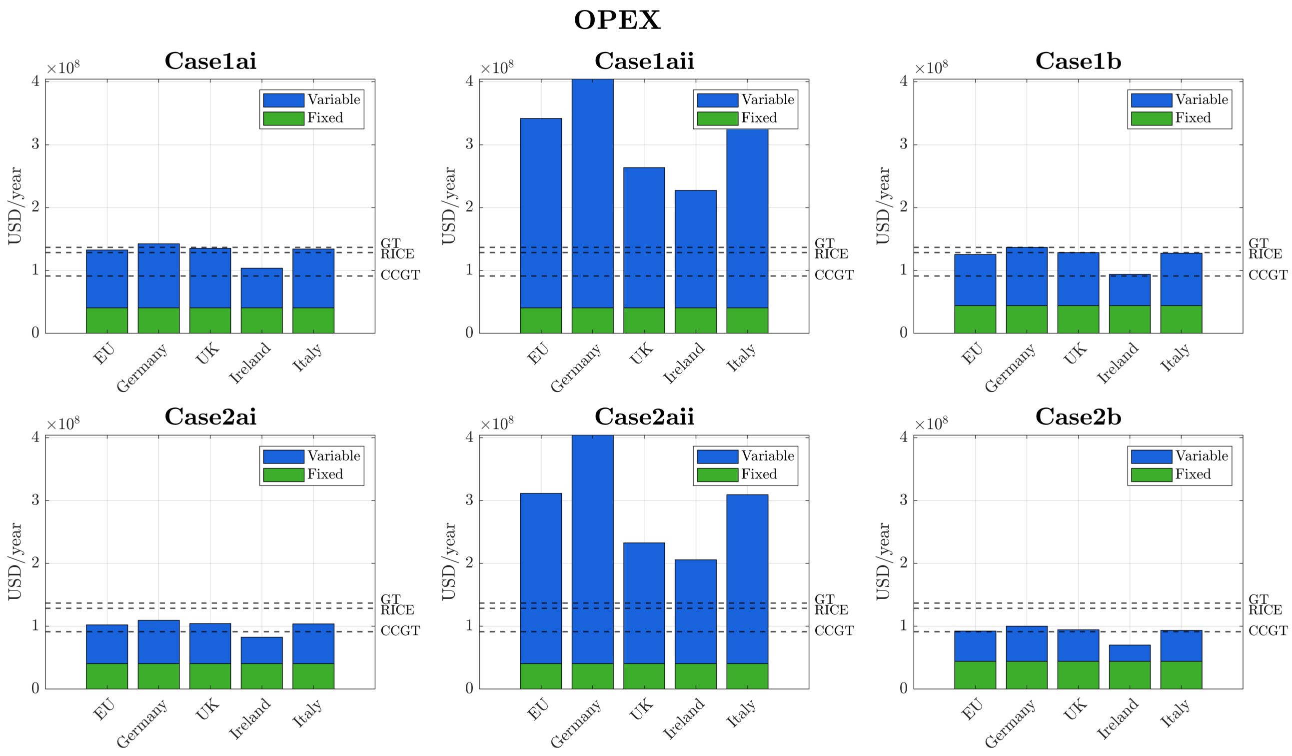


Figure 4.18: OPEX for Bloom and competitor power systems.

When fueled with natural gas, Bloom's OPEX is competitive with all on-site competitors. Moreover, with CHP systems, Bloom outperforms all competitors except CCGT. Meanwhile, Hydrogen systems' OPEX, double those of competitors. This fact is completely attributed to the current fuel price gap between this fuel and natural gas, which is expected to decrease in the future.

LCOE

Results show that across all regions, the simplest baseline Natural Gas Bloom layout yields LCOEs in the 215-270 $/MWh range. Adding post-combustion capture has almost no net effect, since the relatively small efficiency loss and CAPEX and OPEX contributions are balanced by avoided carbon costs. Switching that same layout to hydrogen nearly doubles the LCOE, reflecting high green-hydrogen prices despite similar conversion efficiency.

Moving to CHP with hot-water export cuts SOFC LCOEs by roughly 29–45 $/MWh compared to waste-heat, thanks to the value of useful heat. In that mode, carbon capture further contributes in the decrease of the LCOE, since the heat leveraged from the parasitic losses contributes to the economics of the system, adding to the avoidance of carbon emission penalties . Hydrogen-fueled CHP remains far costlier than natural-gas CHP, though it is about 40 $/MWh cheaper than hydrogen waste-heat-only operation.

When benchmarked against Gas Turbines (around 142–216 $/MWh) and combined-cycle plants (around 110–157 $/MWh), Bloom's SOFCs are slightly more expensive in all studied locations under all configurations, but within a highly competitive cost difference. RICE, with resulting LCOEs of between 170–230 $/MWh, represents a more expensive option than Bloom's Natural Gas CHP configurations in all locations studied but Ireland, where relatively low natural gas prices diminishes Bloom's cost advantage due to higher efficiencies.

Comparing to local retail electricity rates—ranging from about 158 $/MWh in the EU average up to nearly 290 $/MWh in the UK—all Natural Gas configurations undercut grid prices in the UK and Ireland, with CHP configurations standing within a competitive range in the German case. The comparatively low grid prices in the EU-average and Italian cases makes them a far-reach for current found SOFC generation costs. To contrast, Pexapark (2025) reports that their index *PEXA EURO COMPOSITE*, comprising the PPAs developed in Europe in May 2025 is of around 51 €/MWh, but these rely on timely grid access, which as analyzed before, is a major impediment.

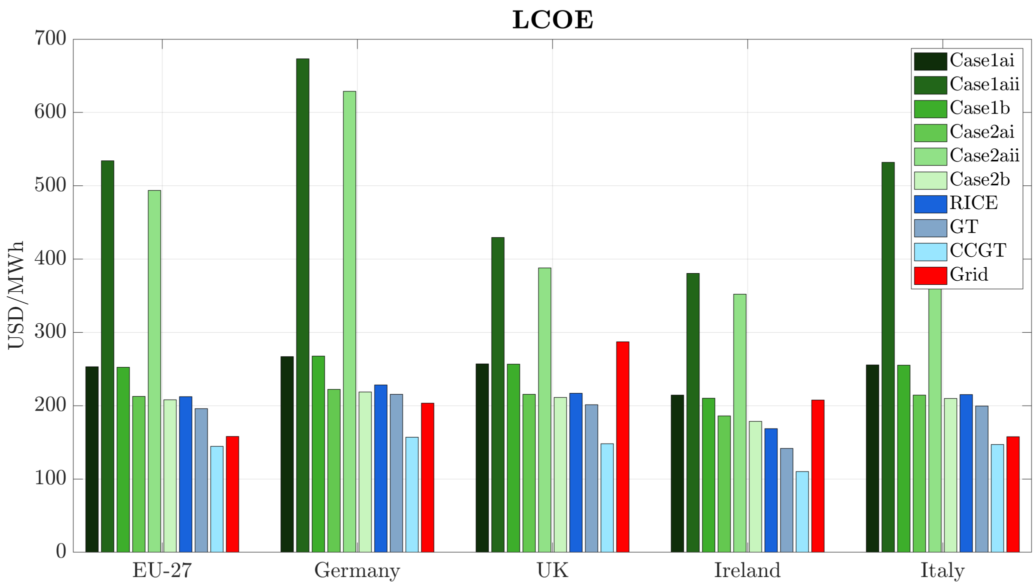


Figure 4.19: LCOE for Bloom and competitor power systems.

Generally speaking, it is observed that Natural Gas CHP represents Bloom's most cost competitive configuration and that the addition of carbon capture implies almost negligible cost variations with the current carbon costs and considered assumptions. Moreover, Bloom's competitiveness tends to be enhanced in locations with higher fuel costs, where its efficiency advantage makes their SOFCs less sensitive to fuel prices. Overall, SOFC cogeneration shows promise when paired with heat export and under high carbon or high-cost fuel regimes, but needs further cost and performance improvements to compete broadly with conventional generation or grid power in some locations.

The resulting cost structure found for Bloom Natural Gas configurations differs from the Hydrogen configuration and that of competitors. The obtained LCOEs for Bloom's Natural Gas systems have a much bigger CAPEX influence than competitors: while they can reach over 45% for some cases, for competitors this value tends to remain under 20-25% (Figure 4.20). On the other hand, when fueled with hydrogen, systems behave more similar to competitors: even if these systems require the considerable CAPEX investment Bloom systems imply, the high cost of fuel shifts the balance towards OPEX in LCOE contribution terms.

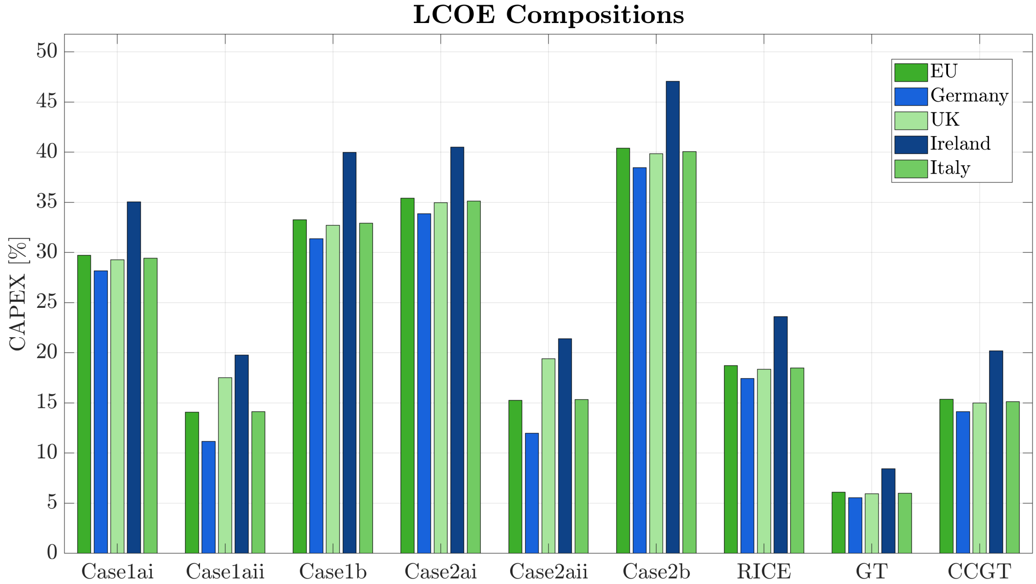


Figure 4.20: LCOE composition for Bloom and competitor power systems.

LCOE – Time Value

Given the highly valuable assets Data Center are, revenues lost due to power deployment delays should be taken into account. While Bloom systems have a delivery time of under 12 months, grid connection processes and Gas Turbine deliveries can take years (Figure 4.21).

If the time-to-power impact in the LCOE is taken into consideration via lease revenues lost in non-operational periods, the situation depicted in the previous section changes. Under this consideration, SOFC systems lower their apparent LCOE significantly, reaching up to 45% of their original values in power-constrained regions such as the UK. In the EU-average case, to exemplify the overall situation, the basic waste-heat SOFC on natural gas without carbon capture falls from roughly 253 \$/MWh to about 197 \$/MWh, and the CHP configuration without capture drops from 213 \$/MWh to around 157 \$/MWh. Even the hydrogen-fueled systems, largely uncompetitive according to the previous analysis developed, see their LCOE trimmed by more than 40%, outcompeting grid prices in the UK market.

By contrast, conventional technologies incur significant penalties once their own deployment lead times are monetized. Gas Turbines' LCOEs climb by 4-64%, and combined-cycle plants' ones jump by 18-111%. Reciprocating Engines, with their short installation times, present a similar behavior to Bloom's, enhancing their competitive position when opportunity costs in high-revenue environments such as the Data Center industry are considered.

The depicted situation shifts the competitive landscape: Bloom Natural Gas configurations now undercut simple GTs and even CCGTs, whereas before they were clearly more expensive. The extent of these shifts varies: countries where lease rates are higher and grid connection times are longer favors the competitive landscape towards fast deployment solutions such as Bloom's.

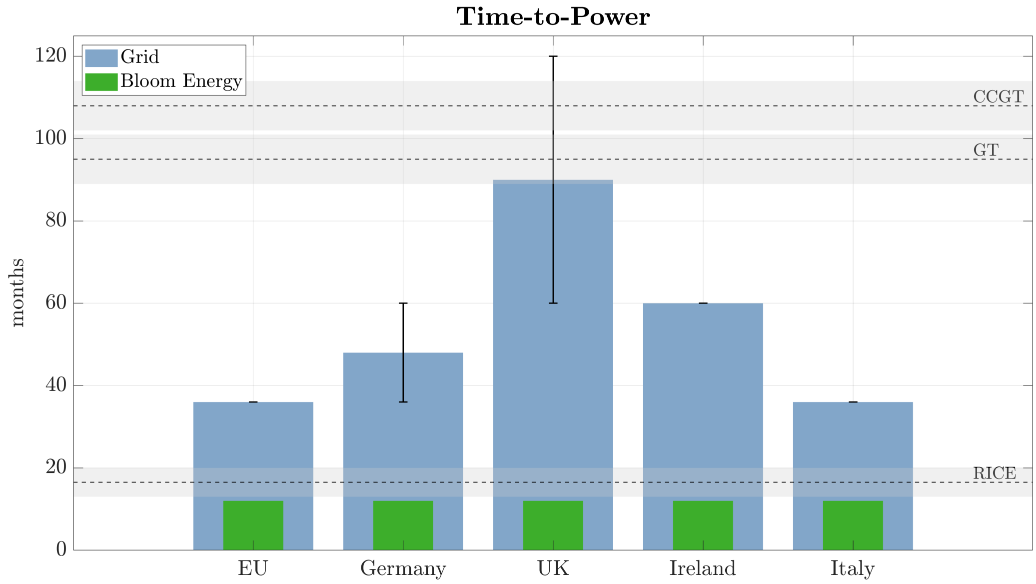


Figure 4.21: Time-to-power for Bloom and competitor power systems.

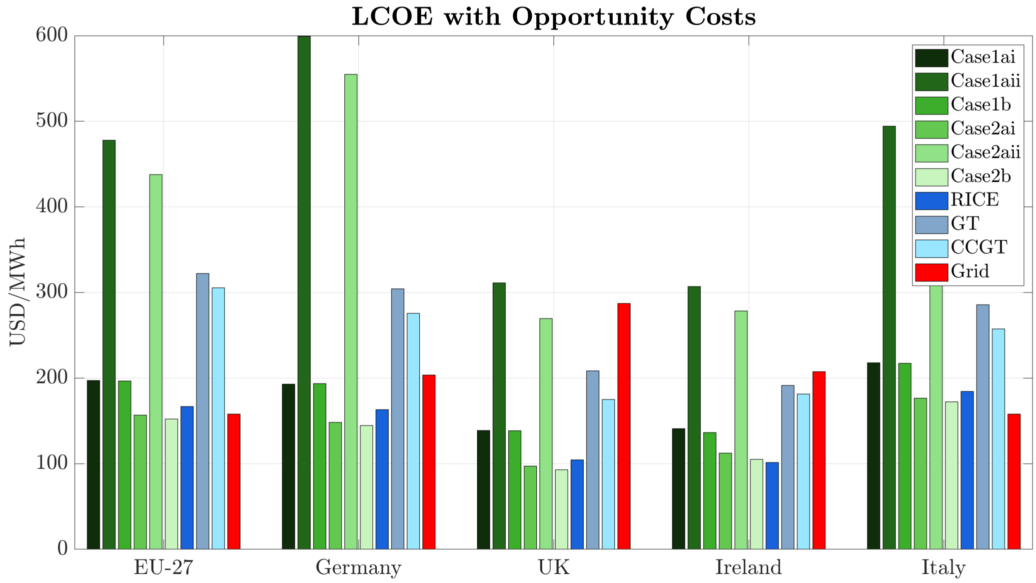


Figure 4.22: LCOE for Bloom and competitor power systems accounting for opportunity costs.

When accounting for opportunity costs, Bloom's Natural Gas CHP cases become the cheapest option in LCOE terms in every location but Ireland. Here, the relatively cheap gas prices and the comparable time-to-power characteristics to Bloom's that RICE presents make it a cheaper solution.

Furthermore, when comparing the obtained results with grid costs, under the opportunity cost accountability framework all Bloom Natural Gas CHP configurations stand below grid prices for all locations studied but Italy, where relatively low grid connection times and grid prices make grid parity more complex. For the German, British and Irish cases, grid prices are outcompeted by all Bloom's gas-fueled configurations, while for the EU-average case only adding CHP makes Bloom's LCOE grid-competitive.

It is worth noticing though, that lease rates, the opportunity cost metric used to quantify Data Center revenues might not always be applicable. In some occasions, Data Centers are part of a company's critical operational infrastructure, which is harder to quantify in lease rates terms and depends on the particular value delivery of the company. Moreover, the developed analysis only considered deployment speed differences, disregarding the lost time due to power supply unavailability. Further analysis could incorporate this to study its impact on the resulting costs.

4.4.4 Benchmarking Summary

Data Centers are complex assets, and their power supply needs to be analyzed through different lenses. The results obtained reveal a nuanced landscape where each technology presents distinct strengths and trade-offs across different performance dimensions. Based on the quantitative analysis presented above, Figure 4.23 presents a qualitative benchmarking of the different power solutions on a simple 1-4 scale, outer rings representing better performances.

It is noted that *Bloom Energy* stands out for its overall environmental performance, outperforming competitors by a great margin in emissions, and water and land use impacts. Additionally, Bloom's technical and operational performance gives the company a competitive advantage over the rest: their SOFC systems stand as the most reliable, fast to deploy, and dynamic, also presenting electrical efficiencies only matched by CCGTs. Even if LCOE results do not place Bloom as the best economic performer, standing together with Reciprocating Engines below Gas Turbines and CCGTs, its low time to power gives the company a tremendous advantage in high-revenue environments such as Data Centers when accounting for opportunity costs.

On the other hand, Gas Turbines offer a balanced profile, performing moderately across most categories. This makes them a versatile option for Data Centers seeking a middle ground between cost, performance, and environmental impact, but their current long delivery times represent a major impediment. On the other hand, CCGT emerges as one of the most efficient and cost-effective solution in terms of LCOE, given its high overall efficiency and economies of scale. However, they are only cost effective at great scale, and they high water consumption, land intensity, and time-to-power reflects the complexity and resource intensity stand as a major roadblock for agile deployments. Finally, RICE are highly responsive assets and cost advantageous in time-value terms due do their rapid delivery, installation and commissioning. Yet, they suffer from the highest environmental impacts, and the less reliability of all technologies analyzed, something critical for Data Center operators.

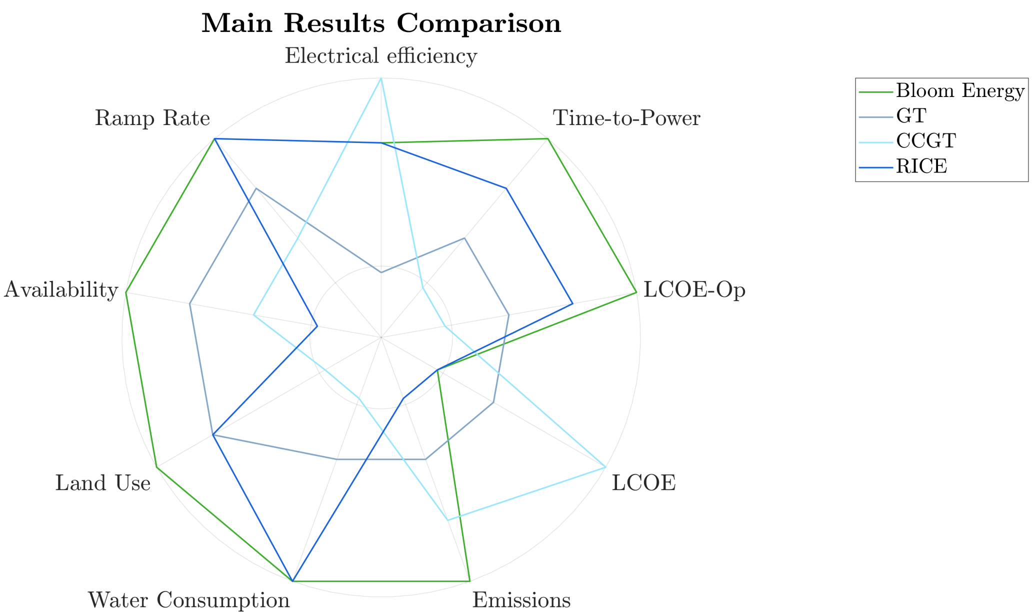


Figure 4.23: Benchmarking summary.

Specific major decision drivers may differ among Data Center developers, be them sustainability, cost, reliability, or deployment speed, influencing technology optimality depending on the case. The study developed shows that *Bloom Energy* is optimal for agile, reliable and environmentally ambitious operations, while CCGT suits large-scale, cost-driven, long-term deployments. Conversely, RICE stands as optimal for flexible, agile needs, while GT offers a balanced compromise across the board, a position compromised by the unprecedented high current market lead times.

4.5 Sensitivity Analysis

To ensure the robustness and reliability of the techno-economic assessment, as well as to explore how results change with the variation of key parameters, a sensitivity analysis is performed. The selected parameters—fuel cost, CO_2 price, interest rate, Bloom's CAPEX, and opportunity costs—reflect a combination of market volatility, regulatory uncertainty, and financial assumptions. Given the complex and dynamic nature of energy markets, financing conditions, and policy landscapes, each variable is systematically varied within realistic bounds derived from recent data, historical trends, and forward-looking projections. This approach aims to capture the uncertainty inherent in long-term energy planning, identify the most influential cost drivers, and provide insights for stakeholders under diverse economic and policy scenarios. The following subsections detail the methodology and assumptions applied to each parameter.

4.5.1 Methodology

Fuel Sensitivity. To analyze the results variation on fuel prices, two fuels were considered: natural gas and hydrogen. For the first case, the base is 2024-H2 EU-27 average according to Eurostat (2025c), including all taxes an levies, while the maximum and minimum EU values considered were the extreme values reported in the last 5 years: 0,1126 $/MWh in H2-2022 EU-27 and 0,019 $/MWh in 2020 (Eurostat, 2025c). For the Hydrogen cases, given that the European average production cost of Green Hydrogen was 218 $/MWh for 2023 (European Hydrogen Observatory, 2023), an upper bound of 270 $/MWh was considered for the analysis. As a lower limit, 44 $/MWh was used based on values reported by Merten et al. (2023) on the estimated 2050 costs of imports from Tunisia to Germany.

CO_2 Price Sensitivity. To assess the impact of carbon pricing on the competitiveness of the different systems, a range of CO_2 prices was considered based on both historical averages and forward-looking projections. The base case is set at 70,1 $/ton, reflecting the 2024 average EU ETS carbon price as reported by ICAP (2024). For the lower and upper bounds, a minimum of 50 $/ton and a maximum of 150 $/ton were selected to reflect both past volatility and anticipated market evolution. The upper bound aligns with forecasts of 145 €/ton by 2030 provided by BloombergNEF (2024).

Interest Rate Sensitivity. The base rate considered for the analysis was of 4%, given that this is the estimated EU average for 2025 (European Central Bank, 2025). Acknowledging that this value presents high variation among the analyzed locations, even reaching 5,7% in Ireland (European Central Bank, 2025), and that is very susceptible to macroeconomic changes, this value is varied from 0% until 8%.

Bloom CAPEX Sensitivity. Given the strong CAPEX influence on the LCOE that Bloom systems present, the impact of it is assessed, the CAPEX of Bloom's Energy Servers were varied from 80% to 120% of their value, reflecting potential fluctuations due to supply chain dynamics, economies of scale and technological advancements, in pessimistic and optimistic scenarios.

Opportunity Costs Sensitivity. Considering the high impact that adding the opportunity costs has on the LCOE for most locations, their components are varied conjunctly to assess their impact: lease rates were varied from 50% to 200% for each location, while the Time-to-Power differential was done so from 0 to 120 months.

Elasticities. Having obtained the sensitivity analysis results, elasticities are calculated. To do so, the ratio of the normalized LCOE variation over the normalized input was calculated, considering values used for the calculation in section 4.4 as the base for normalization:

$$E_x = \frac{\Delta LCOE_x}{\Delta x} \cdot \frac{x_{base}}{LCOE_{base}} \tag{4.85}$$

Where E_x represents the elasticity of the LCOE under variable x, and the Delta variables the variations over the full analyzed interval.

4.5.2 Results

Next, the results of the sensitivity analysis conducted across all cases and regions studied are presented. While detailed graphs are available for each market, only the German case is displayed here for clarity and focus; comprehensive visualizations for all other locations can be found in Appendix D. The analysis considers both absolute LCOE values and LCOE adjusted for opportunity costs, providing a thorough understanding of cost competitiveness under varying economic and operational scenarios.

Main Takeaways

1. Natural gas-fueled SOFCs exhibit lower LCOE sensitivity to gas prices than GT/RICE, whereas Hydrogen cases show larger ones. High gas prices tend to favor Bloom against competitors.

2. Bloom's carbon-price elasticity is lower than competitors, CHP cases with Carbon Capture even registering negative sensitivity as avoided emissions pay back. Therefore, high fuel regimes enhance Bloom's competitive advantage, even if this pushes the LCOE away from grid prices.

3. Interest-rate shifts (0–8%) do not alter the competitive landscape significantly, except for Natural Gas CHP cases when compared in some locations. Under opportunity-cost accounting, the impact of the interest rate on Bloom's LCOE falls significantly, and the economics of Hydrogen cases remains virtually unchanged.

4. Varying Bloom CAPEX ±20% means relative price variations with GT and RICE for all locations but Ireland, where lower fuel costs tend to favor lower efficiency technologies. Hydrogen systems remain virtually unaffected by the CAPEX variations

5. Accounting for lease rates (50–200% of current local market values) and 0–120 months differential deployment versus the grid, Natural Gas configurations undercut German, UK, and Irish grids, while Hydrogen remains uncompetitive in all locations outside the UK even with greater opportunity costs.

6. Fuel alone dominates the LCOE in Bloom Hydrogen systems, but for Natural Gas systems both CAPEX and fuel lead. With opportunity costs, lease rates and time-to-power emerge as the most dominant factors together with fuel and CAPEX.

Fuel

The sensitivity analysis of the LCOE on fuel prices developed shows that Bloom's Natural Gas configurations are less sensitive to natural gas price variations that competitors. This was to be expected given the higher efficiencies Bloom's SOFCs present and the larger CAPEX and fixed OPEX impacts on the LCOE. On the contrary, the Hydrogen systems analyzed present significantly higher variations upon fuel costs given the high share that fuel costs represent in the cost structure.

While only the German case is graphed in this section (Figure 4.24), insights taken from its analysis can be perfectly extrapolated to other markets[14]. It is noted that for natural-gas fueled systems, higher fuel prices tend to separate on-site achievable prices from current grid prices, but at the same time improve Bloom's competitive advantage due to the efficiency gap. CHP systems, additionally, tend to decrease the fuel price sensitivity, as the heating fuel cost avoided serves as a hedge to the increased prices.

[14] See Appendix D for all the additional graphs

Particularly for the different markets, it is observed that in Germany, current fuel prices put all Bloom configurations at costs above grid prices and on-site solutions, except for the case of Natural Gas CHP options, which are virtually at the same cost levels as Gas Turbines and Reciprocating Engines. Natural gas price reductions from around 60 $/MWh to around 45 $/MWh would mean that these options would outcompete grid prices, but at the same time this fuel price reduction would mean that RICE and GT would present themselves in a better position due to their higher fuel cost sensitivity. At the same time, gas-fueled configurations without CHP or Hydrogen ones would need significant fuel price decreases to achieve grid parity.

In Ireland and the UK, high grid electricity prices imply superior prices to the LCOEs of all Bloom's Natural Gas configurations, with the exception of the baseline gas system in the Irish case. As for the German case, lower fuel prices would mean an enlargement of this advantage over the grid, but at the same time a loss of competitive advantage versus on-site competitors. Lower grid prices found in the EU-average and Italian cases mean that only highly aggressive fuel cost reduction would allow the achievement of grid party under the considerations made.

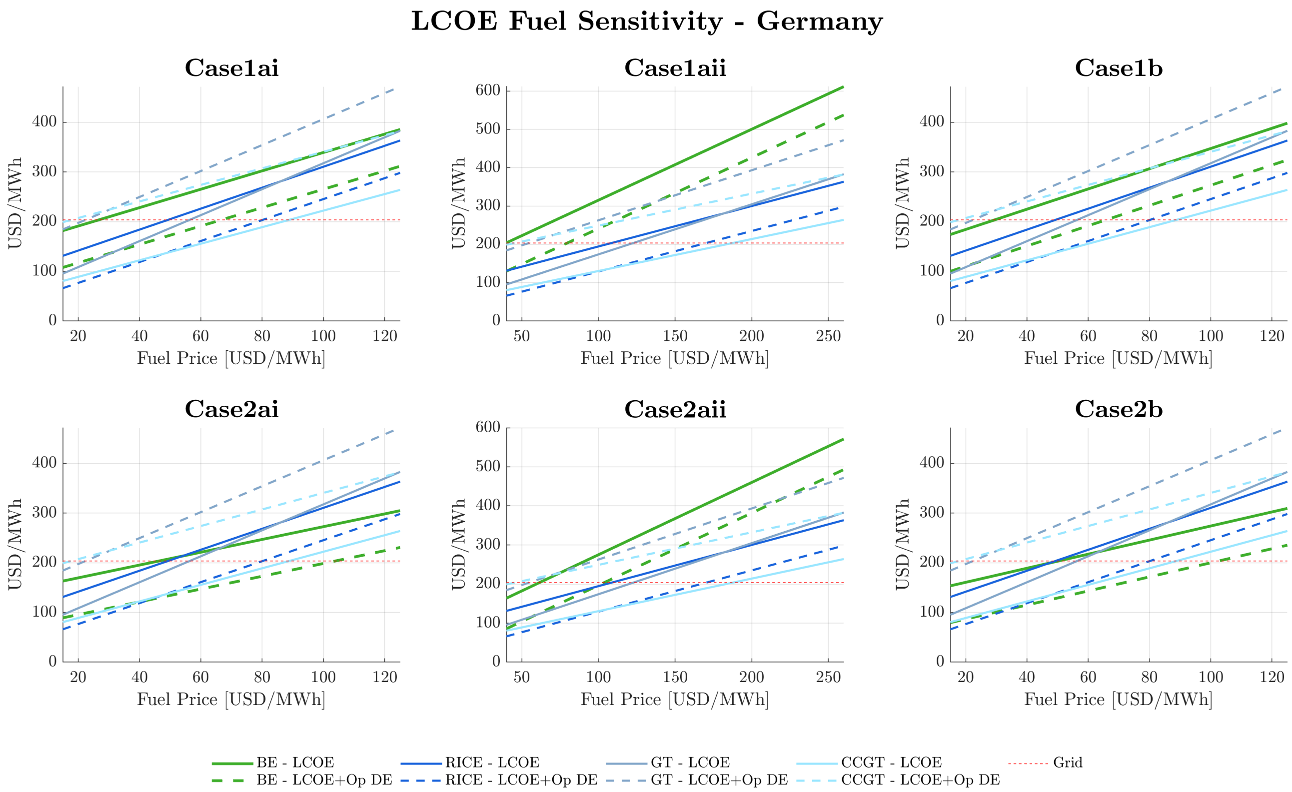


Figure 4.24: LCOE fuel sensitivity in Germany.

When considering the opportunity costs involved, the depicted situation changes given the high impact of Data Center revenue. Under this consideration, while Hydrogen systems still remain uncompetitive around current prices, the competitiveness of Bloom's Natural Gas configurations improves significantly given their deployment velocity advantage. In Germany, to give an example, Natural Gas CHP options outperform all other alternatives, and simple gas configurations are only outcompeted by RICE. For Natural Gas cases without CHP, RICE superiority stands independently of fuel prices, while for CHP options, Bloom presents a cost advantage with gas in the 40-100 $/MWh range. While Ireland and the UK present conceptually similar market characteristics, in Italy the relatively low grid connection times is such that even with opportunity costs considered, no Bloom systems achieve grid parity. Lower fuel prices under the 40 $/MWh threshold could achieve this, but with comparable deployment times and bigger sensitivity to fuel prices, RICE would outcompete even CHP configurations.

CO_2 Price

Given the lower carbon emissions, Bloom's sensitivity to carbon prices tend to be lower than all other competitors, except for the baseline Bloom Natural Gas system when compared to CCGT, which is virtually similar. CHP tends to decrease carbon sensitivity, and furthermore, while Hydrogen and baseline Carbon Capture option are independent from carbon prices, coupling these systems with heat capture generates a negative sensitivity on carbon prices due to the emissions avoided.

This means that higher carbon price regimes tend to favor the company's competitiveness for all cases. In Germany, carbon prices have little effect on Bloom's competitiveness for the baseline NG option, while adding carbon capture to this would only mean reaching its closest competitor -RICE- at carbon prices in the order of 150 $/ton (Figure 4.25). Conversely, in Natural Gas CHP options, carbon prices in the order of 50 $/ton already allow Bloom to outcompete RICE, and ones in the order of 70-100 $/ton to improve Gas Turbine's cost performance, depending on the presence of carbon capture.

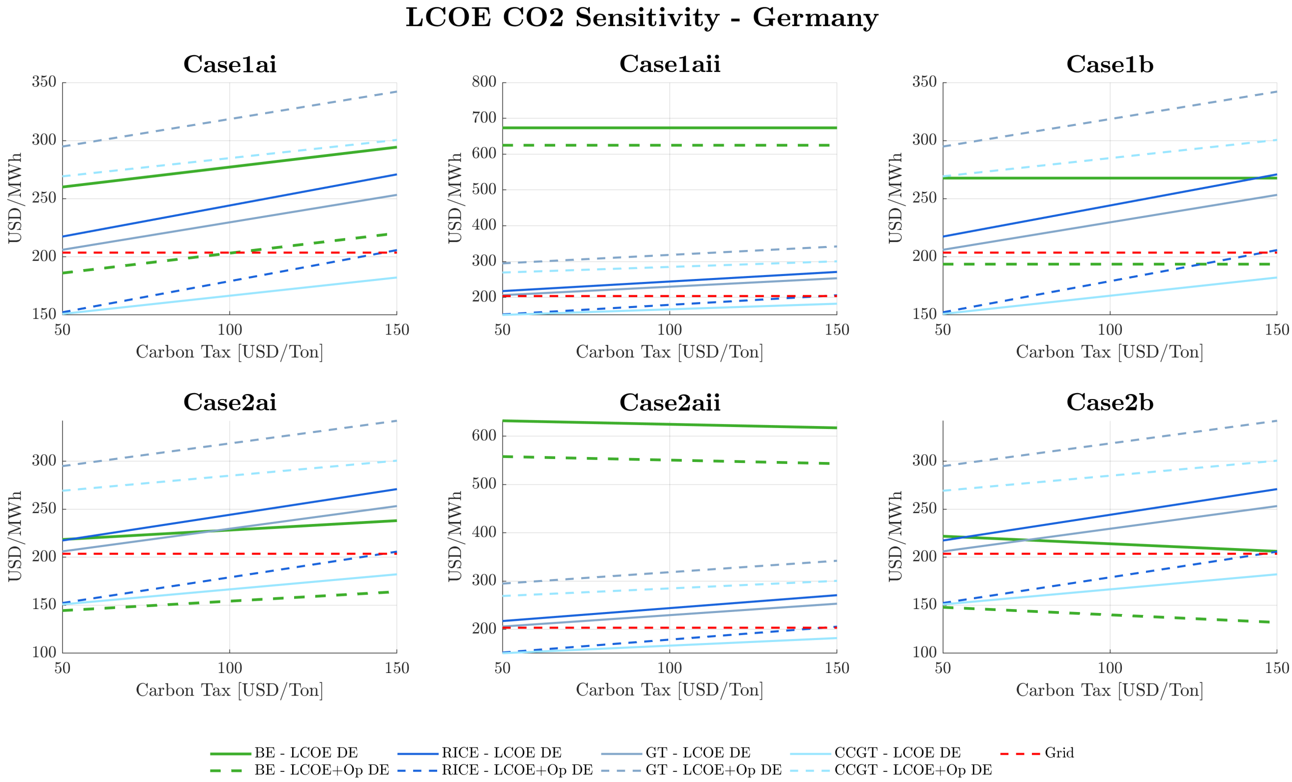


Figure 4.25: LCOE carbon price sensitivity in Germany.

Hydrogen systems, on the other hand, even with their flat or negative sensitivities, present no significant impact on their comparative economic performance upon rising carbon prices, given the current high green hydrogen prices. This means that carbon pricing alone is not likely to be a silver bullet for this systems to become competitive.

Similar to the fuel sensitivity analysis case, other markets present comparable insights with regards to on-site competitors. However, the considerable grid electricity prices difference in the analyzed market implies differences in the impact that carbon prices have on grid parity achievement. In countries such as Ireland or the UK, high grid prices cause that in some or all Bloom Natural Gas cases, even significant increases in carbon prices do not compromise grid parity. Conversely, in Germany, Italy or the EU-average cases, lower grid prices signify that even a significant decrease in carbon prices would not mean achieving it.

Considering opportunity costs significantly changes the landscape, enhancing Bloom's position for all cases and locations. Under this consideration, Bloom NG CHP options in Germany represent the most cost competitive choice, even largely outperforming the grid. Here, the baseline Bloom NG case outperforms the grid at carbon prices below 100 $/Ton, but remains over RICE prices. Similarly for the simple Carbon Capture case, LCOEs below grid prices are achieved independently of carbon prices, but Bloom would only outcompete RICE at carbon prices above the 125 $/Ton figure. Even if specific numbers do not match, this results qualitatively apply to the rest of the markets studied, with the consideration that lower grid prices such as Italy's make grid parity more challenging.

Interest Rate

Considering the greater effect that CAPEX has on the LCOE structure, interest rates represent a bigger influence on the resulting costs for Bloom than for the on-site competitors analyzed. Lower interest rates thus tend to favor higher CAPEX technologies such as Bloom's. However, the impact that this variable has on the LCOE is largely mitigated when accounting for opportunity costs. Given that Data Center lease revenues occur at the initial time-to-power differential with the grid, these tend to balance the large and negative initial cash flows, reducing the impact that interest rates have on the resulting LCOE. Surprisingly, in fast-deployment low-CAPEX options in long grid connection environments, such as RICE in the UK, this consideration even induces a negative sensitivity to interest rates.

As it was the case for the carbon price sensitivity, the different markets analyzed present similar characteristics for the comparison with on-site competitors but mainly differ in the interest rates at which grid parity is achieved, if that is the case. As commented before, opportunity costs consideration tends to improve Bloom's performance across all cases and markets, and insights taken from the carbon price sensitivity analysis could perfectly be extrapolated to this case.

Generally speaking, interest rates were found not to alter the competitive landscape significantly for all studied markets in general, and in Germany in particular, with the exception of Natural Gas CHP options (Figure 4.26). In Germany, for CHP systems without carbon capture, interest rates below 6% and 2,5% mean that Bloom outperforms RICE and GT, respectively, achieving grid parity at an interest rate of around 1%. Adding carbon capture does not change the outcomes significantly, only resulting in a slight increase of these values.

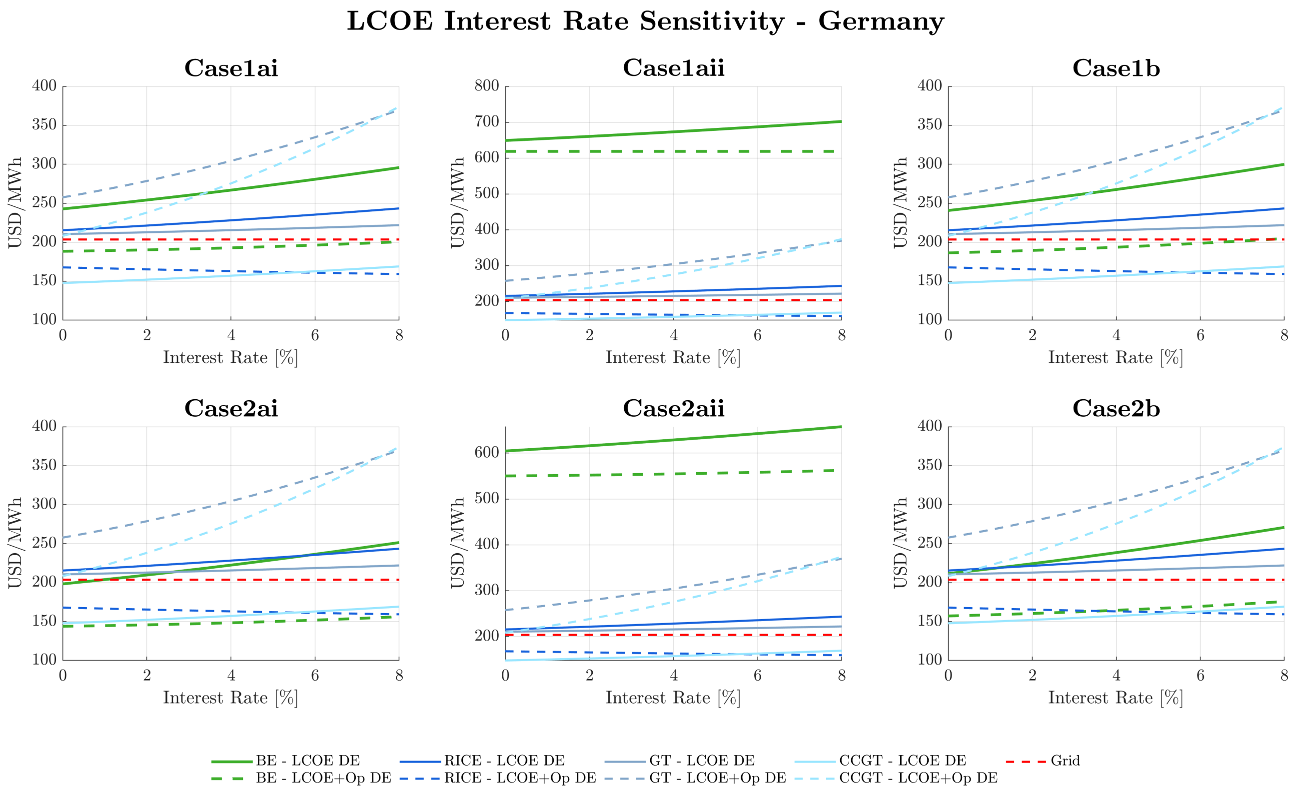


Figure 4.26: LCOE interest rate sensitivity in Germany.

In the German market, as well as in all other markets studied, even strong reductions in the interest rate do not make Hydrogen configurations competitive.

Bloom CAPEX

Bloom's CAPEX represents a large share of the LCOE structure. However, it was found that for all locations studied, varying it in the 80-120% range only alters the competitive landscape significantly in CHP options, except for the Irish case. While Bloom CAPEX variations in the studied range do not change the relative costs among competitors, in Natural Gas CHP cases slight cost variations alter their relative costs of Bloom versus Reciprocating Engines and Gas Turbines. For instance, in Germany a 5-10% reduction in Bloom's costs would mean LCOEs below Gas Turbines, while the CAPEX could increase by 10% and still remain more competitive than RICE (Figure 4.27).

While in Italy the UK and EU-average cases these values move to the -10-20% and +0-5% range, the insights remain valid, but this is not true for Ireland. Here, lower natural gas costs mean that lower efficiency technologies are harder to beat, and only RICE could be outcompeted by Bloom's Natural Gas CHP configuration with a 15% Bloom CAPEX reduction. However, it is observed that in this market, Bloom CAPEX indeed has a significant impact in non-CHP Natural Gas configurations: CAPEX reductions of 5-10% would mean the achievement of grid parity. In all other locations, it was found that variations of CAPEX alone in the range do not alter this fact, as locations where locations where LCOEs stood below of grid prices do not outcompete it with 20% CAPEX reductions, and markets where grid costs were outperformed are not affected by a 20% increase in it.

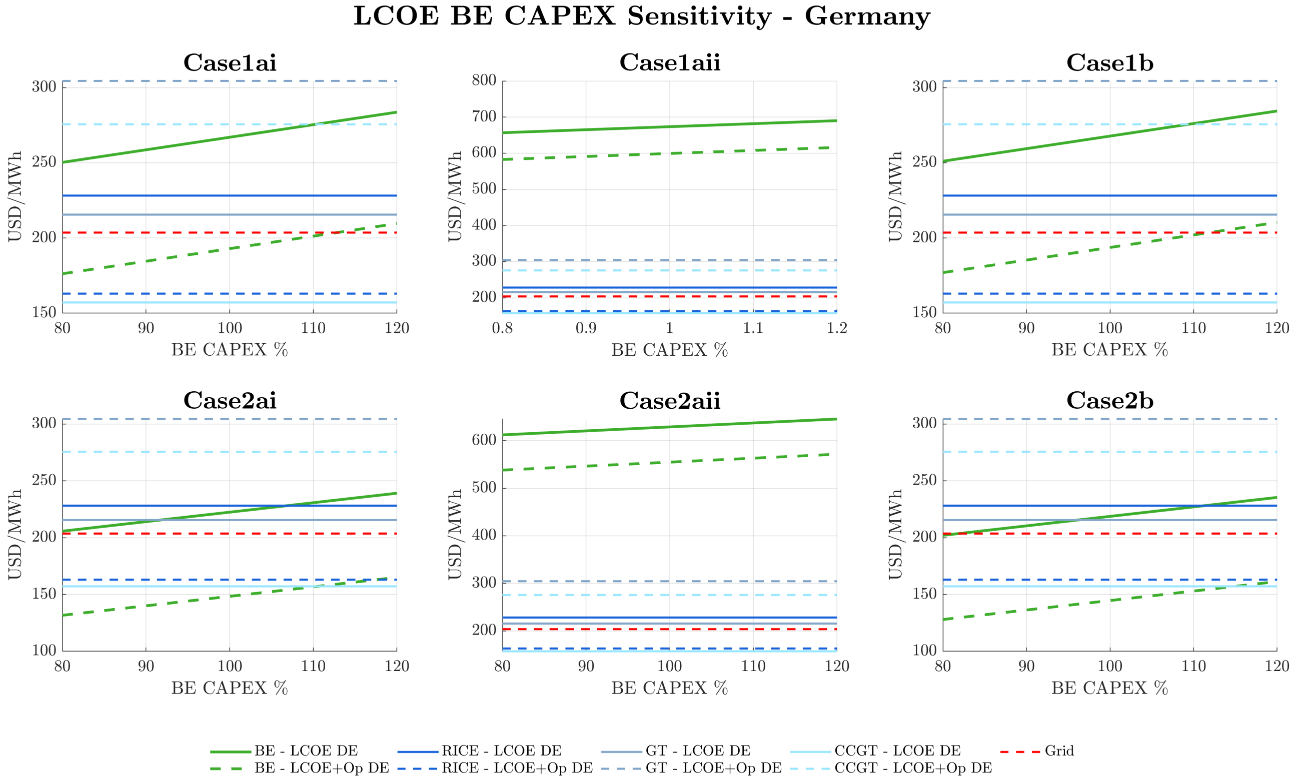


Figure 4.27: LCOE Bloom CAPEX sensitivity in Germany.

On the other hand, Hydrogen systems remain virtually unaffected by the CAPEX variations. This was to be expected given the already discussed relatively low weight that investment costs have on these systems when compared to the current high fuel costs.

When accounting for opportunity costs, the situation is slightly altered. In Germany, simple Natural Gas cases result in better LCOEs than grid prices even with a 10% increment in CAPEX, and stand below all competitors but RICE at all CAPEX levels studied. Moreover, Bloom's Natural Gas CHP cases present the best performance of all in the country, outperforming all competitors even after a 15-20% CAPEX increase, when RICE takes over.

The UK presents similar characteristics to Germany, and while in Italy some similarities also emerge, as Bloom's NG CHP configurations' dominance stands even with a 10% CAPEX increase, grid parity could only be achieved with a 20% CAPEX reduction. In Ireland, on the other hand, even if grid parity is achieved with no influence of CAPEX variations in the studied range, CAPEX reductions in the order of 5-15% would be needed for Bloom to stand as the best performing on-site solution.

Opportunity Costs

As it has been clearly proved by the previous analyses shown, opportunity costs present a large influence in high-revenue and time sensitive sectors such as the Data Center industry. Results show that with current Bloom time-to-power advantages and market Data Center lease rates, grid parity is achieved for all Natural Gas configurations and all markets studied but the EU-average case and Italy.

In Germany, current market values place LCOEs of all Natural Gas configurations below grid prices (Figure 4.28). CHP systems, in particular, stand with great margin, as either lease rates or Bloom's time-to-power advantage could reduce to half and still stand as a more competitive option when compared to the grid. This is the case for the UK and Ireland as well, where all Natural Gas configurations are virtually independent from lease rates and deployment speed advantages within the studied ranges.

Hydrogen cases, conversely, do not achieve grid parity under this lens, and remain far from it for all locations but the UK (see Appendix D). Here, current high grid connection times imply that Hydrogen CHP systems would be more competitive than the grid when accounting for Data Center revenues lost. However, these systems still stand well below other on-site competitors, including all Natural Gas Bloom cases and other competitors.

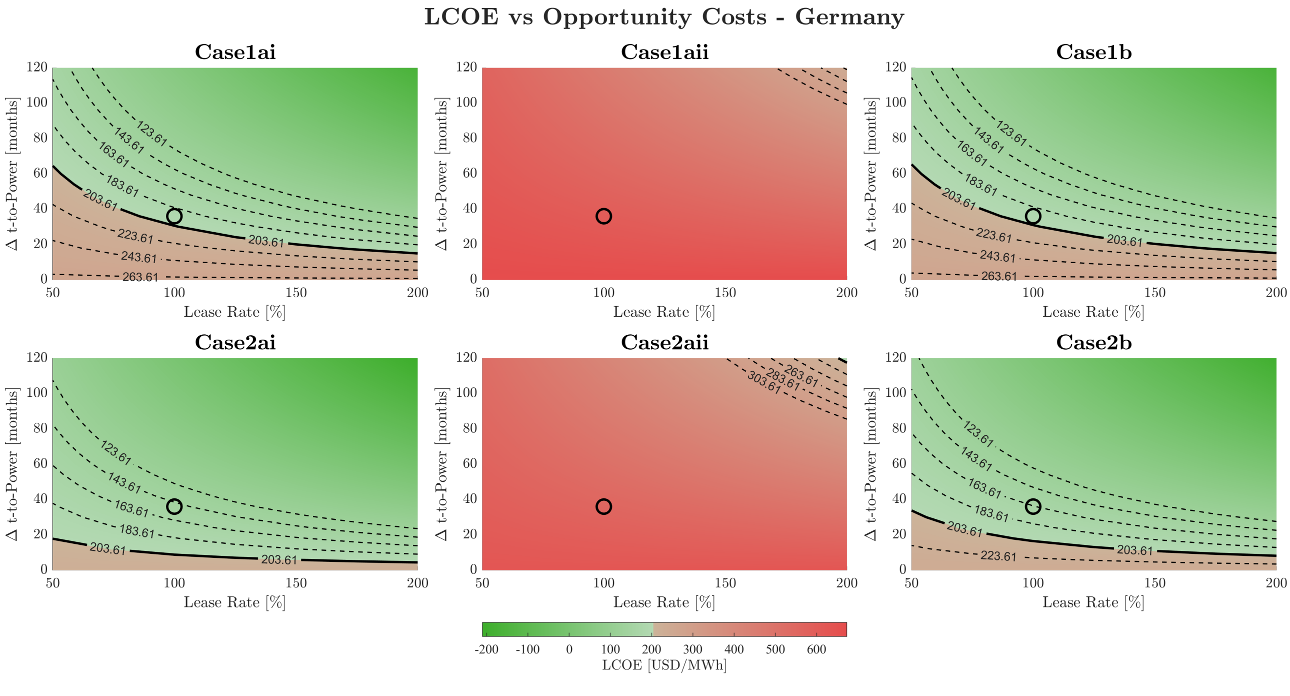


Figure 4.28: LCOE opportunity costs sensitivity in Germany. Circles represent current situation, while black line represents grid price in $/MWh.

In other markets such as Italy, it is observed that the relatively low connection times present imply that no Bloom configurations achieve grid parity at current Data Center lease rates, and this is practically true for the average EU case, where only Bloom Natural Gas CHP cases slightly approximate grid values.

Elasticities

Bloom Systems. Results indicate that fuel price is the dominant driver of LCOE in H_2-based systems, whereas its impact is less pronounced in Bloom systems operating on natural gas (Figure 4.29). In the latter, both CAPEX and fuel cost emerge as the primary contributors to LCOE variability.

In Natural Gas configurations without CHP or Carbon Capture, the interest rate and CO_2 price exert comparable influence. The introduction of CHP lowers the sensitivity to CO_2 pricing, as does carbon capture. When both are combined, the system not only becomes more resilient to carbon cost fluctuations, but can also achieve a net LCOE reduction as CO_2 prices rise.

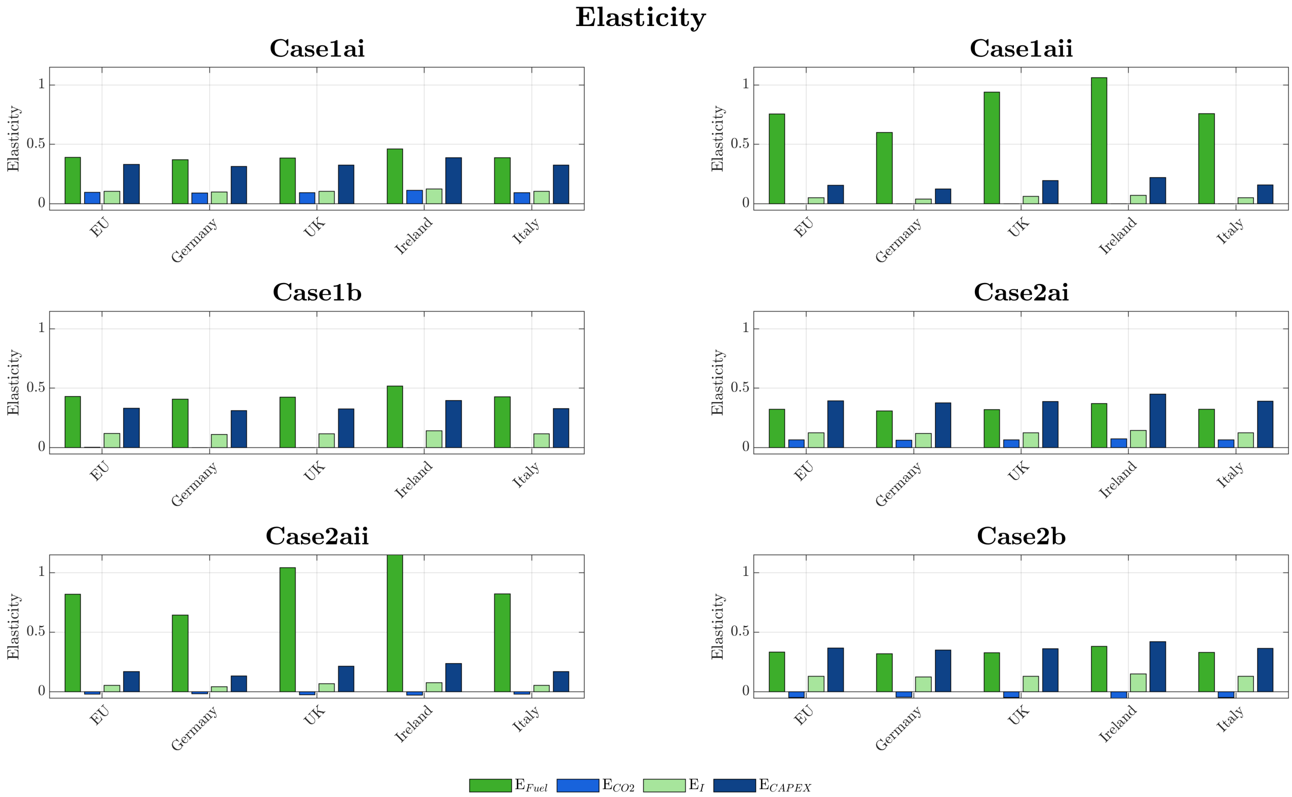


Figure 4.29: Elasticities for Bloom cases.

When opportunity costs are included in the elasticity analysis, fuel remains the primary LCOE driver for H_2 systems, but continues to be less dominant in natural gas configurations (Figure 4.30). In these cases, opportunity-related variables—specifically time-to-power and lease rates—emerge as significant contributors, with notable influence also observed in the H_2 scenarios. CAPEX retains its central role, while the relative importance of interest rates and CO_2 prices diminishes.

Competitor Elasticities. When analyzing competitor systems, fuel clearly stands out as the dominant LCOE driver across all cases, largely due to its substantial contribution to OPEX (Figure 4.31). As expected, this results in a significant influence on overall cost. Carbon pricing also shows notable impact, though it remains secondary to fuel. In contrast, interest rates exert minimal influence on LCOE, reflecting the relatively low CAPEX profile of the competitor technologies.

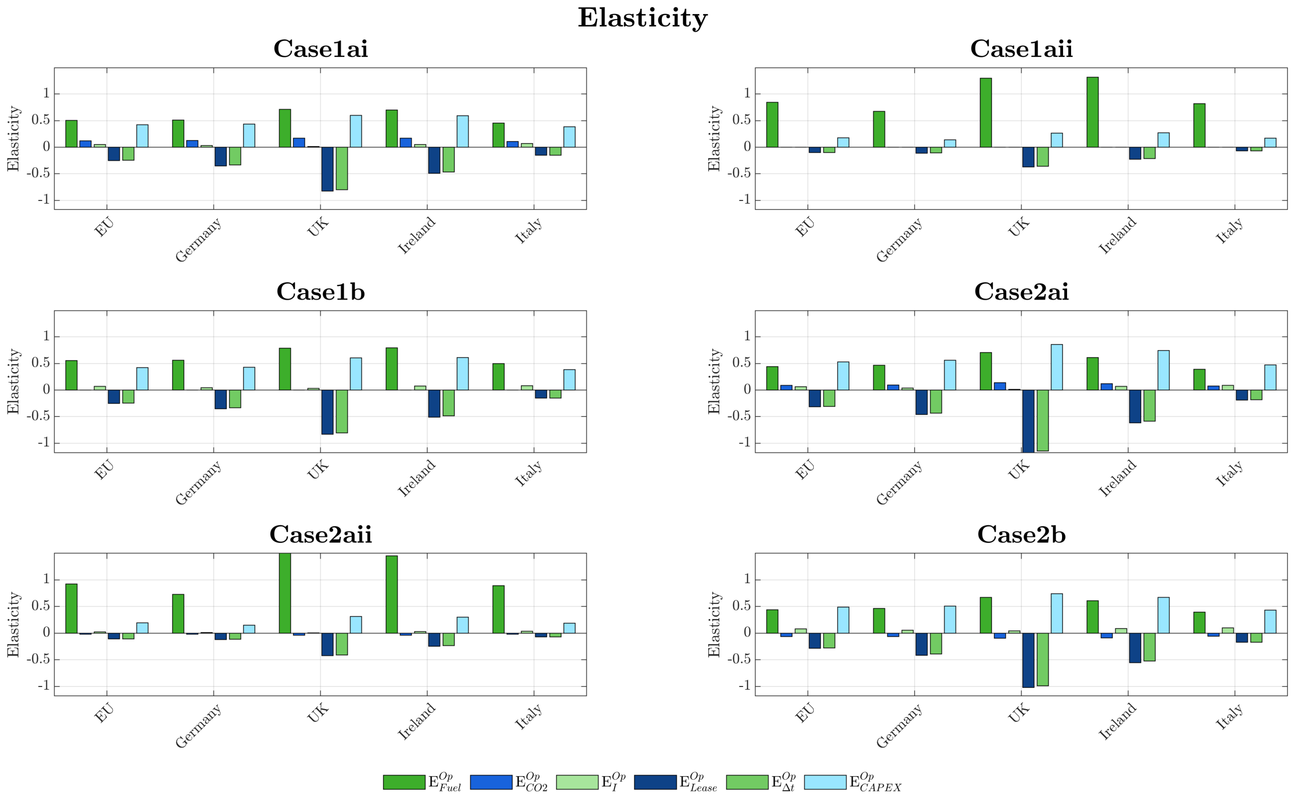


Figure 4.30: Elasticities for Bloom cases when taking into account opportunity costs.

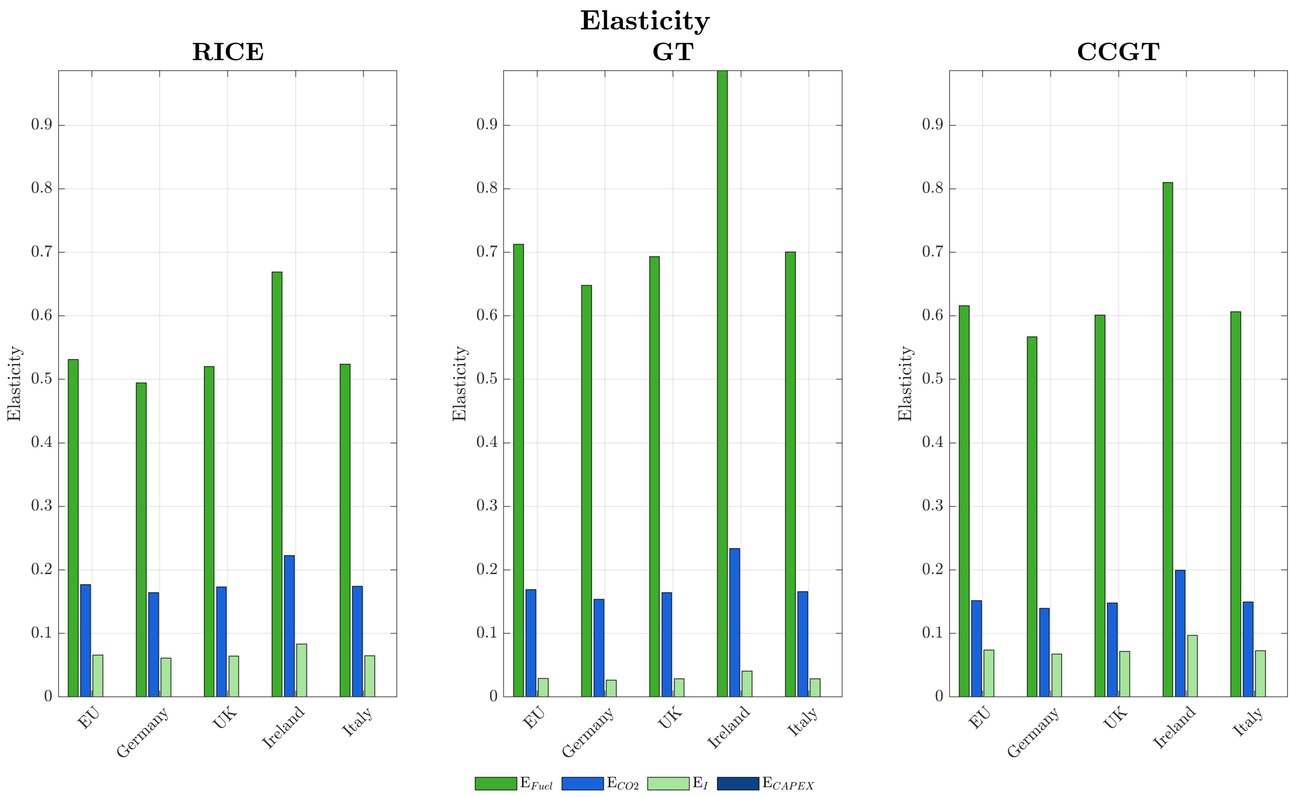


Figure 4.31: Elasticities for on-site competitors.

4.6 Scenario Analysis

To analyze how the dynamics of the studied systems change under different circumstances, following, the evaluation of the performance of Bloom and on-site competitors under varying external conditions is developed. The assessed scenarios include exposure to natural gas price shocks, the presence of

CAPEX and OPEX subsidies, the impact of performance incentives for CHP systems, long-term fuel price evolutions, and cumulative carbon emissions over a 20-year horizon. It should be noted that this assessment is not intended to serve as a detailed or predictive modeling effort, but rather as an exploratory exercise to derive insights and identify key trends under different policy and market conditions.

4.6.1 Methodology

Fuel Price Shock Resilience. Given the high volatility gas prices have had in the last years, it is worth looking into the behavior of the different systems upon fuel price shocks. For this purpose, large consumption industrial Gas prices from 2020 to 2025 were taken from Eurostat (2025c), and the resulting LCOE for each on-site generator, and the grid, were assessed for each location. Plots show normalized values based on current prices, and the standard deviation was employed as a volatility metric.

Subsidies. To analyze a scenario in which subsidies are in place, the LCOE variation on CAPEX and OPEX subsidies was performed. CAPEX subsidies are expressed as a percentage of total installation costs, while OPEX ones as percentage of fuel costs. This was done for each location, and resulting LCOEs were compared to local grid electricity prices according to Eurostat (2025b) for EU countries and UK Government (2025b), for the UK.

Performance Incentives. Similarly, a scenario in which energy savings from CHP systems are incentivized, is analyzed. The energy savings were calculated using the procedure detailed by the European Parliament (2012), and certificate prices for each location were varied from 0 to 50 $/MWh saved, based on a reference price of around 300 €/TEP (28 $/MWh) for Italy under the White Certificates Scheme.

Future Outlook. In this scenario, future estimated prices of hydrogen, natural gas and carbon were included in the analysis. As an extreme simplification, a simultaneous convergence of these parameters from local 2025 values to estimated 2050 ones was assumed. That is, all parameters were considered to be evolving simultaneously and at the same pace [15]. For hydrogen, 2050 prices were 44 $/MWh based on values reported by Merten et al. (2023) on the estimated 2050 costs of imports from Tunisia to Germany, while for CO_2, a value of 500 $/Ton was considered based on CAKE (2024) and Enerdata (2023). The gas price evolution required further considerations. Given that future Gas prices found were TTF values and not location-specific industrial ones, the percentage variation between the current TTF price and the 2050 one was assumed to be translated directly into industrial prices. That is, the 36% expected reduction in TTF prices from the current 41,5 $/MWh (Investing, 2025) to the expected 30,7 $/MWh one in 2050 (GECF, 2023), was assumed to translate in the same proportion to industrial Gas prices in the same period, coming from location-specific values reported by Eurostat (2025c). Conversely, CAPEX and fixed OPEX prices were considered equal to current prices independently of the year for all cases.

Accumulated Emissions. Given the annual emissions calculated in section 4.4, accumulated emissions were calculated for each on-site generator and grid on a 20-year reference period. This was done by extrapolating the annual emissions results obtained to the complete analysis period.

[15] It is acknowledged that this represents a significant limitation in the analysis, but going deeper into the assessment of the specific price evolution tends for each of the parameters is out of the scope of the project. This scenario analysis is done only for exploratory purposes to gain insights on LCOE evolutions only.

4.6.2 Results

Main Takeaways

1. Bloom systems exhibit less OPEX variability under a gas supply shock such as the one experienced in the 2020-2025 period than all on-site power competitors.
2. Under 2025-2050 hydrogen, natural gas and carbon simultaneous price convergence, Bloom NG CHP system needs a 1–17% price evolution to beat GT; Hydrogen CHP requires 42–60% and CC+CHP only 1–5% for most locations.
3. Bloom's NG+CHP achieves grid parity with GT in Germany with 20-25% CAPEX or fuel subsidies, while in the UK and Ireland no subsidies are needed to do so. Bloom's EU average and the Italian cases remain out of reach of grid prices with reasonable subsidy levels.
4. CHP energy-saving certificates at 28 $/MWh imply that Bloom's LCOE under natural gas stands below UK/IE grid prices, while Germany needs marginal increases in certificate prices to do so. In EU-average and Italian cases, certificate prices have virtually no effect in grid parity achievement inside the studied range.
5. Over 20 years, Bloom's NG SOFC emits 5.363 kton CO_2 vs GT 7.388 kton (–27%) and RICE 8.369 kton (–36%). Hydrogen systems yield 0 kton, while with CC emissions drop to 57,7 kton.
6. NG CHP emits 3.073 kton (–58% GT, –63% RICE) and Hydrogen CHP achieves –2.290 kton (net-negative), while grid average is 3.850 kton.
7. Bloom SOFCs—especially Hydrogen or CC+CHP—outperform all on-site and grid mixes in cumulative emissions, making them prime candidates for Data Center decarbonization.

Natural Gas Shock Resilience

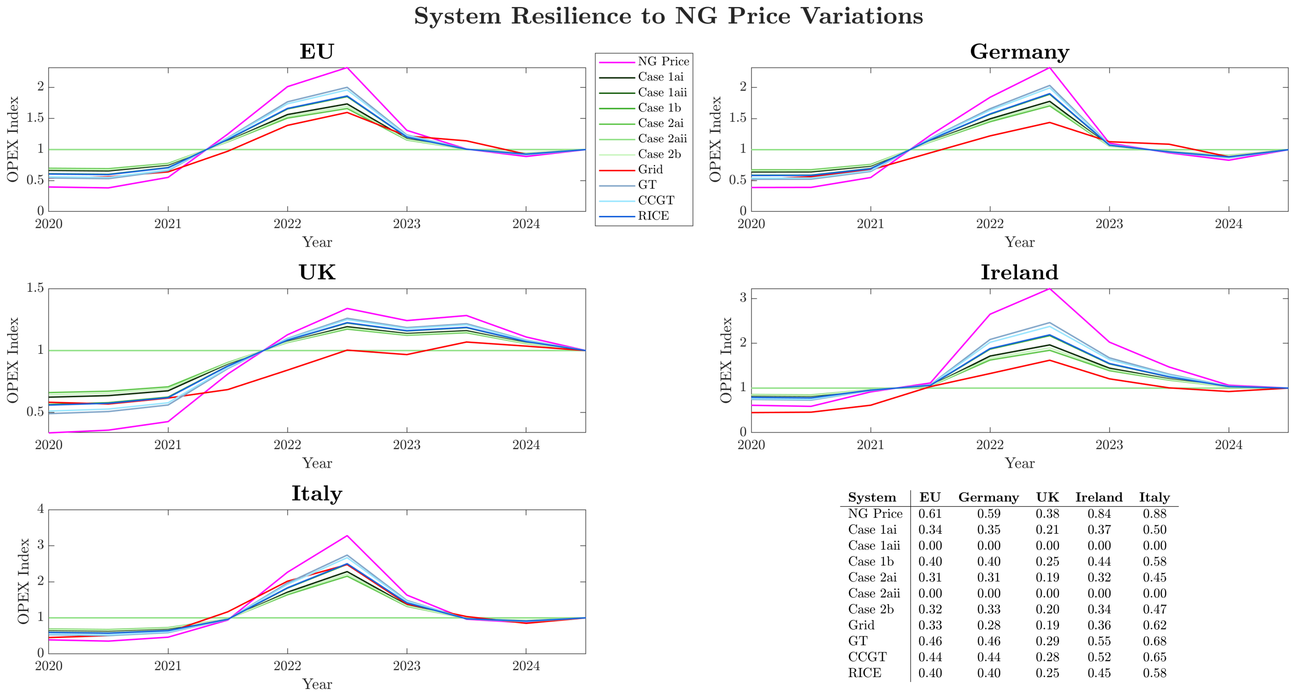
Cost predictability undoubtedly represents an asset for financial planning. If recent history is analyzed, this was far from the case. Gas prices had gigantic volatility in the period 2020-2025, affecting electricity prices along with them. This was particularly notorious in Italy, a bit more moderate in the EU, Germany, and Ireland, and comparatively low in the UK (Figure 4.32).

Given this landscape, when OPEX variations from on-site power generation systems are analyzed over the period, Bloom systems outperformed all other on-site technologies in terms of OPEX predictability across all regions. In every location, the variation in Bloom's operating costs was comparable to that of the grid—and in Italy, even lower across all Bloom configurations. This superior stability in operational expenses provides a critical hedge against fuel market volatility, enabling more robust and reliable long-term financial planning.

The reasons behind this phenomenon are the high cost predictability caused by the significant share of fixed OPEX in Bloom's LCOE structure as opposed to competitors, for which the weight of fuel costs is more determinant given their lower efficiencies.

Future Scenario

When considering the simultaneous evolution of hydrogen, natural gas and carbon prices, new phenomena begins to emerge. As Carbon prices go up, fossil technologies exhibit an increase of costs, moderated by the expected reduction in natural gas prices (Figure 4.33). On the other hand, as hydrogen prices follow its decreasing trend, technologies fueled by it are expected to reduce its costs significantly. Thus, as prices evolves towards 2050 forecasts, the competitive landscape is expected to present significant change.



System	EU	Germany	UK	Ireland	Italy
NG Price	0.61	0.59	0.38	0.84	0.88
Case 1ai	0.34	0.35	0.21	0.37	0.50
Case 1aii	0.00	0.00	0.00	0.00	0.00
Case 1b	0.40	0.40	0.25	0.44	0.58
Case 2ai	0.31	0.31	0.19	0.32	0.45
Case 2aii	0.00	0.00	0.00	0.00	0.00
Case 2b	0.32	0.33	0.20	0.34	0.47
Grid	0.33	0.28	0.19	0.36	0.62
GT	0.46	0.46	0.29	0.55	0.68
CCGT	0.44	0.44	0.28	0.52	0.65
RICE	0.40	0.40	0.25	0.45	0.58

Figure 4.32: System responses to natural gas prices fluctuations.

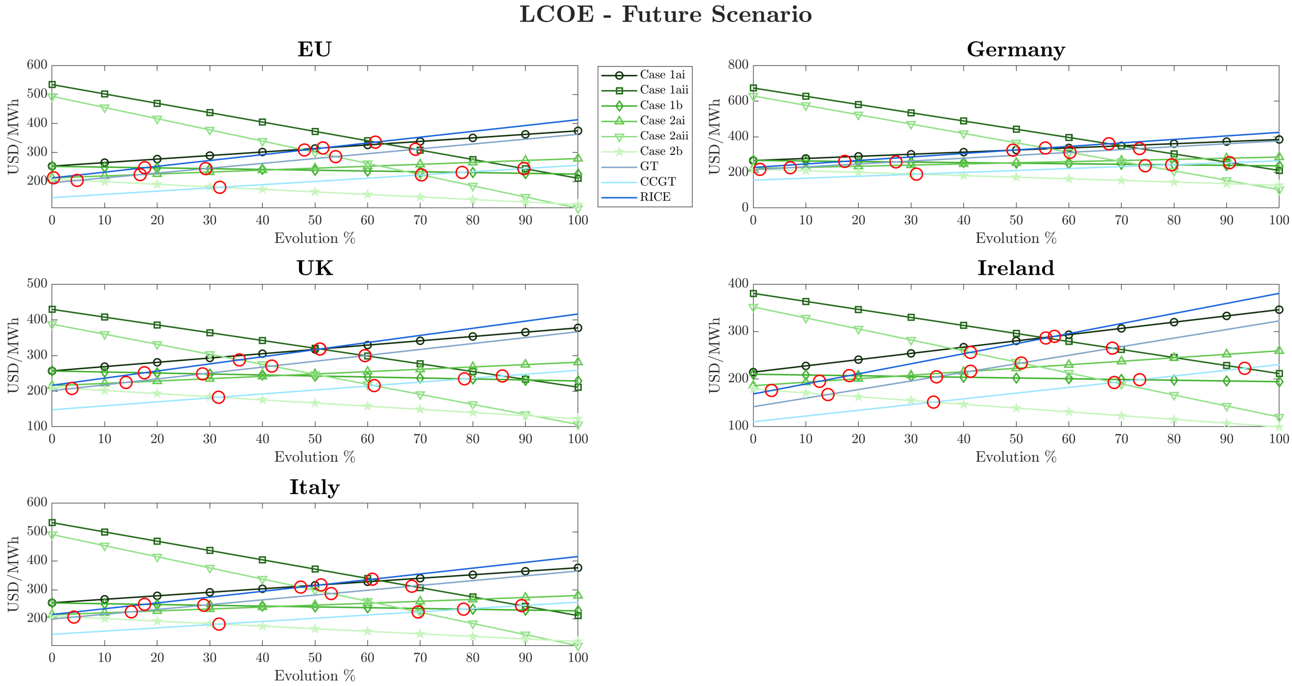


Figure 4.33: Future outlook based on natural gas, hydrogen and carbon prices.

Ceteris paribus, it is observed that even if the price evolutions considered would have different effects in different economies, a general tendency is maintained for all regions studied, with some minor exceptions for the Irish case. As Table 4.24 shows, Bloom Natural Gas CHP configurations could become more competitive than Gas Turbines in the short-medium term, given that prices evolve simultaneously in the 1-17% range towards 2050 values[16]. This is also true for RICE technologies, which in some locations were already found to exhibit higher LCOEs than Bloom's CHP options. Reaching cost parity with CCGT, though, would require further price development, and would only be achieved by hydrogen-fueled systems or ones coupled with carbon capture. Based on the models

[16]Note that the price evolutions of hydrogen, natural gas and carbon are not expected to be simultaneous nor linear, so estimating when this would happen would require further analysis studying actual independent price evolution curves.

developed, Bloom's CHP system with Carbon Capture would be the first Bloom configuration to achieve cost parity with CCGT, when prices approach one third of the 2050 expected prices.

Furthermore, CHP Hydrogen systems were found to be the most promising option within the hydrogen-fueled systems explored. According to the results obtained, cost pairing with RICE and GT could be obtained with a simultaneous price evolution in the 36-60% range. For these systems to approach CCGT's LCOEs, evolutions far into the 60-75% are to be expected.

Table 4.24: Hydrogen, natural gas and carbon evolution level towards 2050 forecasts at which price parity is achieved. IE represents Ireland.

Case	Description	GT	CCGT	RICE
1ai	Base NG	-	-	49–57
1aii	Base Hydrogen	68–73	86–93	51–68
1b	Base Carbon Capture	27–35	73–80	17–18
2ai	NG CHP	7–17; 41 (IE)	-	-; 13 (IE)
2aii	Hydrogen CHP	42–60	61–74	36–48
2b	Carbon Capture + CHP	1–5; 14 (IE)	31–34	-; 4 (IE)

It is important to note that this analysis assumes that all hydrogen, natural gas and carbon prices evolve simultaneously at the same pace. Of course, this represents an extreme oversimplification, but it is still useful to gain insights. Furthermore, another big limitation is that all other parameters apart from fuel and Carbon costs are considered constant to present values in the future, which is highly unlikely. Adding to this, future prices' uncertainty is significant and previous forecasts have shown notable deviations from reality in the past. Considering the present volatile geopolitical situation, this phenomenon could be highly accentuated.

Additionally, OPEX reduction in CHP cases still considers savings stemming from natural gas combustion for water heating purposes. This assumption may not render valid in the future, where technology adoption trends may favor alternative technologies.

Subsidies

Including the presence of CAPEX and OPEX subsidies, represented as percentages of total installation and fuel costs, respectively, implies a re-configuration of the competitive landscape in some locations when compared to the grid but no major differences in most cases within the subsidy ranges studied were found. While in the UK, Ireland and Germany, subsidies could mean a shift in the Bloom-grid price hierarchy for some cases, in Italy and average EU locations, the difference between grid prices and the ones achieved by on-site solutions makes that no reasonable level of subsidies changes it.

In the UK, for Natural Gas cases, Bloom outcompetes grid prices with no subsidies required. Furthermore, results suggest that Hydrogen cases here would be competitive with the grid only if a reduction of around 40-50% in fuel prices is achieved, and that CAPEX subsidies present little impact on resulting LCOEs due to the high share of fuel prices in it.

In Germany and Ireland, the impact of subsidies is more pronounced in Natural Gas cases, as in Hydrogen ones the distance between achievable Bloom costs under this fuel and grid prices is practically unbridgeable with reasonable subsidy levels. Natural gas-fueled systems tend to present comparable or greater variation on CAPEX subsidies than fuel ones under this scheme, given the already analyzed significant weight CAPEX has on the LCOE for Bloom cases. In Germany, NG CHP cases can achieve grid parity with sole 25% subsidies of either CAPEX or fuel, or linear combinations of the two, and adding Carbon Capture implies a slight decrease of these values, reaching 20%. Systems that do not incorporate CHP here remain far from the grid price, requiring strong subsidy levels to achieve parity, and for Hydrogen cases grid parity is not achieved within the studied subsidy range.

Finally, the distance between grid and achievable costs by Bloom systems in Italy and the EU-average is such that no reasonable level of subsidies makes grid parity feasible. However, grid parity does not represent the full picture. The need of reliable on-site solutions is a must in some cases and, as it was previously explored, Bloom presents significant advantages across multiple dimensions over on-site competitors.

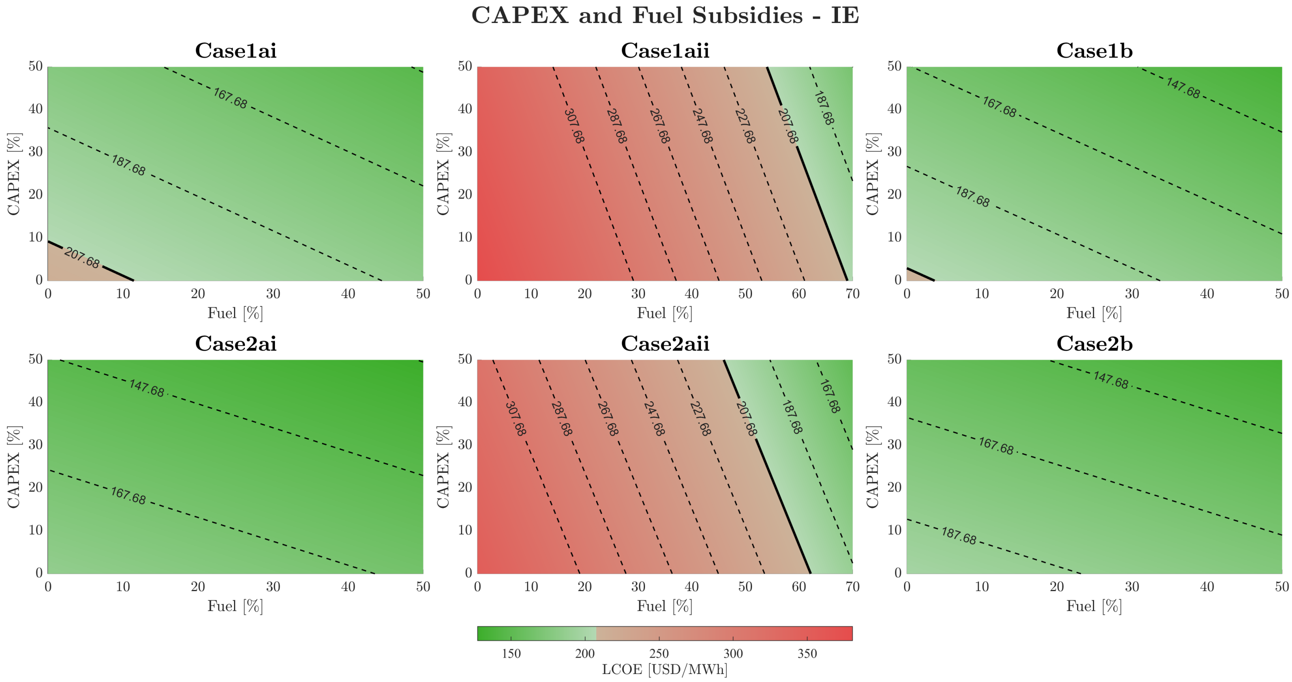


Figure 4.34: Results variation over CAPEX and OPEX subsidies, expressed as a percentage of fuel costs.

Performance Incentives

The addition of performance incentives for primary energy savings in CHP cases assuming a reference price of 300 €/TOE[17] implies that in the UK and Ireland, the resulting LCOEs for the NG CHP case stand well below local grid prices (Figure 4.35). For the German case, this is not true only for a very small margin, meaning that little increases in certificate prices over this value would mean grid parity, while for the average EU and Italian cases this is not the case even with strong increases in certificate prices. When adding carbon capture to the mix, the described situation does not change qualitatively, observed LCOEs only presenting a slight variation. Hydrogen CHP cases do not achieve grid parity even with the presence of high certificate prices within the range analyzed.

This analysis shows that location-specific assessments should be performed in order to determine the impact that these kind of measures have on incentivizing technologies such as SOFCs. As it was shown, the effectiveness of these initiatives are highly location-dependent, and more detailed and thorough analysis coupling the simplified one presented here with additional incentives and taxes would be needed to determine their actual impact on technology cost-competitiveness.

Accumulated Carbon Emissions

When analyzing the accumulated carbon emissions over a 20-year period for all power solutions studied, it is observed that Bloom systems present a notorious advantage over conventional on-site generation technologies. Even in the simple non-CHP Natural Gas configuration without carbon capture, the SOFC emits 5.363 kton CO_2 over a twenty-year period—27% less than a simple gas turbine at 7.388 kton and 36% lower than RICE at 8.369 kton. Switching this same configuration to Hydrogen eliminates direct emissions entirely, resulting in absolute savings of over 7.000 kton, and effectively achieving 100% abatement in each case.

[17] This is based on reference White Certificate prices for Italy.

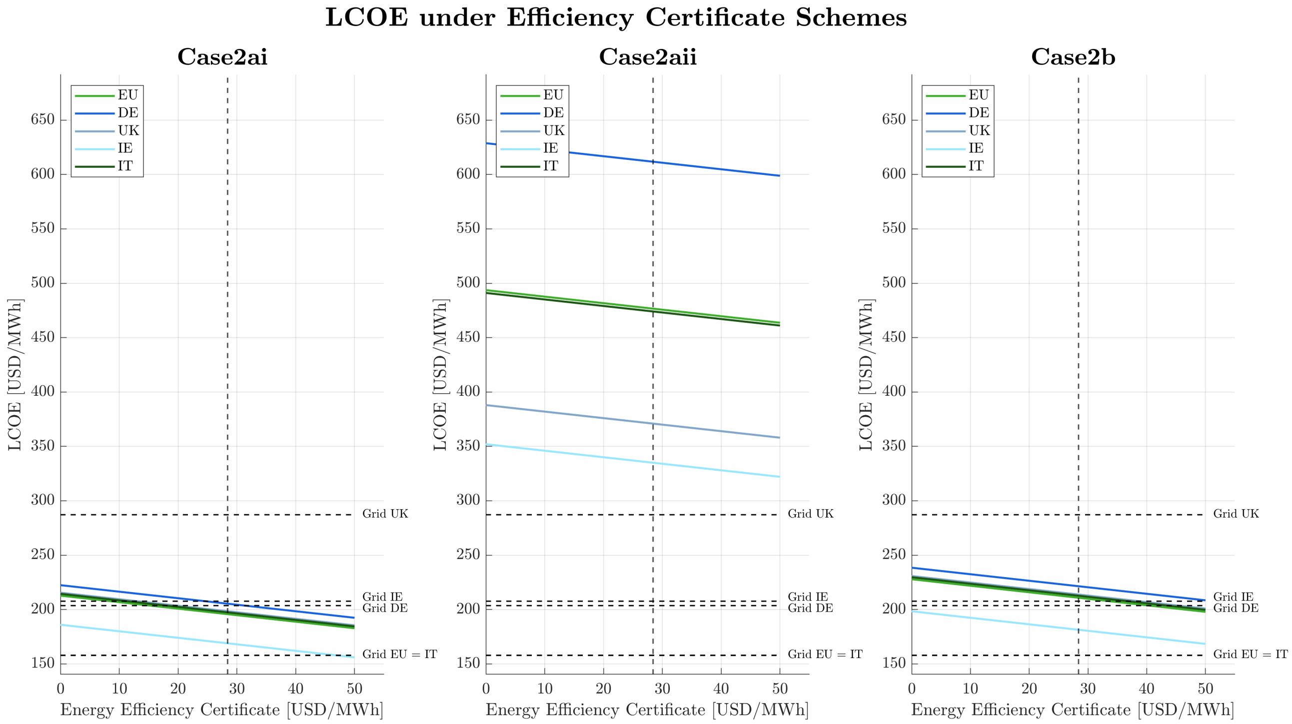


Figure 4.35: LCOE variation under different efficiency certificate prices for CHP systems.

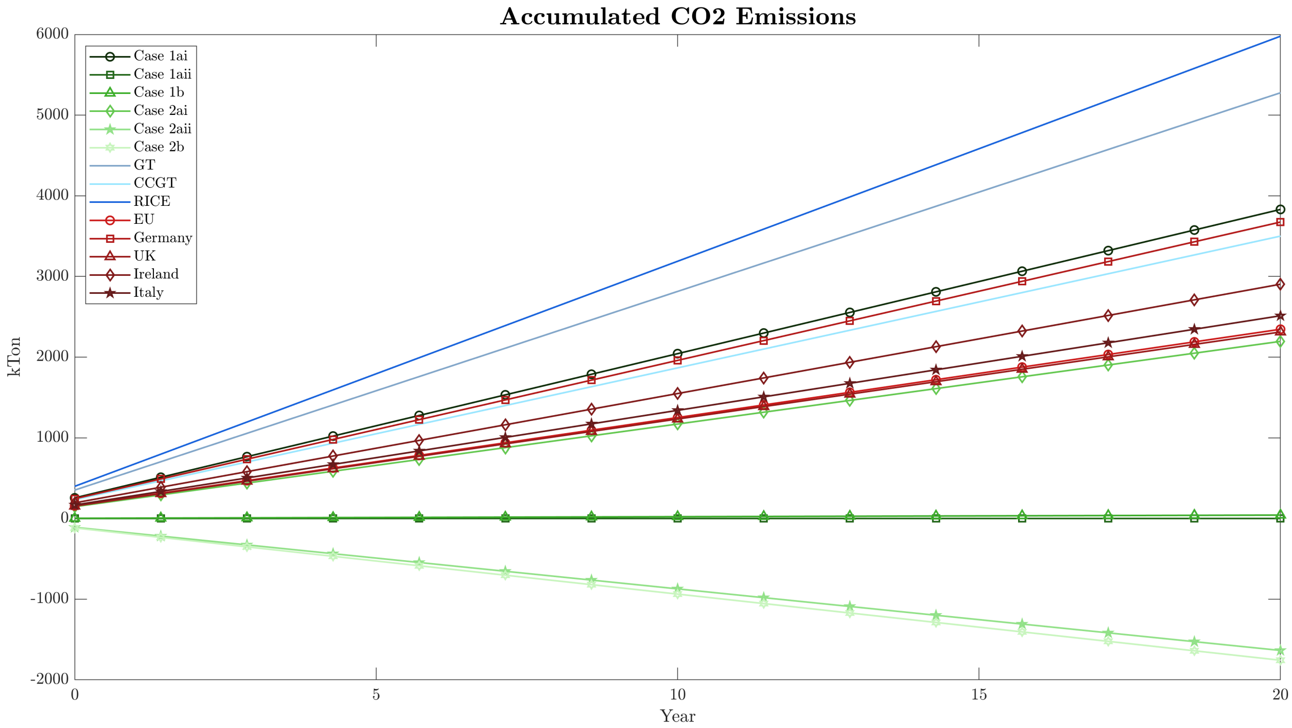


Figure 4.36: Accumulated carbon emissions over a 20-year period for different power supply technologies.

When carbon capture is added, emissions fall to just 57,7 kton, capturing nearly all direct CO_2. This yields a reduction of 7.330 kton versus GT (99,2%) and 8.311 kton versus RICE (99,3%). Even against a modern combined-cycle gas turbine (CCGT), which emits 4.900 kton, the capture-equipped SOFC achieves a 99% reduction, saving 4.842 kton.

In the CHP configuration, the emissions profile improves even further. The NG-fueled CHP SOFC without capture emits 3.073 kton, which represents a 58% reduction compared to GT and a 63% cut versus RICE. Transitioning this system to Hydrogen drives direct emissions to a net-negative balance of –2.290 kton. Compared to GT, this reflects a change of -131% (from +7.388 to –2.290 kton), and

-127% relative to RICE.

Finally, Hydrogen CHP and NG-CHP with Carbon Capture consist of the best performing cases in this regard. These achieve net-negative direct emissions of over –2.300 kton, highlighting their potential not only to increase system efficiencies but to avoid carbon emissions in external processes. It is important to note that, even if systems with Carbon Capture present more emissions per unit of energy produced than Hydrogen systems, their energy penalty implies more heat available and thus more fuel consumption for heating processes available.

When benchmarked against grid electricity mixes, the SOFC systems also show compelling advantages. Considering current emission factors, the average European gridwould emit 3.284 kton of CO_2, while national figures range from 3.237 kton in the UK to 5.144 kton in Germany. The NG SOFC CHP case already performs better than most grid mixes, emitting 3.073 kton—6.4 % less than the EU average and 40 % less than Germany's. Hydrogen-fueled and capture-equipped configurations outperform all grid references by a wide margin, achieving reductions well beyond 100% when accounting for fuel consumption avoided.

Results suggest that deploying Bloom SOFC systems for on-site generation can offer a lower-carbon alternative to grid reliance, especially in countries with more carbon-intensive electricity mixes. Particularly, hydrogen-fueled systems or ones coupled with carbon capture in CHP configurations, offer notorious reductions in emissions. These systems far exceed the performance of competitors, positioning SOFCs as a strategic enabler for decarbonizing high-density infrastructure like Data Centers.

Chapter 5

Conclusions

Data Centers are essential assets to support modern lifestyle, and their demand is likely to keep increasing as the digital economy and AI become even more integral to society. Moreover, as observed in the last years, their ever-increasing computational demand is unlikely to be offset by efficiency gains alone in the short-medium term: Data Centers will be one of the key drivers of European electricity demand in the next decade, largely contributing to its growth after years of stagnation. This, complemented equally by policy and regulatory efforts, suggests that the sector is expected to stand as one of the biggest investors in clean technologies in the near future.

The facilities' inherent high energy intensity, coupled with their usual substantial water consumption and short-cycle-hardware demand, significantly undermines the sustainability of the sector. This reinforces the sector's environmental footprint and illustrates the enduring tension between societal infrastructure needs and ecological preservation. It is undeniable that Data Centers are currently high-impact assets, yet their indispensable role in supporting modern economies makes their sustainable transformation both urgent and non-trivial.

Adding to these issues, the extreme geographical concentration observed within Europe brings about significant challenges to the industry, particularly in securing timely access to power. The current aging and underdeveloped grids cannot cope with the fast pace of Data Center deployment, causing both local infrastructure strains as well as development hurdles, as grid connection timelines do not match market time-to-power requirements.

Timely power access, added to reliability, cost and energy dependency considerations are increasingly driving Data Center operators to make use of on-site power solutions, sometimes even pushed by local authorities. These solutions reduce the load on the electricity grid, enhance the much-needed grid flexibility, and free up capacity for new developments requiring grid access, having a significant impact on the grid operator's ability to manage infrastructure efficiently and strategic planning. Additionally, these tend to largely reduce power access periods for developers, as well as mitigate their reliance on the power grids and potentially diminish the facilities' environmental impacts.

Bloom Energy could potentially play a key role in this evolving landscape. The company's SOFC systems represent a technically, economically, and environmentally robust solution. In addition to Bloom's proven reliability and industry experience, these offer a key strategic advantage: time-to-power. While traditional grid connections or alternative on-site solutions like Gas Turbines can require 3 to 10 years for full deployment, Bloom's modular systems can be operational in under a year, a decisive factor in high-revenue environments where delays translate to significant opportunity costs.

The study demonstrates that, beyond fast deployment, Bloom's systems offer superior efficiency and reliability compared to alternative solutions. Natural Gas CHP configurations were found to be particularly cost-competitive, frequently outperforming both other on-site technologies and the grid in terms of overall cost. In contrast, hydrogen-fueled systems remain economically unviable at current fuel prices—unless deployed in scenarios characterized by very long grid connection delays and strong subsidy support. Crucially, when opportunity costs—driven by time-to-power and Data Center lease revenues—are factored into the analysis, the competitive landscape shifts markedly. Bloom's deployment agility yields substantial economic benefits in regions with extended grid interconnection timelines and high lease rates, reinforcing its position, alongside Reciprocating Engines, as a leading solution. Conversely, technologies with significantly longer lead times, such as Gas Turbines and CCGTs, see their competitiveness considerably diminished under these conditions.

From an environmental perspective, Bloom's SOFCs consistently outperform other on-site technologies. Even baseline Natural Gas systems generate 28–36% less carbon emissions than Gas Turbines and Reciprocating Engines, with CHP and Carbon Capture options offering further reductions, in some cases even reaching net-negative emissions. Non-carbon emissions, land, and water use intensities also heavily favor these solutions—making them especially compelling in sustainability-sensitive regions. Furthermore, results show that carbon capture addition brings about considerable sustainability improvements at a marginal cost increase, so the role of this technology in the energy transition to fully green systems stands as a considerable opportunity.

Compared to competitors, Bloom's systems were found to have a more favorable sensitivity profile in some key cost drivers. Their lower exposure to CO_2 pricing reflects the systems' inherently low emissions, making them more resilient under tightening carbon regulations than competitors, and even presenting economic benefits with rising carbon prices in CHP systems with carbon capture or hydrogen as fuel. While interest rate sensitivity is somewhat higher due to larger upfront investments, this is offset by the lower operational cost volatility. Moreover, when factoring in opportunity costs tied to Data Center lease rates, Bloom consistently outperforms slower-deploying alternatives. In short, Bloom's advantage lies not only in its baseline competitiveness, but in its robustness under a variety of future policy, fuel price, and financial conditions, representing a key asset for long-term planning.

However, it is important to highlight that Bloom's current competitive edge is largely dependent the existing context of long grid interconnection timelines and the absence of robust, scalable, cost-competitive and fast-to-deploy clean alternatives. If electricity grid access were to become significantly faster and more predictable, and no stringent environmental constraints were applied, Bloom's comparative advantage could erode. This was clearly demonstrated by the dominance of opportunity-related variables such as lease rates and time-to-power differential as cost-drivers in the time-value sensitivity analysis developed. In such scenarios, Gas Turbines or CCGTs, which present both CAPEX and LCOE advantages, could reemerge as preferred options for on-site generation.

Furthermore, while results show potentially improved future competitiveness for Bloom under the explored scenarios, it is important to situate these findings within a wider landscape considering broader sources of uncertainty. Risks such as sudden changes in carbon pricing regimes, interest rates spikes, or changing permitting and zoning regulations could significantly alter the economic viability of the explored technologies. Similarly, rapid advancements in competing technologies such renewable systems coupled with energy storage, modular nuclear reactors, geothermal systems, or fast grid development efforts could reshape the competitive landscape in some locations. Despite these uncertainties, the flexibility, modularity, and robust supply chain of Bloom's SOFC systems position them as resilient assets under a variety of plausible future scenarios. These systems maintain strong performance not only under current conditions, but also under technically-feasible and policy-aligned pathways.

From a policy and regulatory perspective, the competitiveness of *Bloom Energy*'s SOFC systems is highly influenced by evolving frameworks. Carbon pricing mechanisms have the potential to shift the economic balance in favor of low-carbon solutions, especially when paired with carbon capture or hydrogen integration. If carbon prices rise in line with current projections, these technologies will become more cost competitive, at the same time that alternative, more polluting technologies, will be pushed to the opposite direction. Similarly, incentives such as tax credits for CHP systems or subsidies for green hydrogen use can substantially improve the cost-competitiveness of these technologies. Countries that implement such policies are expected to showcase an increase of low-carbon solutions for the sector. These policy levers, if effectively aligned, could magnify the economic and environmental advantages demonstrated in this study, suggesting a potential role for Bloom in supporting Europe's digital and energy transitions.

Moving to true net zero in the Data Center sector demands more than direct emissions reductions, though. While green hydrogen represents a promising low-carbon fuel, today it remains prohibitively expensive and its supply infrastructure is nascent; only transformative incentives and strategic public–private initiatives will ever make hydrogen-fueled SOFCs cost-competitive at scale. In the meantime, low-carbon pathways such as Natural-Gas CHP with Carbon Capture can drive direct CO_2 emissions close to zero in a more cost-effective manner. However, they still rely on fossil fuel inputs and present significant upstream and end-of-life impacts. At the same time, many leading operators have pledged ambitious carbon-free goals; yet, these efforts largely stop at energy procurement and fail to address Scope III emissions, mismatches between renewable generation profiles and real-time consumption, or lifecycle impacts. A genuine net zero agenda must therefore encompass cradle-to-grave considerations. Achieving this pathway is a formidable challenge, and current industry commitments fall far short of the comprehensive transformation required.

The obtained results present valuable insights on how Bloom systems and alternative power solutions perform on technical, economic and environmental dimensions in Data Center applications, including innovative approaches that broadened and deepened the understanding of these systems under a wide variety of scenarios and conditions. Despite this, the studies done could be further enhanced. Costs employed for the economic analysis developed were based on mixed estimations between literature data and Bloom's expertise. Future studies could either employ a fuel-specific bottom-up modeling from component-level designs or leverage real project data from operational Data Centers. Moreover, a geographical discrimination of cost weights could be performed to present location-specific cost structures, including incentives and local taxation schemes to increase economic modeling accuracy.

On the environmental front, developing a custom Life Cycle Analysis of Bloom's Energy Servers would be of an extreme interest to holistically evaluate its sustainability performance under a wide spectrum of dimensions on a cradle-to-grave basis, and compare the results with competitors. This would enable a more comprehensive benchmarking approach to consider all the elements in the power supply value chain and confirm if the overall impact situation has a correlate with the direct environmental impact considered. Moreover, it could enhance the sustainability of Bloom's products by optimizing the strategical development of design and manufacturing approaches to reduce lifecycle impact.

Additionally, exploring the integration of Bloom's SOFC systems into hybrid renewable configurations could offer significant value. By combining SOFCs with solar or wind systems, these setups could address the key intermittency and dispatchability limitations of renewables while reducing the overall environmental footprint of Data Center power supply in a cost-effective manner. Moreover, this approach could be further enhanced by integrating electrolysis and hydrogen storage, enabling the system to operate as a fully self-sufficient energy loop—independent of external fuel or grid supply, and capable of balancing loads through on-site hydrogen-fueled SOFCs. Even if currently these approaches may not be currently cost-effective, the identification and quantification of technical and economic barriers present could allow forward strategic planning to overcome these issues.

To conclude, as Data Centers become foundational to Europe's economic and digital future, the need for sustainable, fast-to-deploy, and reliable energy systems becomes urgent. This thesis has shown that *Bloom Energy*'s SOFC systems offer a combination of agility, efficiency, and environmental performance, with significant advantages in time-sensitive markets. Yet, the path to net zero is complex and will require sustained policy support, technology development, and lifecycle-level thinking. The next generation of infrastructure will be defined not only by cost or emissions, but by resilience to uncertainty, alignment with climate goals, and ability to adapt across markets. In this evolving landscape, *Bloom Energy* is well-positioned to play a leading role.

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Appendix A

Tables

Chapter Description

This section presents specification tables and auxiliary data used in the calculations.

Contents

A.1 Bloom Energy Server Specifications

Table A.1: Energy Server 6.5 Technical Highlights for natural gas (Bloom Energy, 2024b).

Parameter	Specification
Electrical output	325 kW, 480/415/400/380 V, 3-ph, 3W and 4W, 50/60 Hz
Fuel input	Natural Gas
Cumulative electrical efficiency	65 - 53% (LHV net AC)
Heat rate (HHV)	6.131 – 7.519 kJ/kWh
Average lifetime efficiency w/ thermal	>90% (exhaust heat available @ >350 ºC)
CO_2 emissions @ state efficiency	308 – 378 kg/MWh
NOx	0,001 kg/MWh
SOx	Negligible
CO	0,005 kg/MWh
Noise levels	<65 dBA @ 3 m
Operating temperature	-20 ºC to 45 ºC
Enclosure type	Outdoor

Continued on next page

Parameter	Specification
Altitude	<2,000 m
Seismic rating	ASCE7 SDC (Seismic Design Category) D
Weight (w/skid)	14,8 mt
Dimensions (w/skid)	9 m x 2,5 m x 1,3 m
Safety	FC1, UL 1741, UL 1998, CE, KESCO
Utility interaction	IEEE 1547 2018, UL 1741 SB, CA Rule 21, CEI 016, KEPCO, G99, C10/11, VDE
EMC	EN 55011/KN11, EN 61000, KN32, KN35
Data interface	Sunspec, Modbus, IEC 61850
External communication	CAN, Ethernet
Utility communication	IEEE 2030.5, DNP3

A.2 Low Heating Values

Table A.2: LHV of Natural Gas and Hydrogen for Selected Countries

Country	Natural Gas LHV [MJ/m³]		Hydrogen LHV [MJ/m³]	
	Value	Source	Value	Source
EU-27 average	35,23	(Eurostat, 2025a)	10,8	(TU Delft, 2025)
Germany	34,82	(Eurostat, 2025a)	10,8	(TU Delft, 2025)
Ireland	35,60	(Eurostat, 2025a)	10,8	(TU Delft, 2025)
Italy	34,23	(Eurostat, 2025a)	10,8	(TU Delft, 2025)
UK	35,58	(Eurostat, 2025a)	10,8	(TU Delft, 2025)

Appendix B

Technical Modeling of SOFCs

Chapter Description

This section presents an overview of the detailed concentrated parameters modeling of SOFC systems.

Contents

Although not directly applied in the main system analysis, a detailed understanding of concentrated-parameter modeling of SOFC systems provides valuable conceptual support. Here, the key electrochemical, thermodynamic, and reforming phenomena that govern SOFC behavior at the cell and stack level are presented. Next, the foundational equations describing current generation, voltage losses, internal reforming of methane, and heat flows within the cell are outlined.

B.1 General Cell Electrochemistry

Cell current. The current developed depends on the flow of reactants consumed at the anode $\dot{n}$. The relation between these variables can be obtained using the Faraday law (Santarelli, 2014a):

$$\dot{n}_f = \frac{I}{z_f F} = \frac{iA}{z_f F} \tag{B.1}$$

$$\dot{n}_{ox} = \frac{I}{z_{ox} F} = \frac{iA}{z_{ox} F} \tag{B.2}$$

Where I represents the total current, z the number of electrons transferred, F is Faraday's constant, A the active surface of the cell, f the fuel and ox the oxidant.

Cell Voltage. The voltage that an electrochemical fuel cell is able to produce is determined by the change in Gibbs free energy of the overall chemical reaction ΔG (Chaisantikulwat et al., 2008). The maximum voltage that can be achieved by a fuel cell, or equivalently, the reversible cell potential E_{rev} or the open circuit voltage V_{oc}, is determined by the Nernst law (Khotseng, 2019):

$$E_{rev} = \frac{\Delta G}{zF} \; , \tag{B.3}$$

This expression, by developing the Gibbs free energy term, can be shown equivalent to (Khotseng, 2019):

$$E_{rev} = -\frac{\Delta G^{\circ}}{zF} - \frac{RT}{zF} \ln \left(\frac{\prod_{\text{Products}} a_i^{\nu_i}}{\prod_{\text{Reactants}} a_i^{\nu_i}} \right) , \tag{B.4}$$

where $\Delta G^0(T)$ is the Gibbs free energy change at standard state, R the universal gas constant, T the temperature, a_i is the activity of species i, and ν_i is the stoichiometric coefficient of species i in the reaction.

The operating voltage V_{op}, though, is inevitably lower than the open circuit voltage V_{oc} due to the irreversibilities present in the system. Almutairi (2020) presents the following model for the operating voltage of the cell V_c:

$$V_{\text{c}} = V_{\text{c}}(i) = V_{\text{oc}} - \eta_{\text{ohm}} - \eta_{\text{act}} - \eta_{\text{dif}} , \tag{B.5}$$

where V_{op} is the cell voltage, V_{oc} is the open circuit potential, η_{ohm} is the ohmic polarization, η_{act} is the activation polarization and η_{diff} is the diffusion polarization and i is the cell current density.

These overpotentials η_i are described as the following:

- η_{act} is related to the charge transfer processes occurring during the electrochemical reactions on electrode surfaces, and it depends on the nature of type of electrode, ionic interactions, ion-solvent interactions and the electrode-electrolyte interface (Khotseng, 2019). The activation polarization is usually expressed using the Butler–Volmer equation, which can be simplified to (Santarelli, 2014b):

$$\eta_{\text{act}} = \eta_a + \eta_c = \frac{R \cdot T}{\alpha^a \cdot F} \cdot \sinh^{-1}\left(\frac{i}{2 \cdot i_{0,a}}\right) + \frac{R \cdot T}{\alpha^c \cdot F} \cdot \sinh^{-1}\left(\frac{i}{2 \cdot i_{0,c}}\right) , \tag{B.6}$$

  where η_a and η_c are the anodic and cathodic overpotentials, α^a and α^c, the anodic and cathodic charge transfer coefficients, and $i_{0,a}$ and $i_{0,c}$ the anodic and cathodic exchange current densities.

- η_{ohm} is the sum of anode, cathode and electrolyte resistances, being the last one the most important contribution (Khotseng, 2019). This can be expressed as the product of the Area Specific Resistance ASR and the current density i (Das et al., 2007):

$$\eta_{ohm} = ASR \cdot i \tag{B.7}$$

- η_{act}: occurs due to a decrease in the concentration of the reactants at the catalyst due to mass transport constraints at high currents (Khotseng, 2019). A simple model presented by Almutairi (2020) represents this overpotential as

$$\eta_{\text{dif}} = \frac{RT}{nF} \ln\left(1 - \frac{i}{i_L}\right), \tag{B.8}$$

  where i_L is the limiting current estimated from the overall mass transfer coefficient.

Cell Power Calculation. The power developed by a cell can be calculated by multiplying the current by the developed voltage:

$$P_{\text{cell}} = i \cdot A \cdot V_c \tag{B.9}$$

Stack Power Calculation. To obtain the total stack power, the power developed by a cell needs to be multiplied by the total number of cells n_{cells}.

$$P_{\text{stack}} = P_{\text{cell}} \cdot n_{\text{cells}} \tag{B.10}$$

Internal reforming In the case of operation with hydrocarbons, an internal reforming process takes place within the anode of the cells. The most common hydrocarbon fuel for SOFCs is methane, which undergoes a reforming reaction in the presence of steam (Santarelli, 2014a):

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \ , \tag{B.11}$$

which is endothermic and dependent on temperature.
Additionally, the water-gas shift (WGS) reaction occurs (Santarelli, 2014a):

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \ , \tag{B.12}$$

which is exothermic and regulates the composition of the gas mixture inside the anode.
That is, the hydrogen produced after the internal reforming is the main fuel of the cell (Santarelli, 2014a).

The equilibrium constants for these reactions are given by the following expressions (Santarelli, 2014a):

$$K_{\text{p},reforming} = \frac{p_{\text{CO}} \cdot p_{\text{H}_2}^3}{p_{\text{CH}_4} \cdot p_{\text{H}_2\text{O}}} \tag{B.13}$$

$$K_{\text{p},WGS} = \frac{p_{\text{CO}_2} \cdot p_{\text{H}_2}}{p_{\text{CO}} \cdot p_{\text{H}_2\text{O}}} \tag{B.14}$$

where p_i represents the partial pressure of species i.

If we define:

- $x_1 \rightarrow$ mol/s of CH_4 that reacts
- $x_2 \rightarrow$ mol/s of CO that reacts
- $x_3 \rightarrow$ mol/s of H_2 that reacts

The system of three nonlinear equations (Equation B.16 - Equation B.18) is solved for the three unknowns (x_1, x_2, x_3), with K_p expressed in terms of molar fractions y_i (Santarelli, 2014a):

$$y_i = \frac{p_i}{p_{cell}} \tag{B.15}$$

$$Kp_{\text{reforming}} = \left\{ \frac{\left(\frac{CO_i + x_1 - x_2}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{H_{2i} + 3 \cdot x_1 + x_2 - x_3}{\dot{n}_i + 2 \cdot x_1}\right)^3}{\left(\frac{CH_{4i} - x_1}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{H_2O_i - x_1 - x_2 + x_3}{\dot{n}_i + 2 \cdot x_1}\right)} \right\} p_{\text{cell}}^2 \tag{B.16}$$

$$Kp_{\text{shift}} = \left\{ \frac{\left(\frac{H_{2i} + 3 \cdot x_1 + x_2 - x_3}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{CO_{2i} + x_2}{\dot{n}_i + 2 \cdot x_1}\right)}{\left(\frac{CO_i + x_1 - x_2}{\dot{n}_i + 2 \cdot x_1}\right)\left(\frac{H_2O_i - x_1 - x_2 + x_3}{\dot{n}_i + 2 \cdot x_1}\right)} \right\} \tag{B.17}$$

$$x_3 = U_f \cdot (3 \cdot x_1 + x_2 + H_{2i}) \tag{B.18}$$

where:

- CO_i, H_2O_i, CH_{4i}, H_{2i}, CO_{2i} are inlet mole flows to the stack.
- $\dot{n}_i$ is the total mole flow into the stack.
- U_f is the fuel utilization coefficient in the cell.

Having the set of solutions x_1, x_2, x_3, the composition of the exit flow e of the anode can be calculated as (Santarelli, 2014a):

$$\dot{n}_{CH_4,e} = \dot{n}_{CH_4,i} - x_1 \tag{B.19}$$

$$\dot{n}_{CO,e} = \dot{n}_{CO,i} + x_1 - x_2 \tag{B.20}$$

$$\dot{n}_{CO_2,e} = \dot{n}_{CO_2,i} + x_2 \tag{B.21}$$

$$\dot{n}_{H_2O,e} = \dot{n}_{H_2O,i} - x_1 - x_2 + x_3 \tag{B.22}$$

$$\dot{n}_{H_2,e} = \dot{n}_{H_2,i} + 3x_1 + x_2 - x_3 \tag{B.23}$$

The relation between the current I and the mole flow of hydrogen consumed x_3 is given by Faraday's law (Santarelli, 2014a):

$$I = x_3 \cdot 2F \tag{B.24}$$

B.2 Thermodynamic Balance of the Cell

Santarelli (2014a) provides the following models to describe the different heat flows ϕ of the cell:

- **Electrochemistry**

$$\phi_{\text{ech}} = n_{\text{cell}} \cdot I \cdot \left(\frac{-\Delta h(T_{\text{cell}})}{2 \cdot F} - V_c \right) \tag{B.25}$$

For the case of methane fuel, these heat flows should also be considered (Santarelli, 2014a):

- **Reforming at T_{cell}**

$$\phi_{\text{ref}} = x_1 \cdot \left(3 \cdot \bar{h}_{H_2} + \bar{h}_{CO} - \bar{h}_{H_2O} - \bar{h}_{CH_4} \right) \tag{B.26}$$

- **Water Gas Shift**

$$\phi_{\text{shift}} = x_2 \cdot \left(\bar{h}_{H_2} + \bar{h}_{CO_2} - \bar{h}_{CO} - \bar{h}_{H_2O} \right) \tag{B.27}$$

Appendix C

Results Summary

Chapter Description

This section presents a table summarizing the key results obtained.

Table C.1: Key results from the techno-economic and environmental study developed.

Summary of key results										
			1			**2**				
	Configuration	Wasted Heat			CHP - Hot Water Production			**Competitors**		
	Case	a		b	a		b			
	Subcase	i	ii	-	i	ii	-			
	Carbon Capture	No	No	Yes	No	No	Yes			
Variable	**Fuel**	NG	H_2	NG	NG	H_2	NG	**GT**	**CCGT**	**RICE**
Performance										
Electrical Efficiency	%	54%	54%	54%	54%	54%	54%	38%	60%	47%
Total Efficiency	%	54%	54%	54%	81%	81%	81%	38%	60%	47%
Net Useful Electrical Efficiency	%	54%	54%	49%	54%	54%	49%	38%	60%	47%
Net Useful Total Efficiency	%	54%	54%	49%	81%	81%	77%	38%	60%	47%
Net Electrical Power Supplied	MW	100,0	100,0	110,0	100,0	100,0	110,0	100,0	100,0	100,0
	MWh/year	744600	744600	819060	744600	744600	819060	744600	744600	744600
Thermal Power Supplied	MW	0,0	0,0	0,0	50,8	50,8	55,9	0,0	0,0	0,0
	MWh/year	0,0	0,0	0,0	378101,2	378101,2	415911,3	0,0	0,0	0,0
Hot water Produced	kg/h	0,0	0,0	0,0	484,7	484,7	533,1	0,0	0,0	0,0
	ton/year	0,0	0,0	0,0	3608767,2	3608767,2	3969644,0	0,0	0,0	0,0
Fuel Power	MW	185,2	185,2	203,7	185,2	185,2	203,7	261,4	166,7	211,0
Fuel Energy	MWh/yr	1378889	1378889	1516778	1378889	1378889	1516778	1946031	1241000	1570886
Direct Fuel consumption										
EU-27	m3/h	1,89E+04	6,17E+04	2,08E+04	1,89E+04	6,17E+04	2,08E+04	2,67E+04	1,70E+04	2,16E+04
	m3/yr	1,41E+08	4,60E+08	1,55E+08	1,41E+08	4,60E+08	1,55E+08	1,99E+08	1,27E+08	1,61E+08
Germany	m3/h	1,91E+04	6,17E+04	2,11E+04	1,91E+04	6,17E+04	2,11E+04	2,70E+04	1,72E+04	2,18E+04
	m3/yr	1,43E+08	4,60E+08	1,57E+08	1,43E+08	4,60E+08	1,57E+08	2,01E+08	1,28E+08	1,62E+08
UK	m3/h	1,87E+04	6,17E+04	2,06E+04	1,87E+04	6,17E+04	2,06E+04	2,64E+04	1,69E+04	2,13E+04
	m3/yr	1,40E+08	4,60E+08	1,53E+08	1,40E+08	4,60E+08	1,53E+08	1,97E+08	1,26E+08	1,59E+08
Ireland	m3/h	1,87E+04	6,17E+04	2,06E+04	1,87E+04	6,17E+04	2,06E+04	2,64E+04	1,69E+04	2,13E+04
	m3/yr	1,39E+08	4,60E+08	1,53E+08	1,39E+08	4,60E+08	1,53E+08	1,97E+08	1,25E+08	1,59E+08

Table C.1 continued from previous page

Summary of key results										
		1			**2**			**Competitors**		
	Configuration	Wasted Heat			CHP - Hot Water Production					
	Case	a		b	a		b			
	Subcase	i	ii	-	i	ii	-			
	Carbon Capture	No	No	Yes	No	No	Yes			
Variable	**Fuel**	NG	H_2	NG	NG	H_2	NG	**GT**	**CCGT**	**RICE**
Italy	m3/h	1,95E+04	6,17E+04	2,14E+04	1,95E+04	6,17E+04	2,14E+04	2,75E+04	1,75E+04	2,22E+04
	m3/yr	1,45E+08	4,60E+08	1,60E+08	1,45E+08	4,60E+08	1,60E+08	2,05E+08	1,31E+08	1,65E+08
Net Fuel consumption										
EU-27	m3/h	1,89E+04	6,17E+04	2,08E+04	1,37E+04	4,48E+04	1,51E+04	2,67E+04	1,70E+04	2,16E+04
	m3/yr	1,41E+08	4,60E+08	1,55E+08	1,02E+08	3,34E+08	1,12E+08	1,99E+08	1,27E+08	1,61E+08
Germany	m3/h	1,91E+04	6,17E+04	2,11E+04	1,39E+04	4,48E+04	1,53E+04	2,70E+04	1,72E+04	2,18E+04
	m3/yr	1,43E+08	4,60E+08	1,57E+08	1,03E+08	3,34E+08	1,14E+08	2,01E+08	1,28E+08	1,62E+08
UK	m3/h	1,87E+04	6,17E+04	2,06E+04	1,36E+04	4,48E+04	1,50E+04	2,64E+04	1,69E+04	2,13E+04
	m3/yr	1,40E+08	4,60E+08	1,53E+08	1,01E+08	3,34E+08	1,11E+08	1,97E+08	1,26E+08	1,59E+08
Ireland	m3/h	1,87E+04	6,17E+04	2,06E+04	1,36E+04	4,48E+04	1,50E+04	2,64E+04	1,69E+04	2,13E+04
	m3/yr	1,39E+08	4,60E+08	1,53E+08	1,01E+08	3,34E+08	1,11E+08	1,97E+08	1,25E+08	1,59E+08
Italy	m3/h	1,95E+04	6,17E+04	2,14E+04	1,41E+04	4,48E+04	1,55E+04	2,75E+04	1,75E+04	2,22E+04
	m3/yr	1,45E+08	4,60E+08	1,60E+08	1,05E+08	3,34E+08	1,16E+08	2,05E+08	1,31E+08	1,65E+08
Environmental										
Emissions										
CO2										
Total Scope I emissions	kTon/year	255,4	0,0	274,7	255,4	0,0	280,9	351,0	232,8	297,2
Avoided Emissions	kg/year	0,0	0,0	272,0	109,0	109,0	398,1	0,0	0,0	0,0
Net Scope I emissions	kTon/year	255,4	0,0	2,7	146,4	-109,0	-117,1	351,8	233,3	398,5
Total upstream emissions	kTon/year	47,654	3,171	51,257	33,135	2,205	36,449	67,3	42,9	54,3
Well-to-Energy total emissions	kTon/year	303,052	3,171	54,004	179,491	-106,837	-80,689	419,1	276,2	452,8
NOx	kg/year	744,600	0,00	800,892	-98859,861	-99604,461	-108745,847	1021033,5	677230,4	11024178,3
SOx	kg/year	3,425	0,00	3,684	-757,819	-761,244	-833,600	10848,5	7195,6	1588,8

Table C.1 continued from previous page

Summary of key results										
		1			**2**				**Competitors**	
	Configuration	Wasted Heat			CHP - Hot Water Production					
	Case	a		b	a		b			
	Subcase	i	ii	-	i	ii	-			
	Carbon Capture	No	No	Yes	No	No	Yes			
Variable	**Fuel**	NG	H_2	NG	NG	H_2	NG	**GT**	**CCGT**	**RICE**
CO	kg/year	3723,000	0,00	4004,459	-22447,985	-26170,985	-24692,783	261639,8	173540,3	856535,4
CH4	kton CO2e/year	0,000	0,00	0,000	-0,1345	-0,1345	-0,1479	0,823	0,546	101,325
VOCs	kg/year	2978,400	0,00	3203,567	-1503,780	-4482,180	-1654,158	6700,5	4444,3	318836,5
UHC	kg/year	2978,400	0,00	3203,567	-4930,933	-7909,333	-5424,026	62538,3	41215,6	7349452,2
PM2.5	kg/year	0,000	0,00	0,000	-591,963	-591,963	-651,159	1276,3	846,5	208,3
Noise										
Water Consumption										
Total annual water consumption	m3/year	2851,8	2851,8	3067,4	2851,8	2851,8	3137,0	2851,8	2851,8	2851,8
Land Use										
Total land use	m^2	5905,9	5905,9	5905,9	5905,9	5905,9	5905,9	5905,9	9440,0	9440,0
Land use per annual energy produced	m^2/MWh	0,8	0,8	0,8	0,8	0,8	0,8	0,8	1,3	1,3
Economics										
CAPEX	M$	761,4	761,4	805,7	762,2	762,2	851,0	154,0	286,0	402,6
Fixed OPEX	M$/ year	40,8	40,8	41,2	40,8	40,8	44,2	5,1	4,4	4,5
Variable OPEX										
EU-27	M$/year	91,6	300,8	93,9	61,5	270,7	48,2	132,0	86,8	124,0
Germany	M$/year	101,9	404,5	104,9	68,7	371,3	56,1	146,5	96,1	135,7
UK	M$/year	94,5	223,0	97,0	63,5	192,0	50,4	136,1	89,4	127,3
Ireland	M$/year	63,0	186,6	63,0	41,6	165,2	26,2	91,5	61,0	91,3
Italy	M$/year	93,4	299,4	95,8	62,8	268,8	49,6	134,5	88,4	126,1
LCOE										

Table C.1 continued from previous page

Summary of key results										
		1			**2**			**Competitors**		
	Configuration	Wasted Heat			CHP - Hot Water Production					
	Case	a		b	a		b			
	Subcase	i	ii	-	i	ii	-			
	Carbon Capture	No	No	Yes	No	No	Yes			
Variable	**Fuel**	NG	H_2	NG	NG	H_2	NG	**GT**	**CCGT**	**RICE**
w.o. Opportunity Costs										
EU-27	\$/MWh	253,1	534,0	261,1	212,8	493,7	208,1	196,0	144,7	212,4
Germany	\$/MWh	267,0	673,3	276,0	222,4	628,8	218,7	215,5	157,2	228,2
UK	\$/MWh	257,0	429,5	265,3	215,5	388,0	211,1	201,5	148,2	216,8
Ireland	\$/MWh	214,6	380,6	219,6	186,0	352,0	178,7	141,7	110,0	168,5
Italy	\$/MWh	255,6	532,2	263,7	214,5	491,1	210,0	199,4	146,9	215,2
w. Opportunity Costs										
EU-27	\$/MWh	197,1	478,0	205,1	156,8	437,7	152,1	322,3	305,3	166,7
Germany	\$/MWh	192,9	599,3	201,9	148,4	554,7	144,7	304,4	275,5	163,0
UK	\$/MWh	138,7	311,2	146,9	97,2	269,6	92,8	208,6	175,0	104,5
Ireland	\$/MWh	141,0	307,0	146,0	112,4	278,4	105,0	191,3	181,5	101,4
Italy	\$/MWh	217,7	494,4	225,9	176,7	453,3	172,2	285,6	257,3	184,3

Appendix D

Additional Results

Chapter Description

This section presents results not presented in the main document for conciseness purposes.

Contents

D.1 Environmental Analysis

NOx

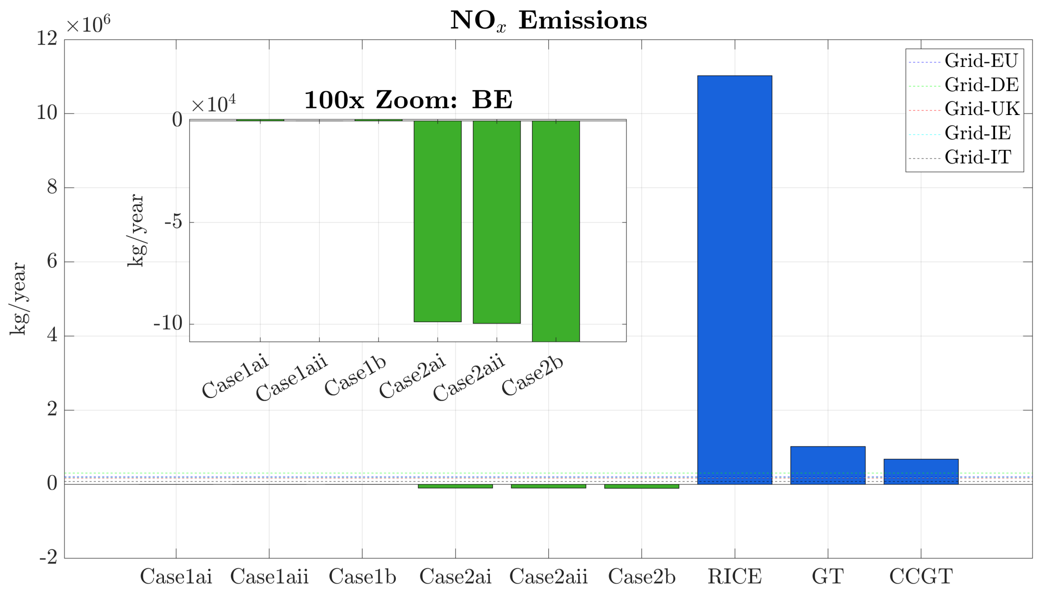

Figure D.1: NOx emissions of Bloom and competitor power systems.

SOx

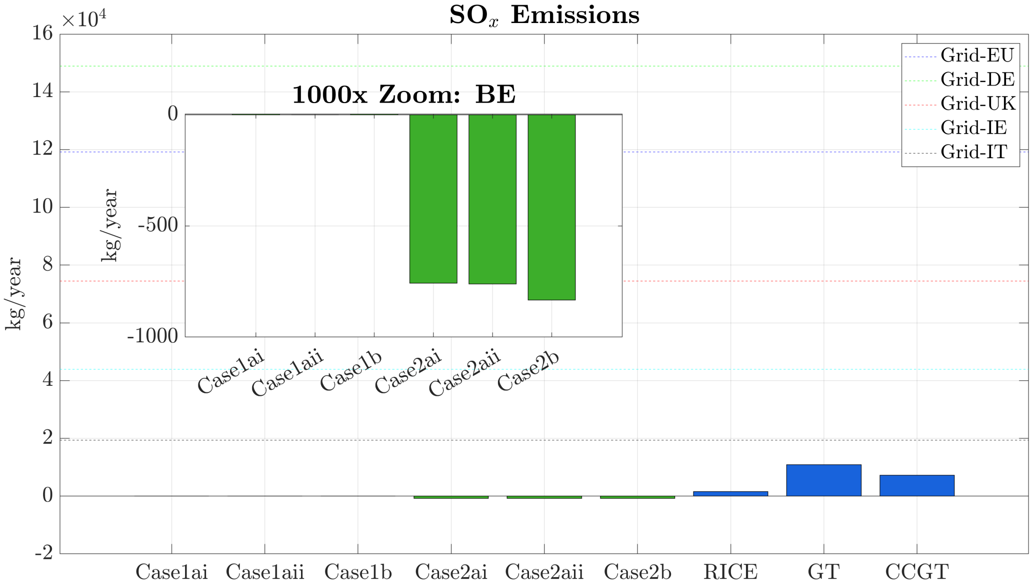

Figure D.2: SOx emissions of Bloom and competitor power systems.

CO

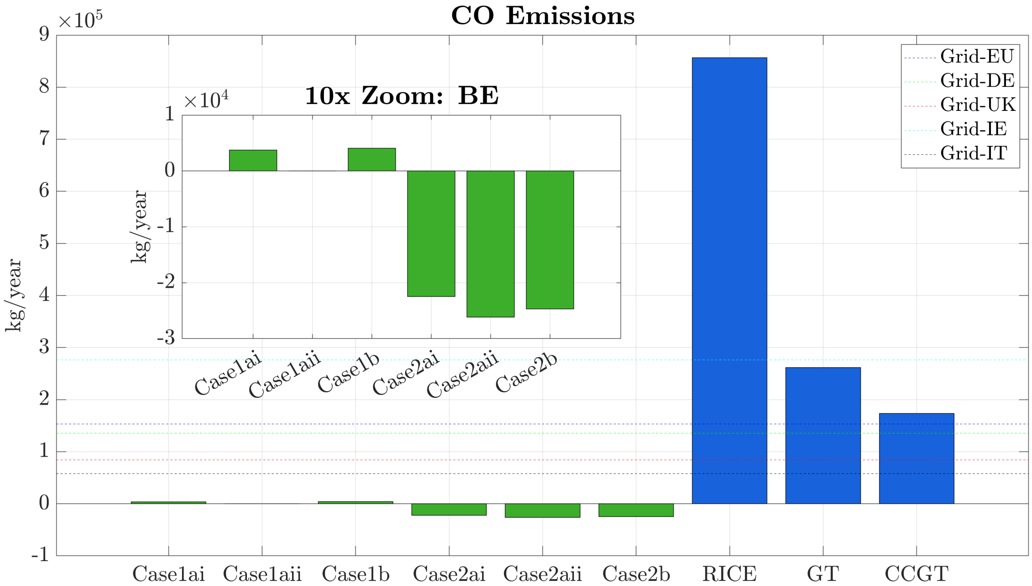

Figure D.3: CO emissions of Bloom and competitor power systems.

Methane Slip

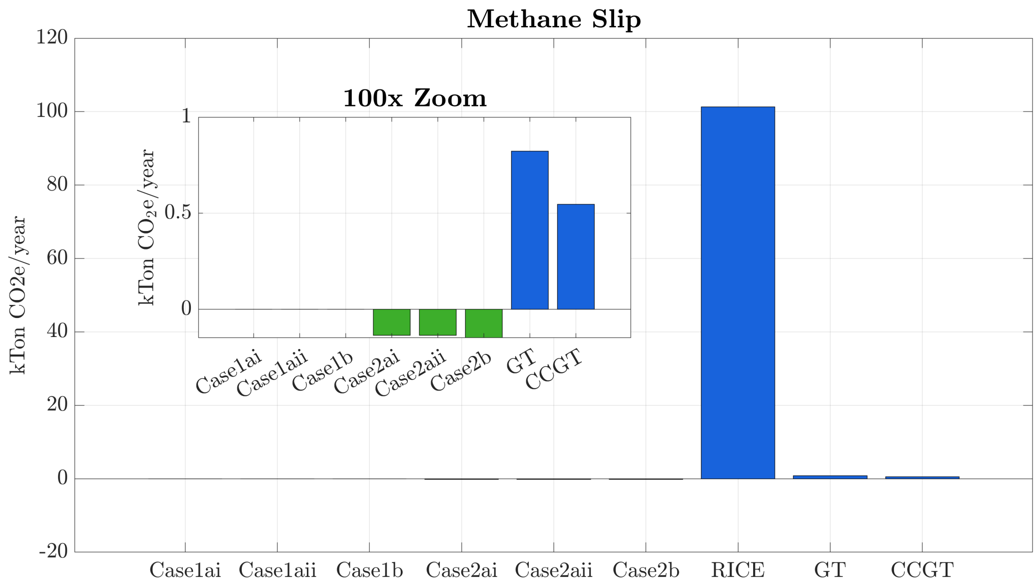

Figure D.4: Methane emissions of Bloom and competitor power systems.

VOCs

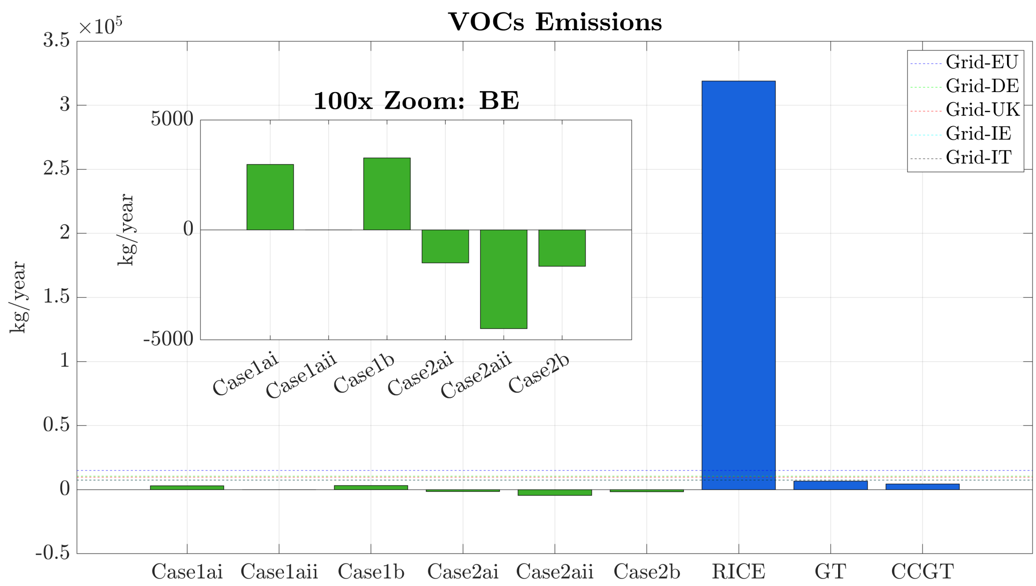

Figure D.5: VOCs emissions of Bloom and competitor power systems.

PM2.5

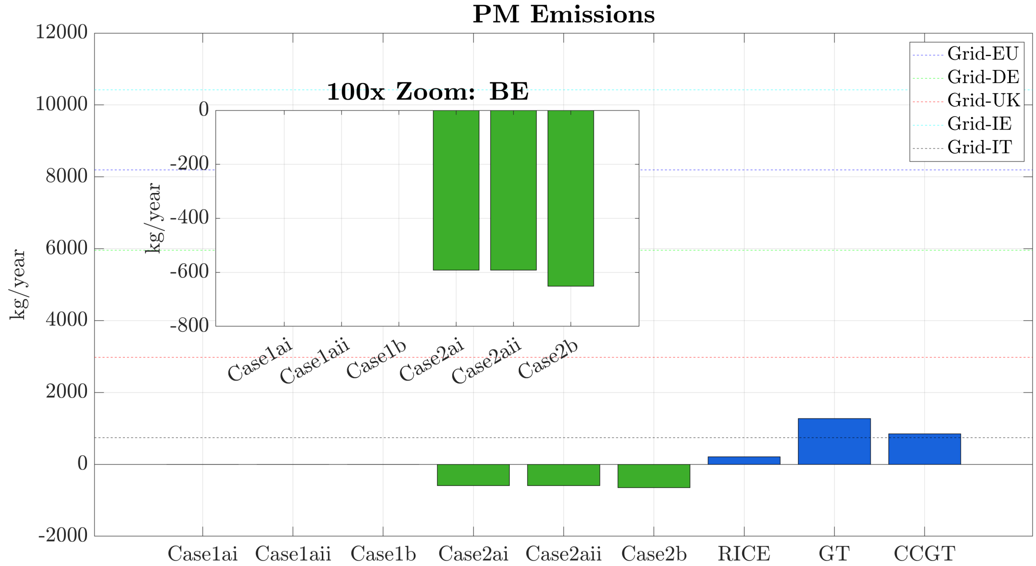

Figure D.6: Particulate matter emissions of Bloom and competitor power systems.

D.2 Fuel Sensitivity Analysis

European Union

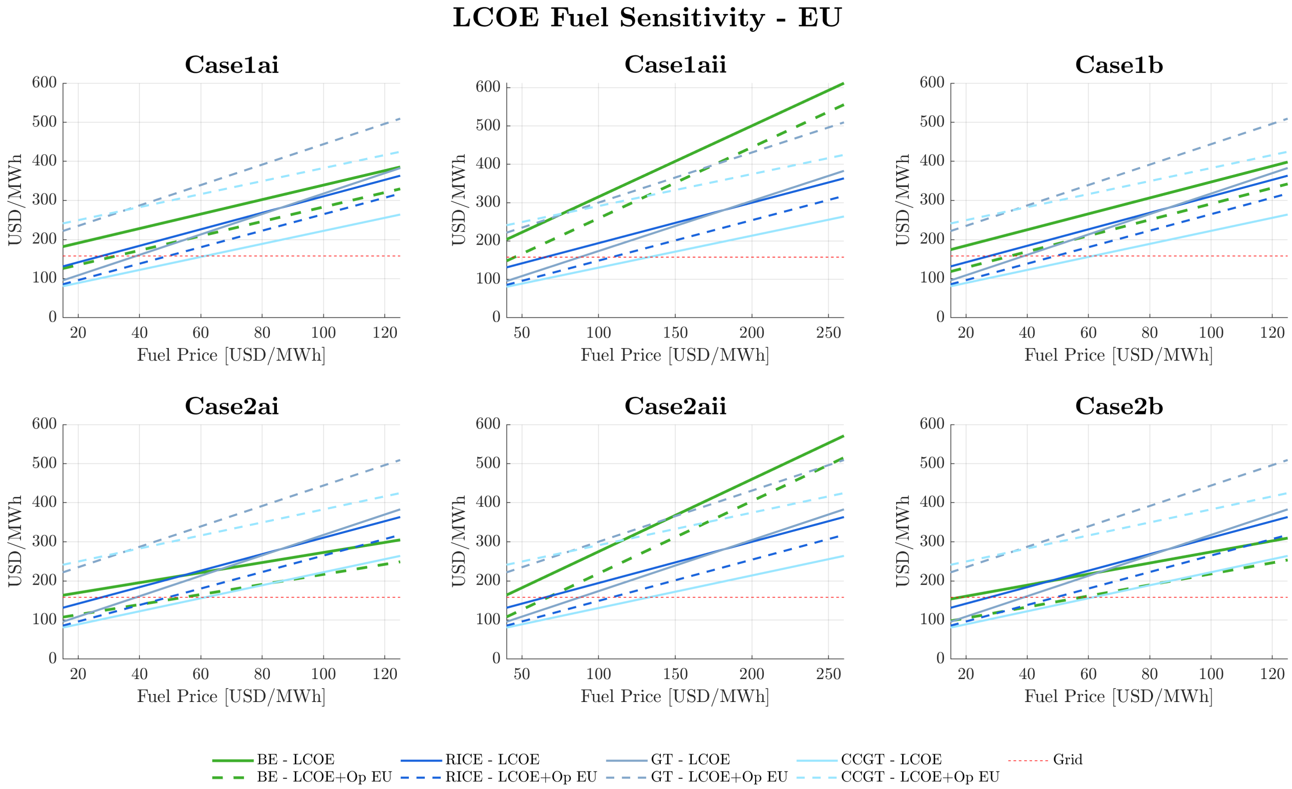

Figure D.7: LCOE fuel sensitivity in the EU.

Germany

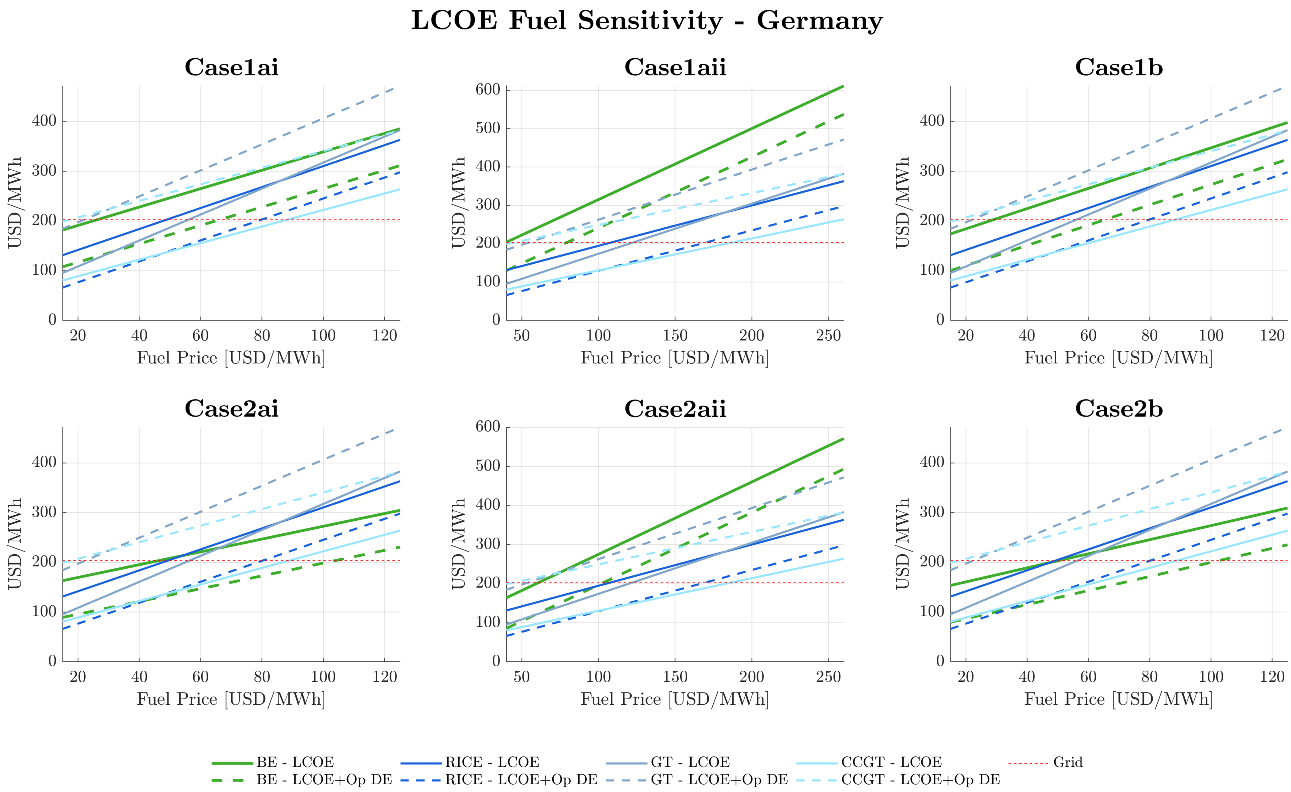

Figure D.8: LCOE fuel sensitivity in Germany.

United Kingdom

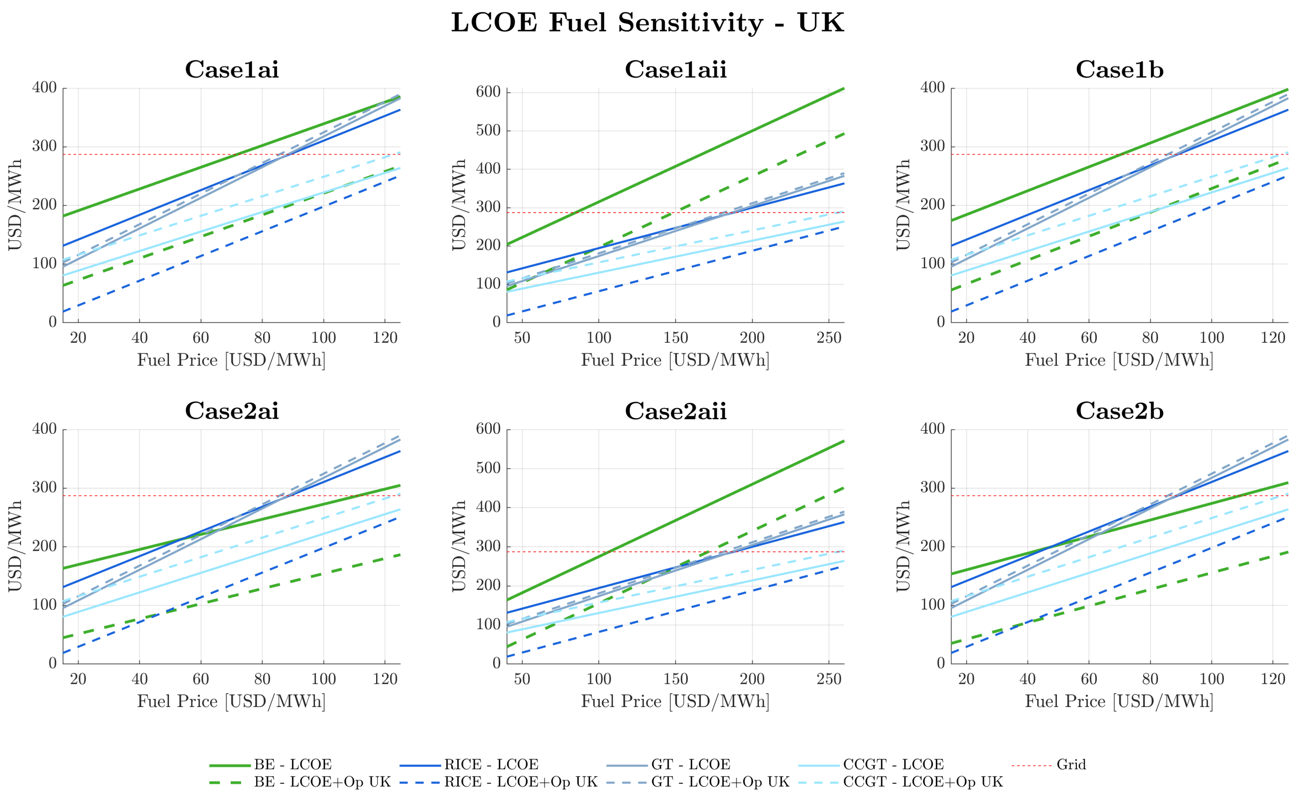

Figure D.9: LCOE fuel sensitivity in the UK.

Ireland

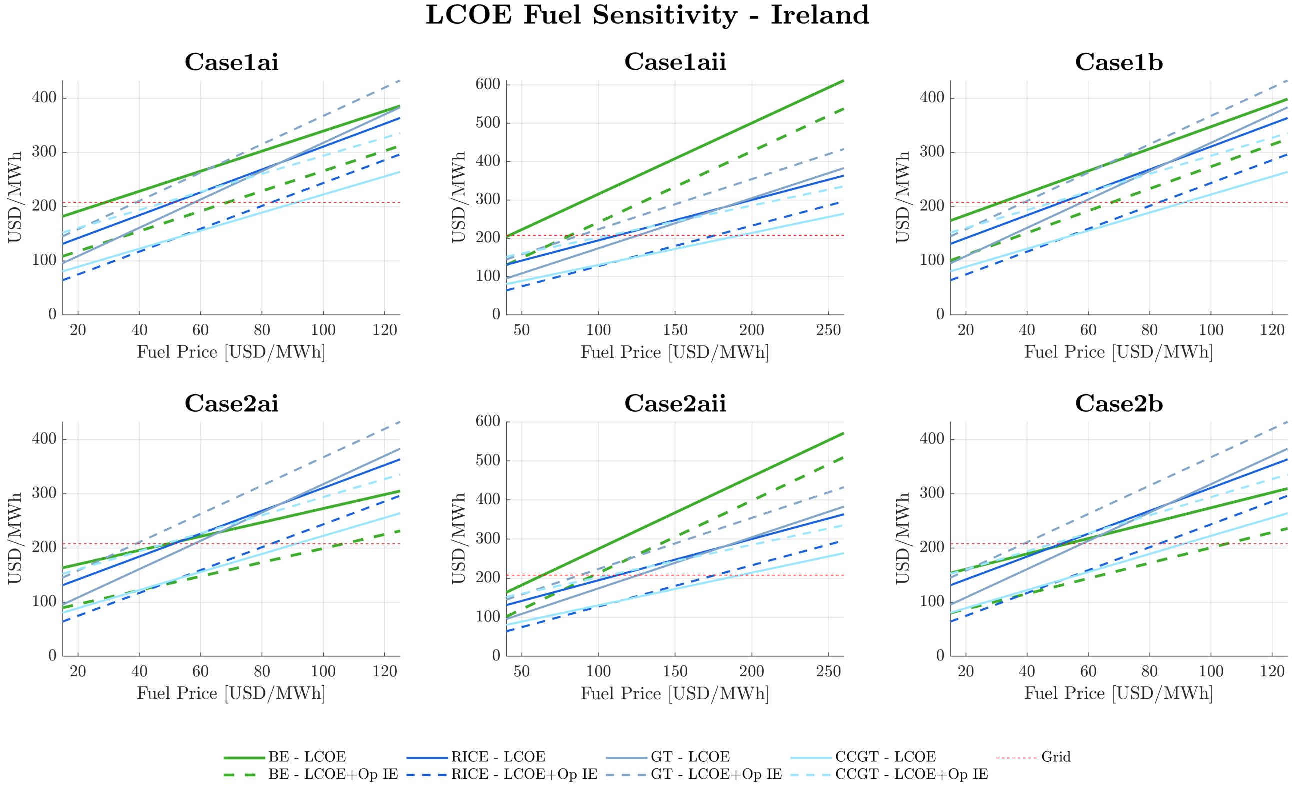

Figure D.10: LCOE fuel sensitivity in Ireland.

Italy

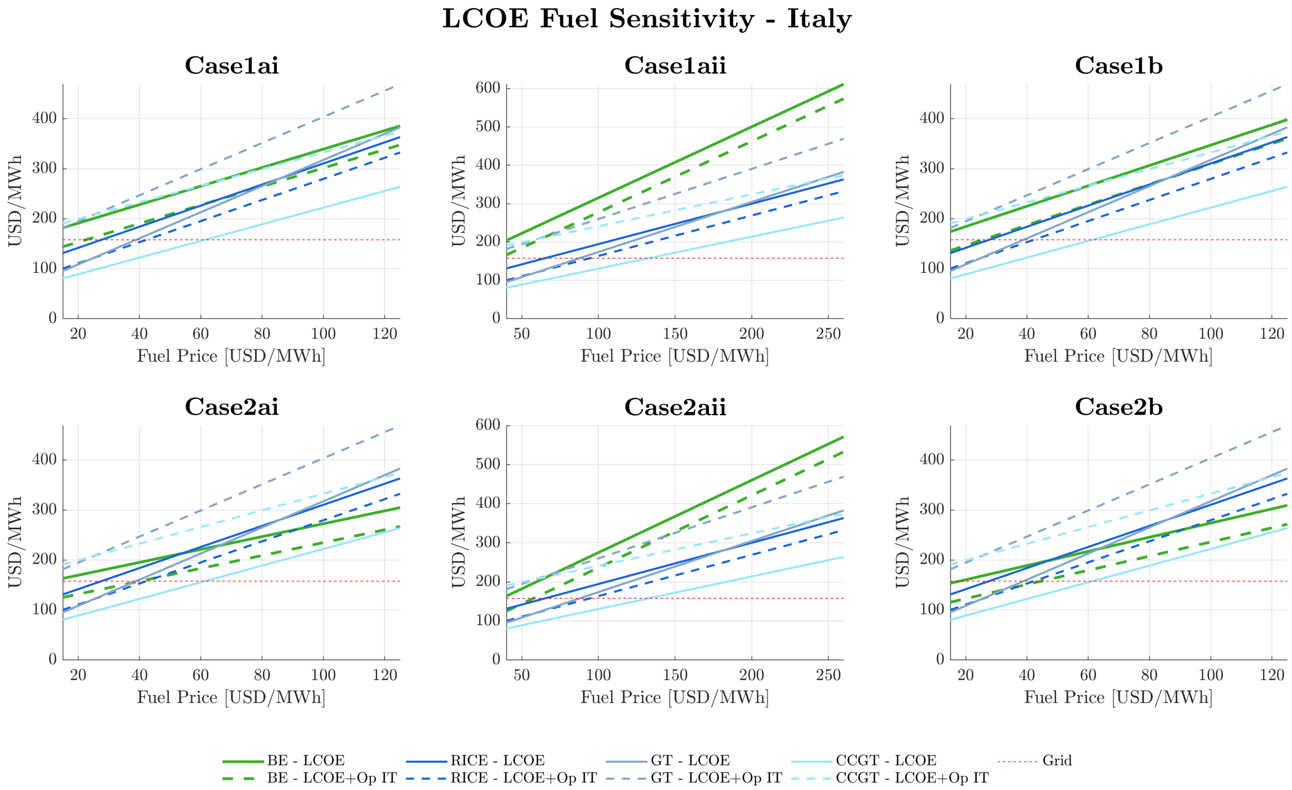

Figure D.11: LCOE fuel sensitivity in Italy.

D.3 Carbon Price Sensitivity Analysis

European Union

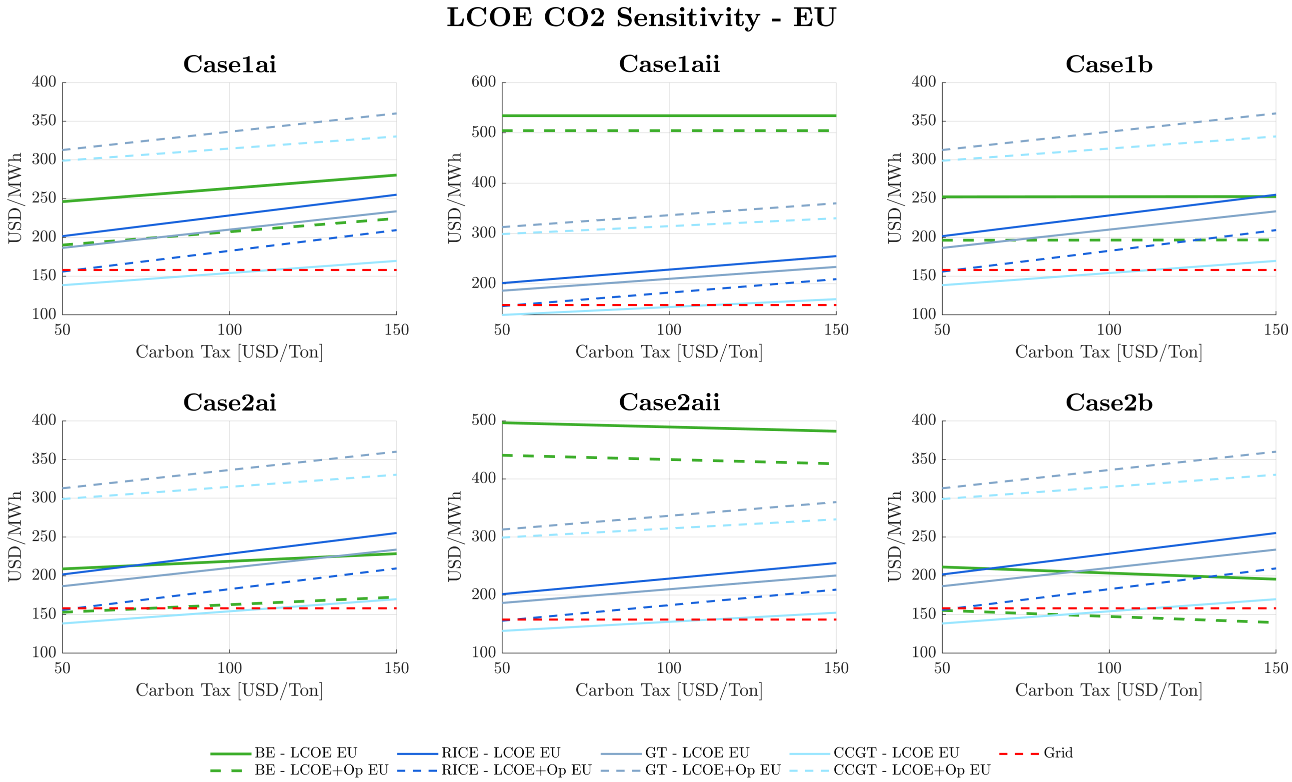

Figure D.12: LCOE carbon price sensitivity in the EU.

Germany

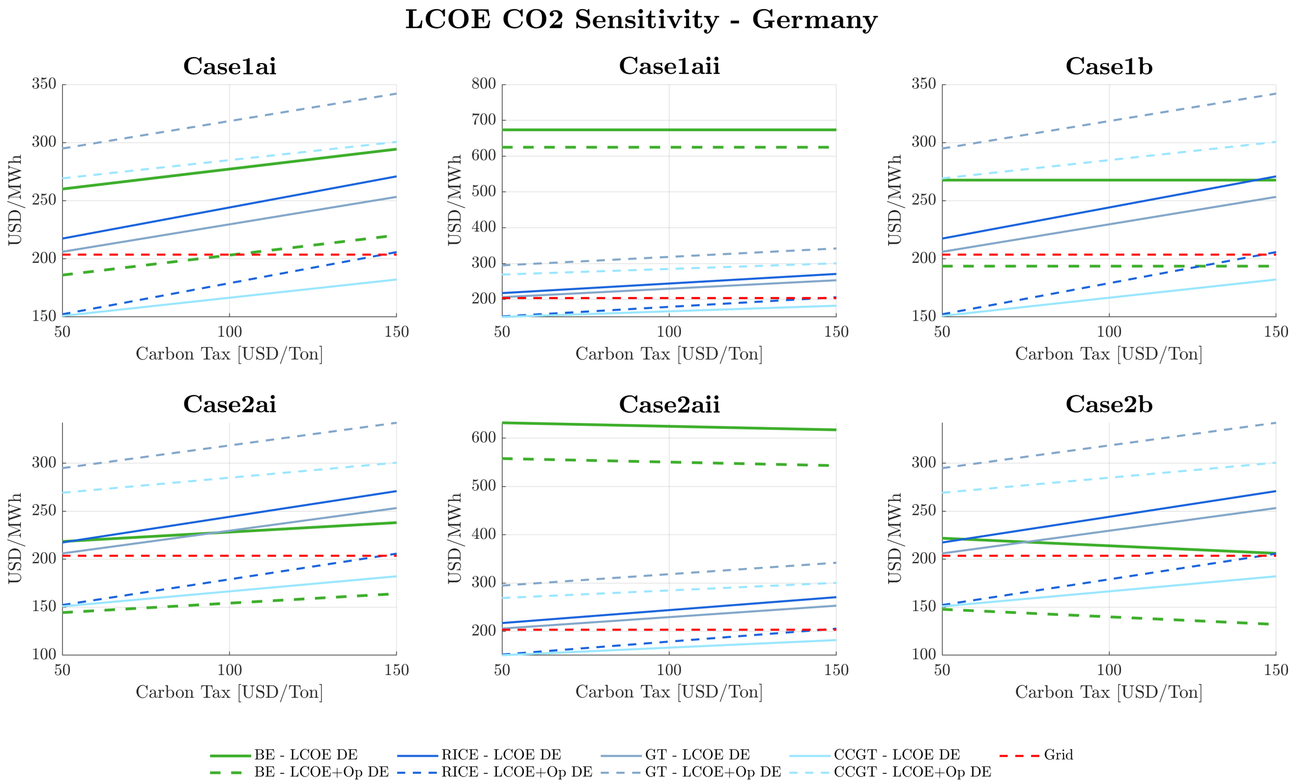

Figure D.13: LCOE carbon price sensitivity in Germany.

United Kingdom

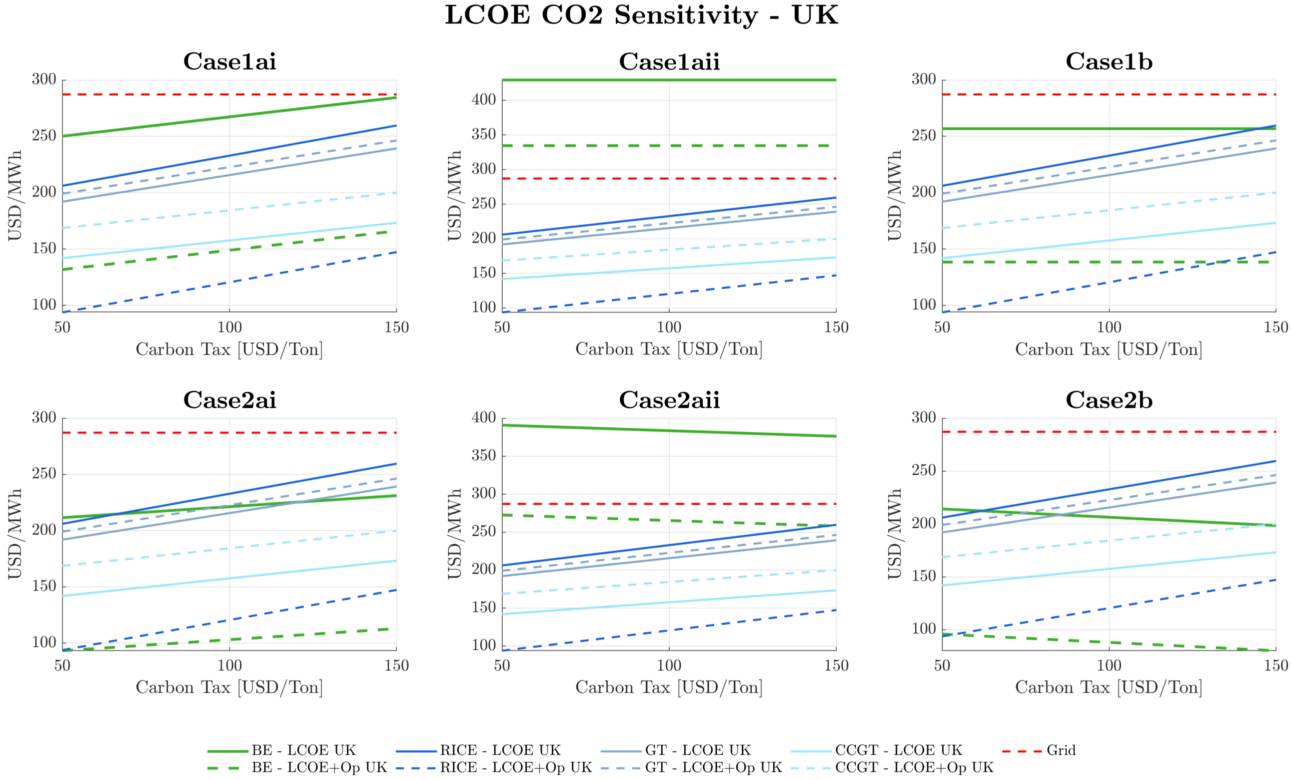

Figure D.14: LCOE carbon price sensitivity in the UK.

Ireland

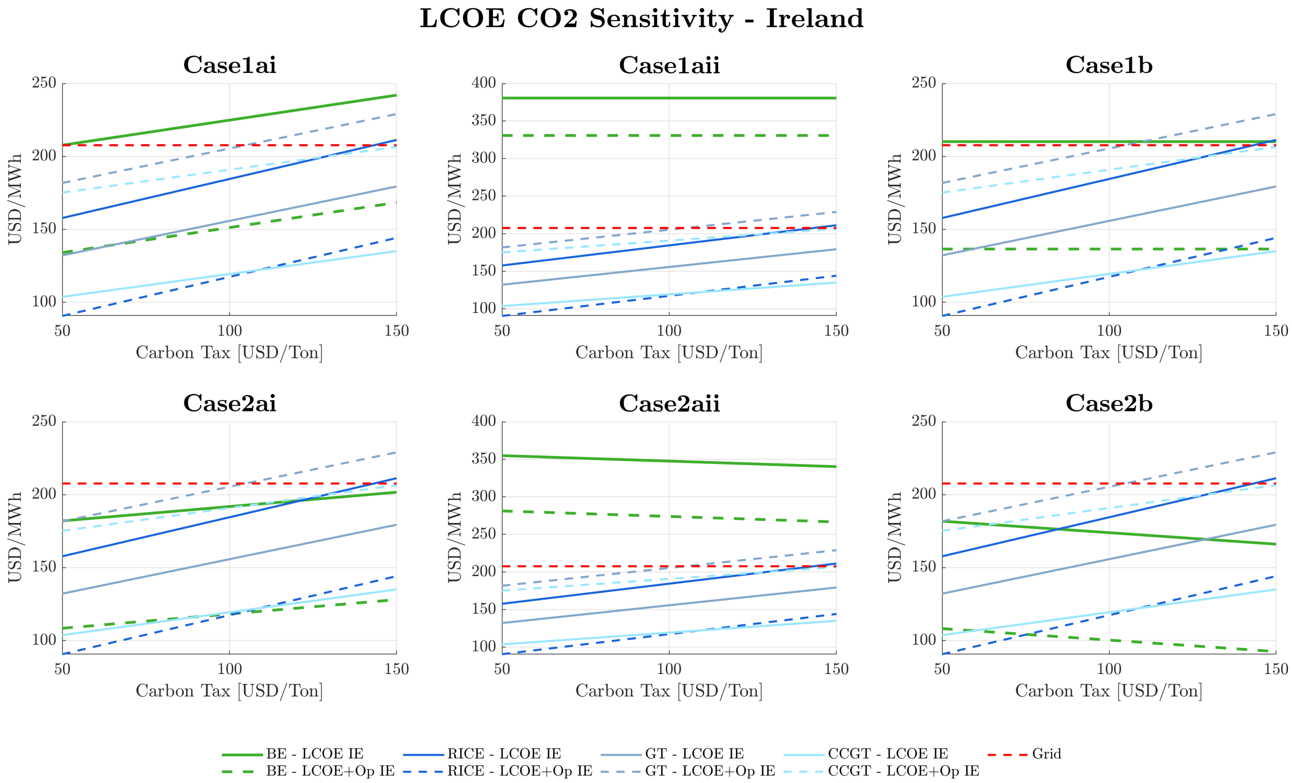

Figure D.15: LCOE carbon price sensitivity in Ireland.

Italy

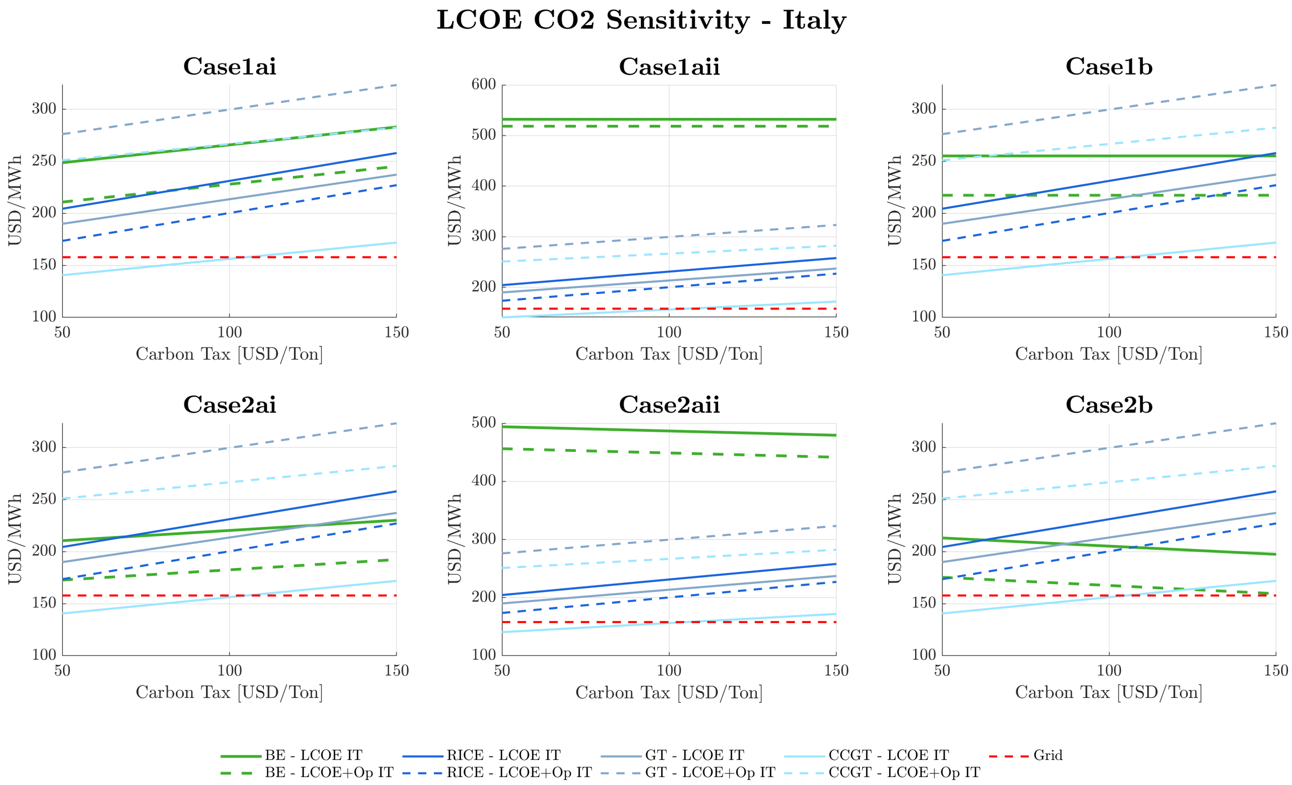

Figure D.16: LCOE carbon price sensitivity in Italy.

D.4 Interest Rate Sensitivity Analysis

European Union

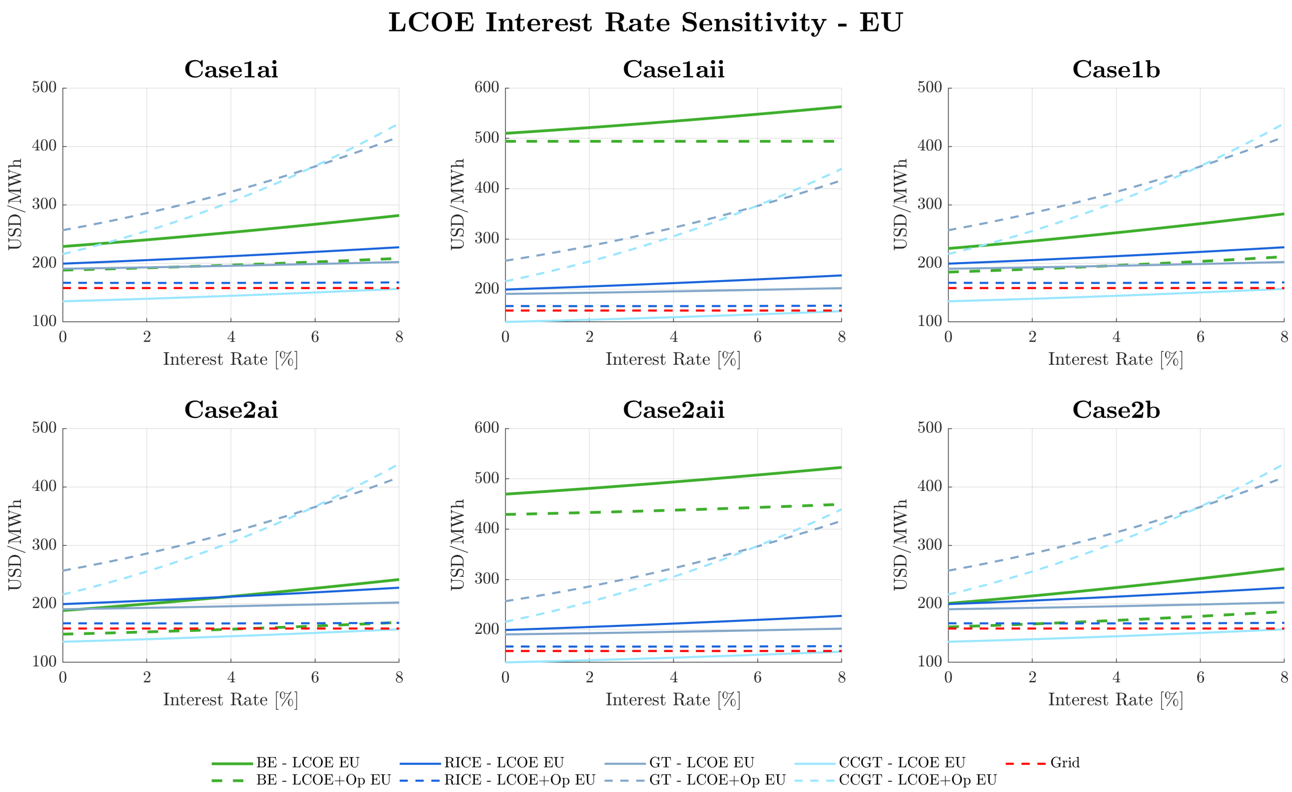

Figure D.17: LCOE interest rate sensitivity in the EU.

Germany

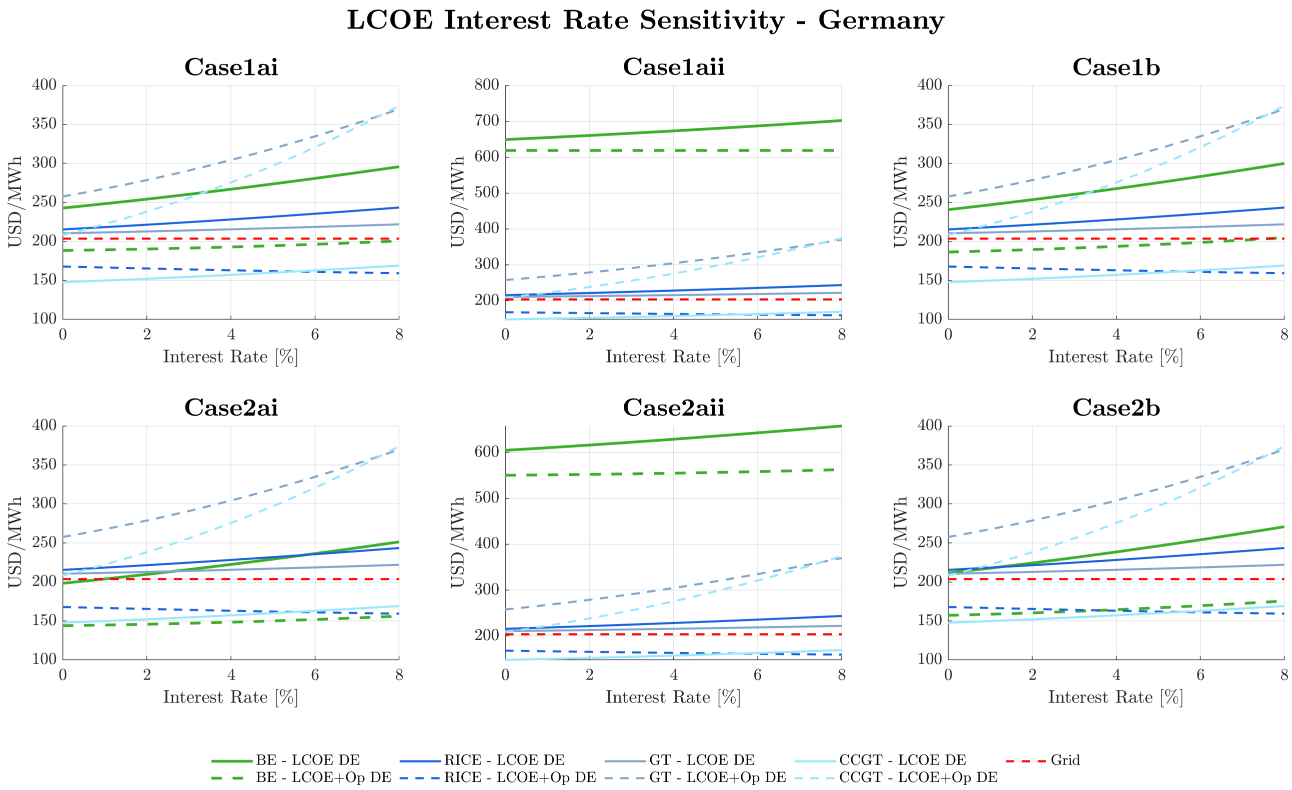

Figure D.18: LCOE interest rate sensitivity in Germany.

United Kingdom

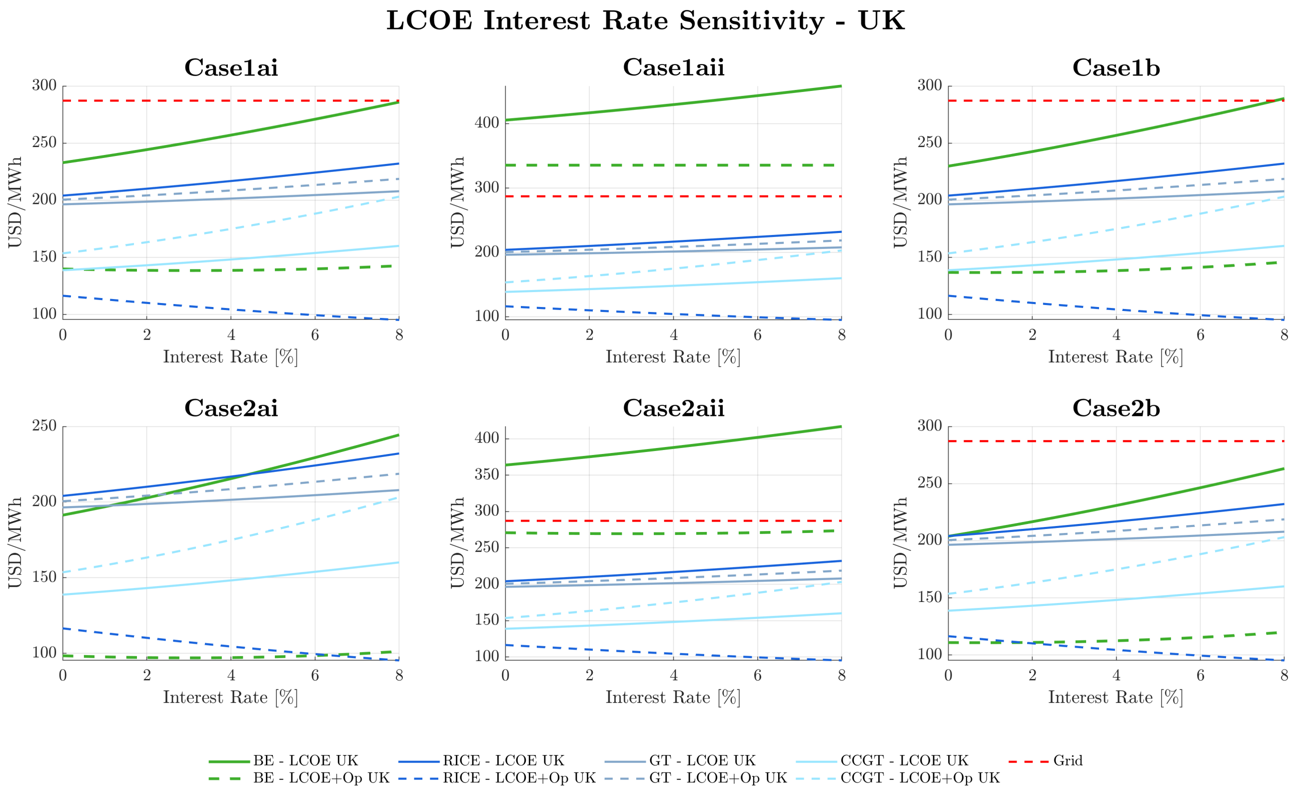

Figure D.19: LCOE interest rate sensitivity in the UK.

Ireland

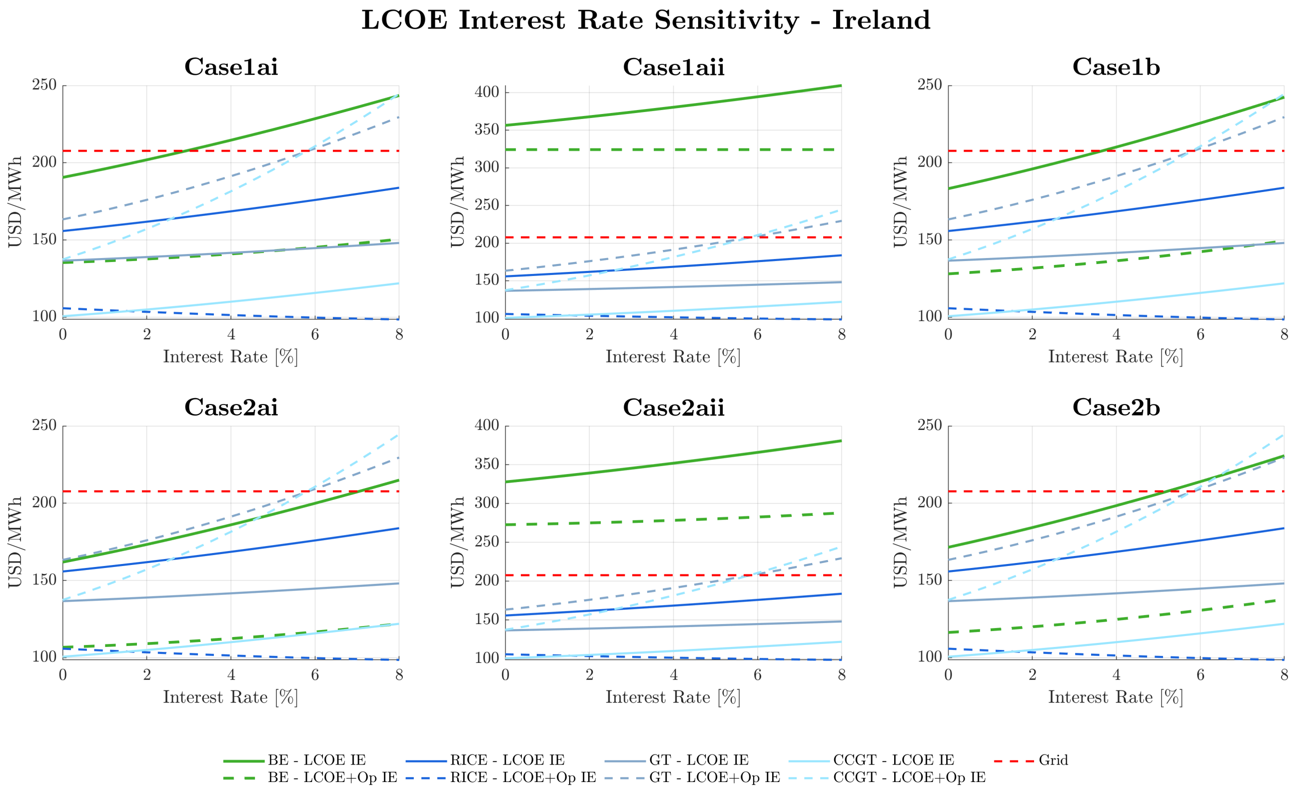

Figure D.20: LCOE interest rate sensitivity in Ireland.

Italy

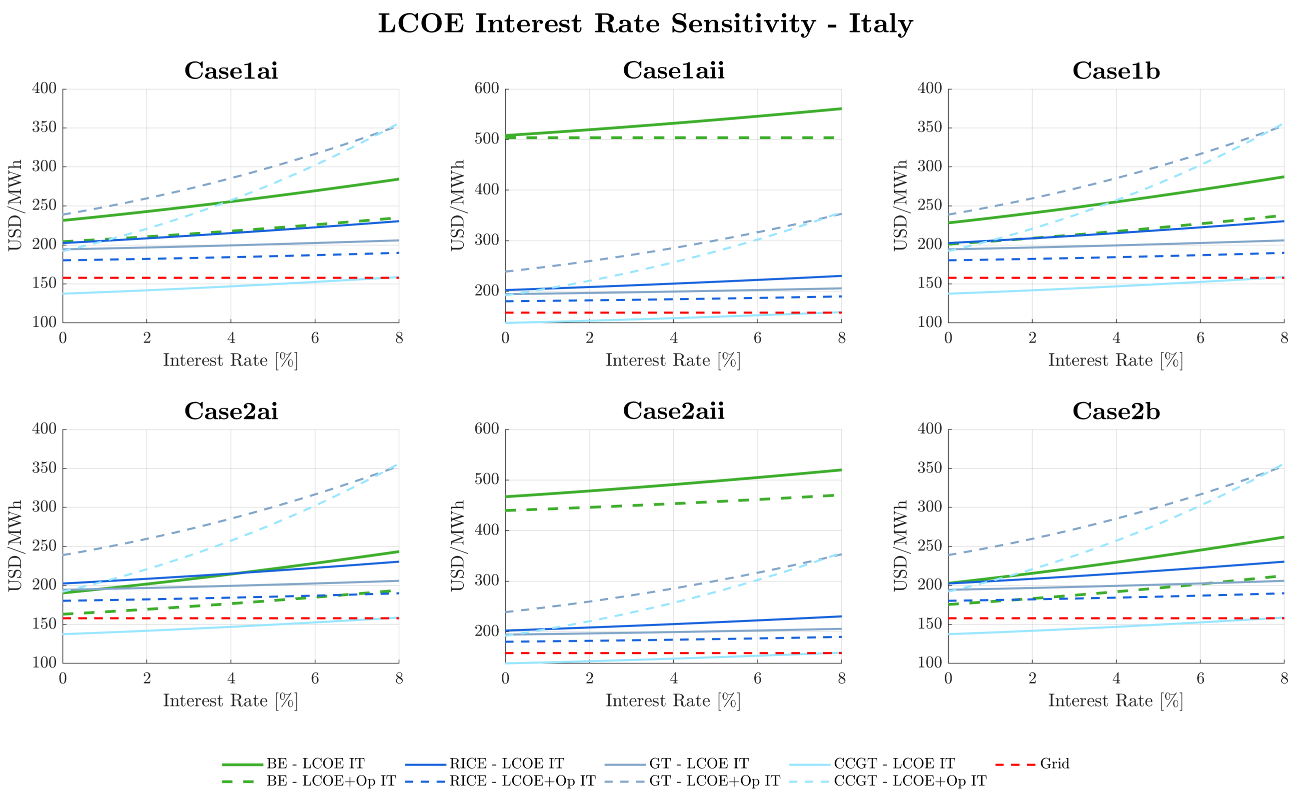

Figure D.21: LCOE interest rate sensitivity in Italy.

D.5 Bloom CAPEX Sensitivity Analysis

European Union

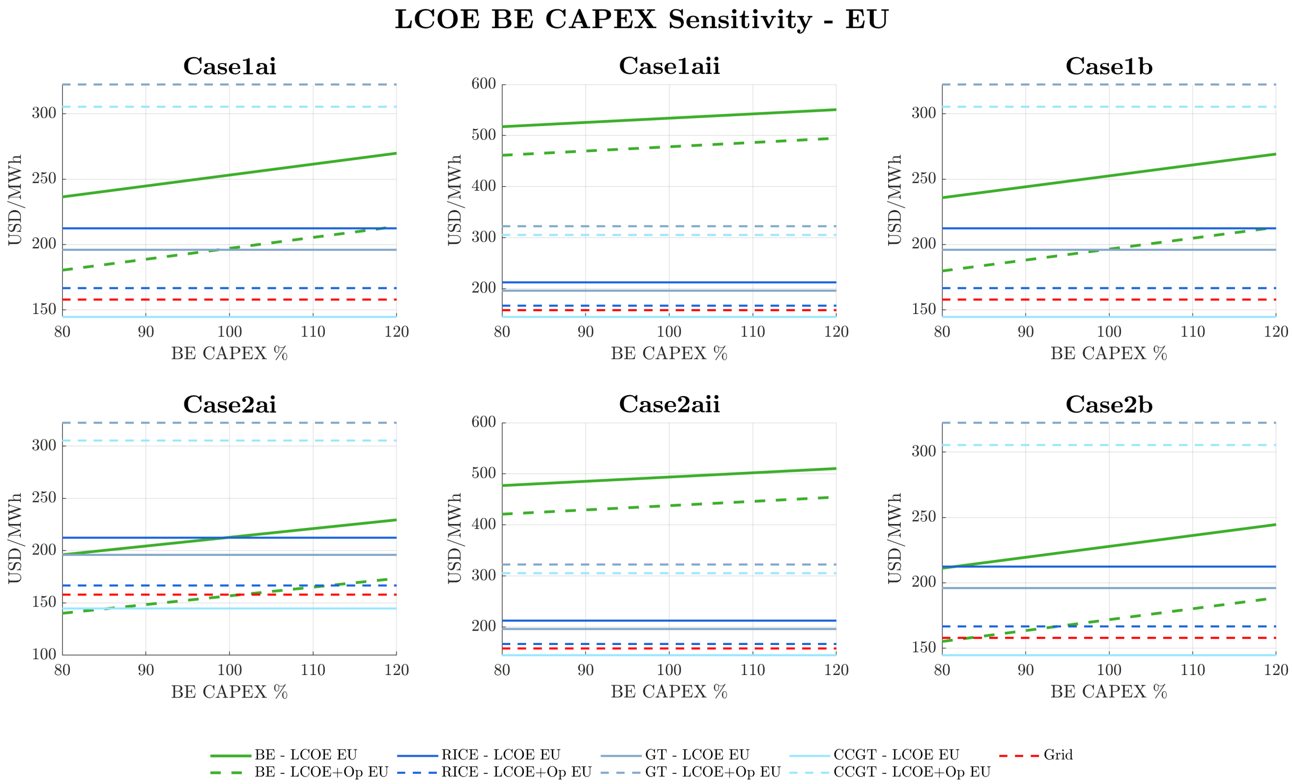

Figure D.22: LCOE Bloom CAPEX sensitivity in the EU.

Germany

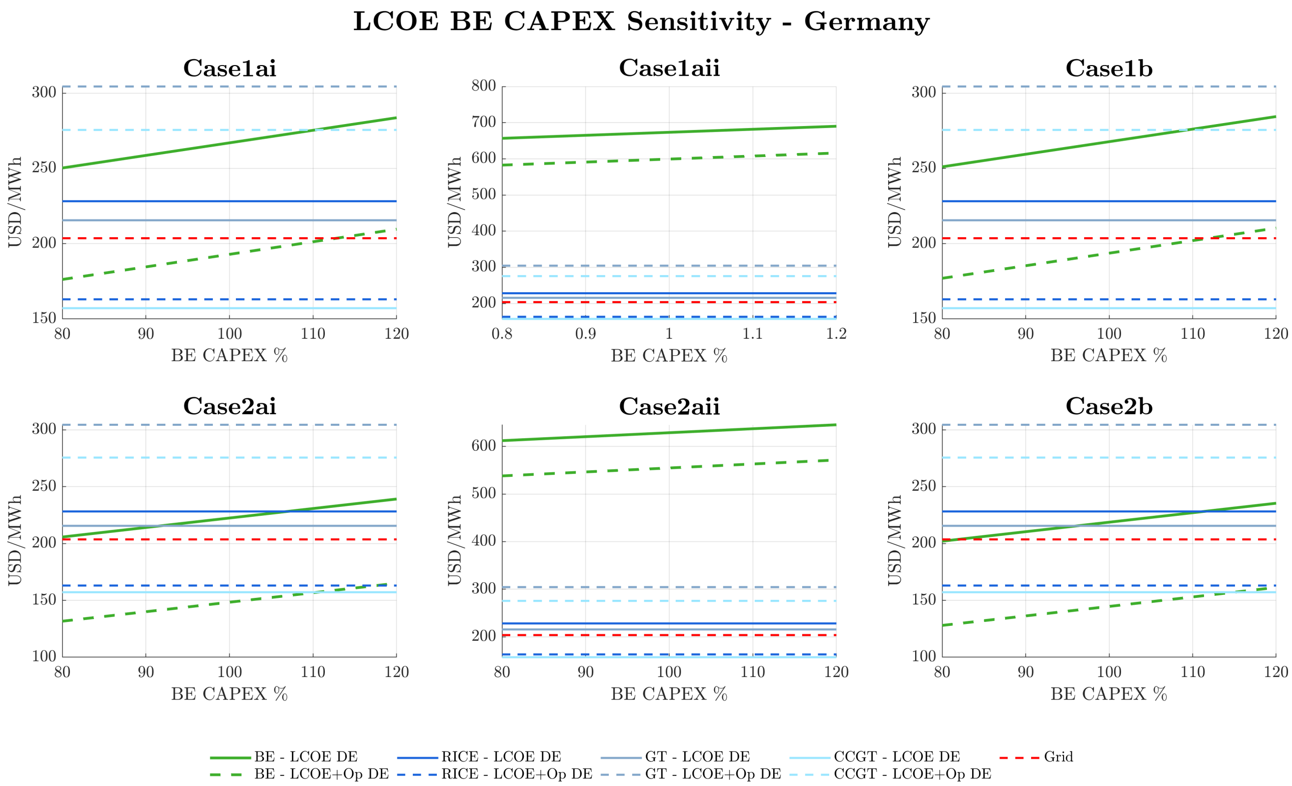

Figure D.23: LCOE Bloom CAPEX sensitivity in Germany.

United Kingdom

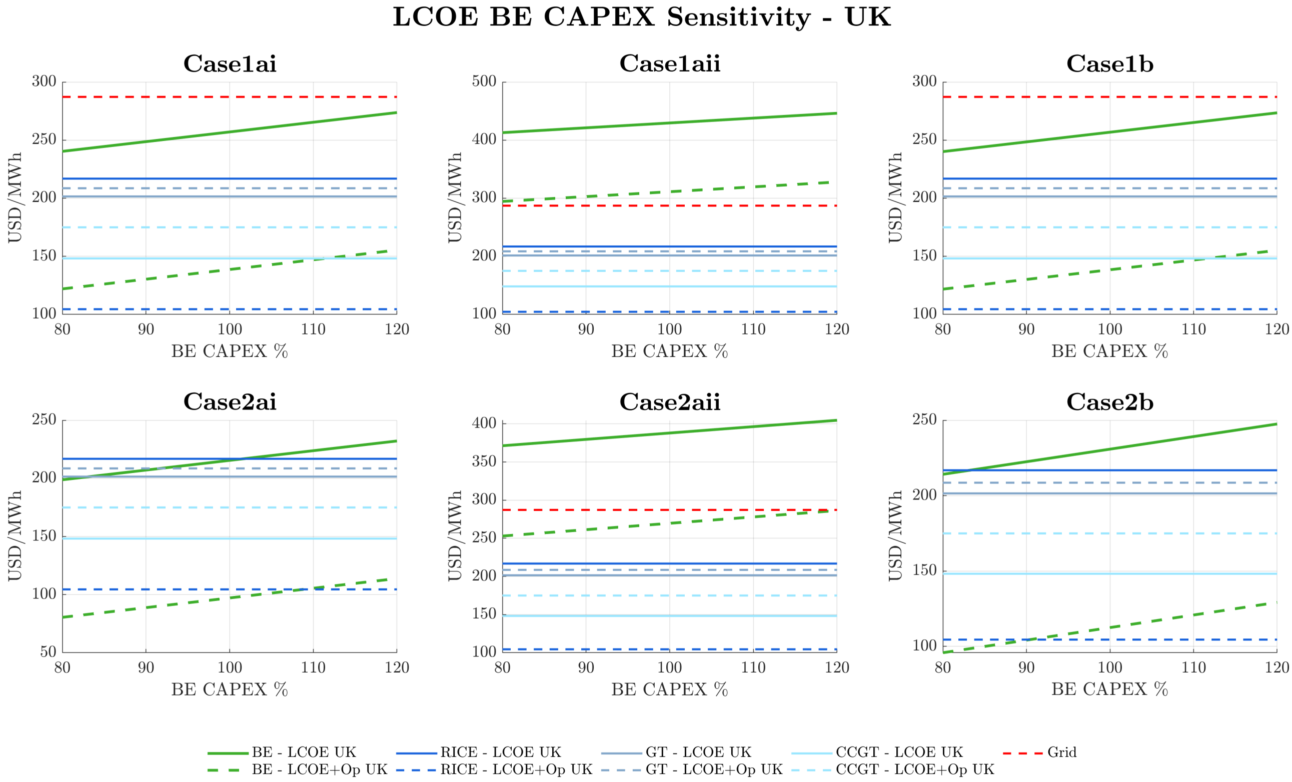

Figure D.24: LCOE Bloom CAPEX sensitivity in the UK.

Ireland

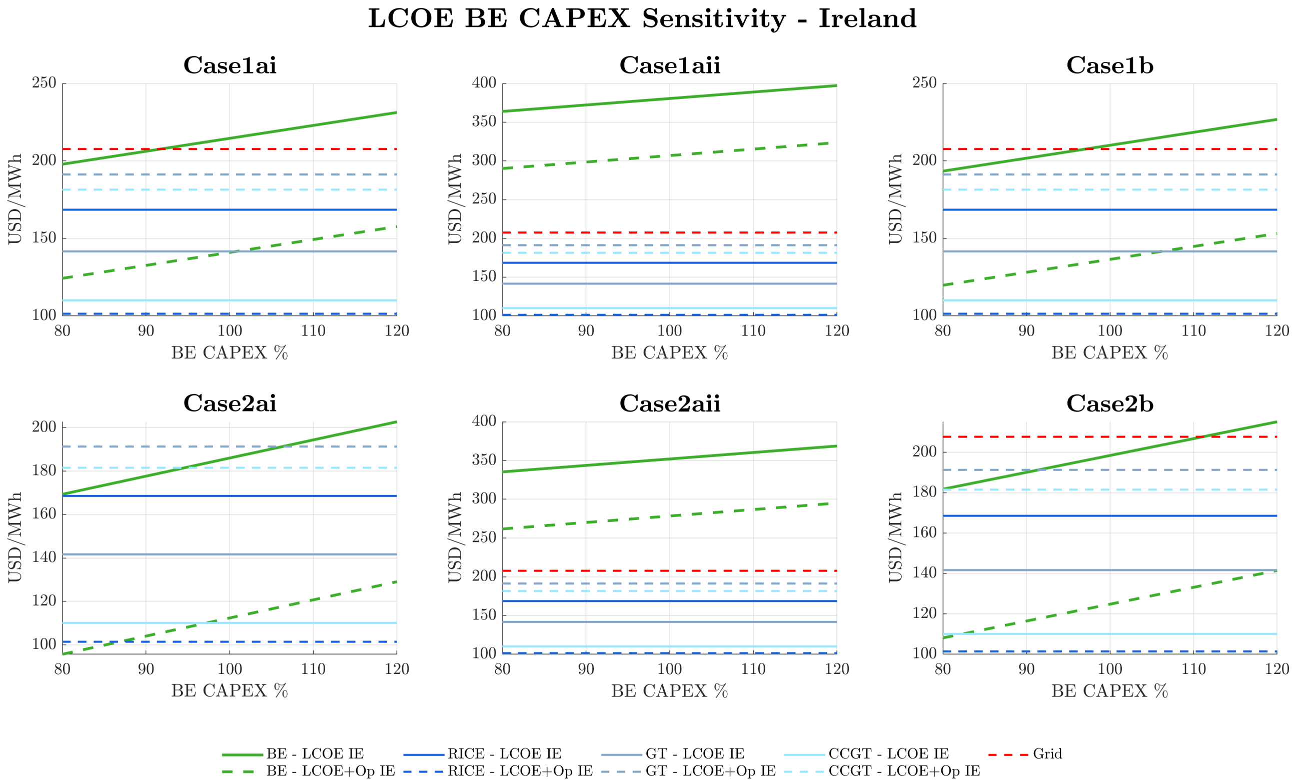

Figure D.25: LCOE Bloom CAPEX sensitivity in Ireland.

Italy

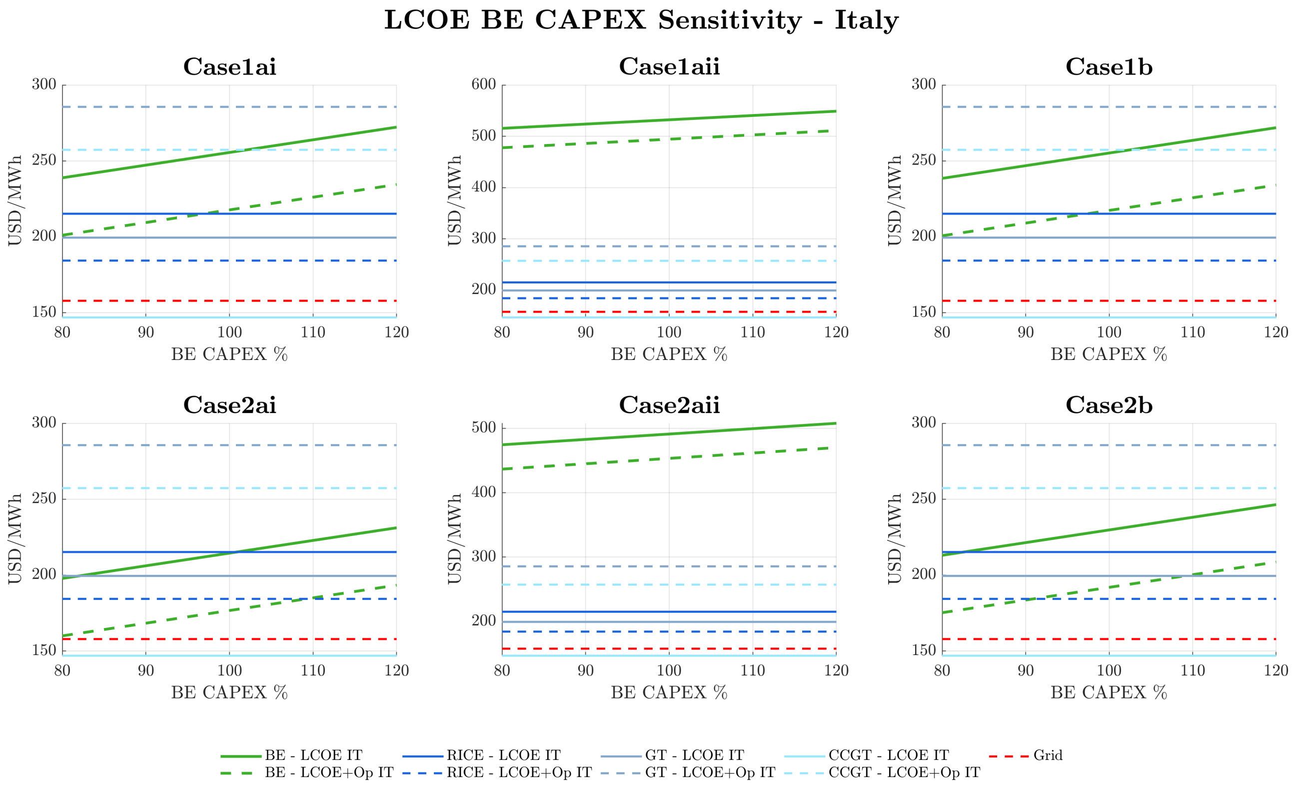

Figure D.26: LCOE Bloom CAPEX sensitivity in Italy.

D.6 Opportunity Costs Analysis

European Union

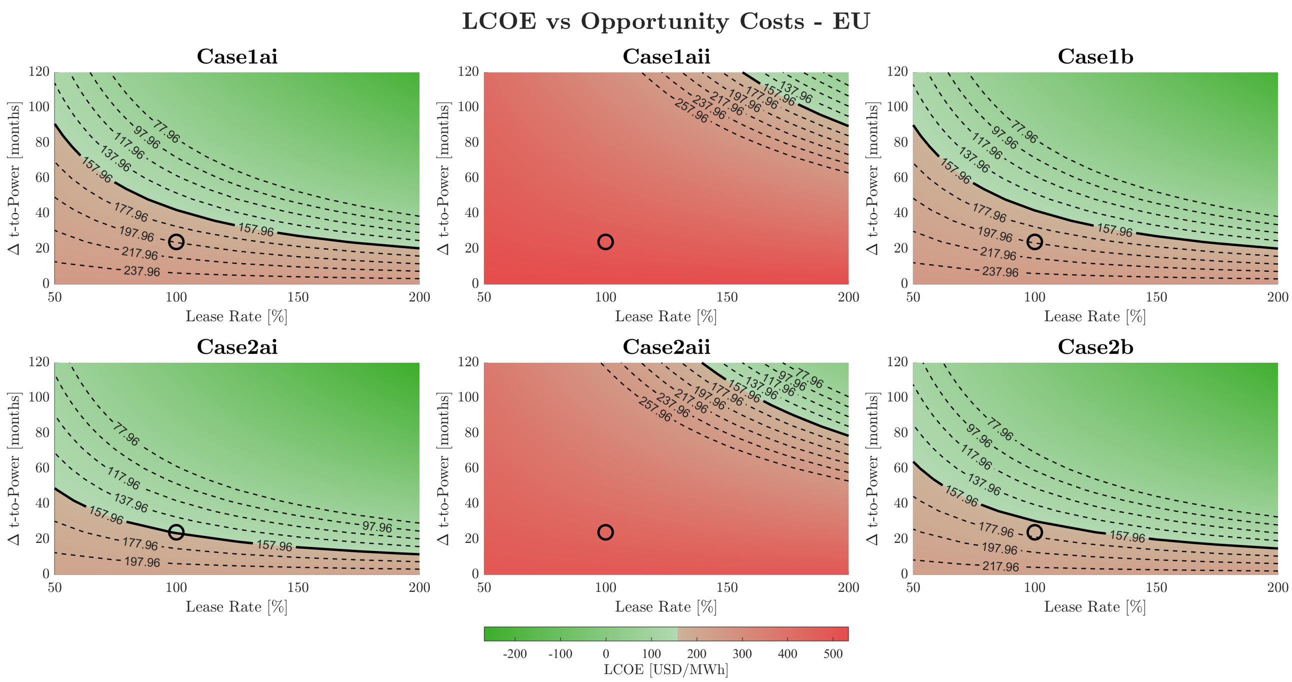

Figure D.27: LCOE opportunity costs sensitivity in the EU.

Germany

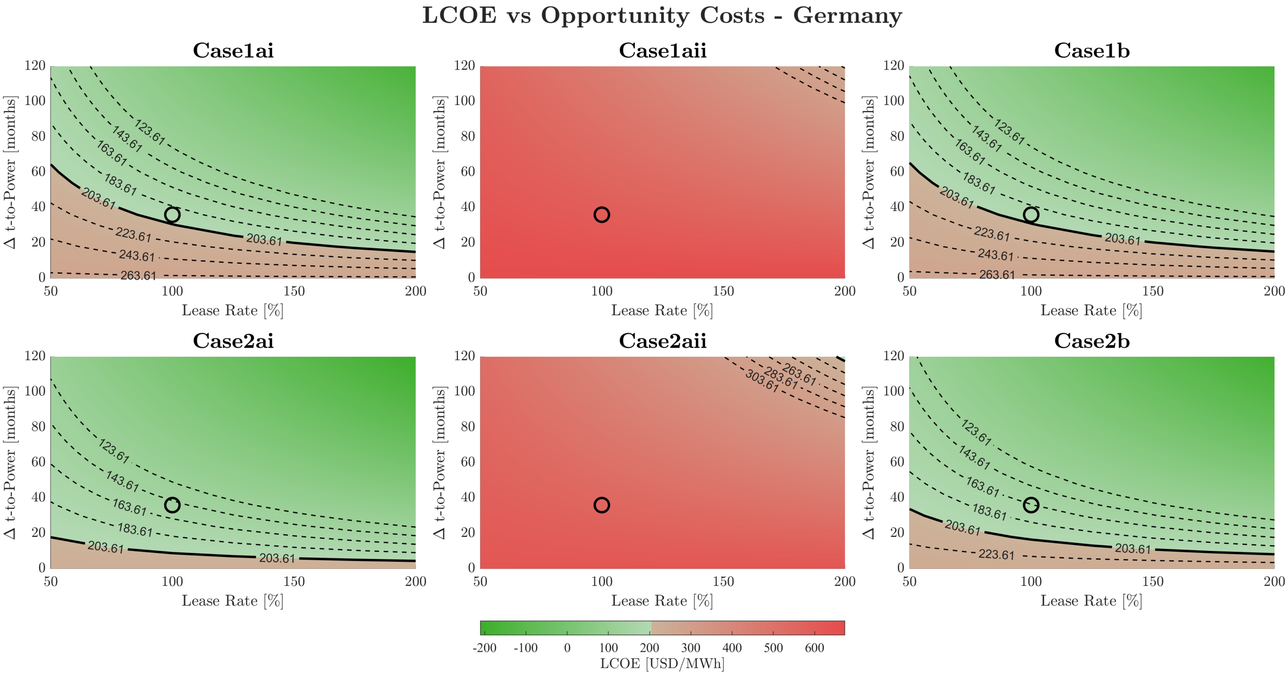

Figure D.28: LCOE opportunity costs sensitivity in Germany.

United Kingdom

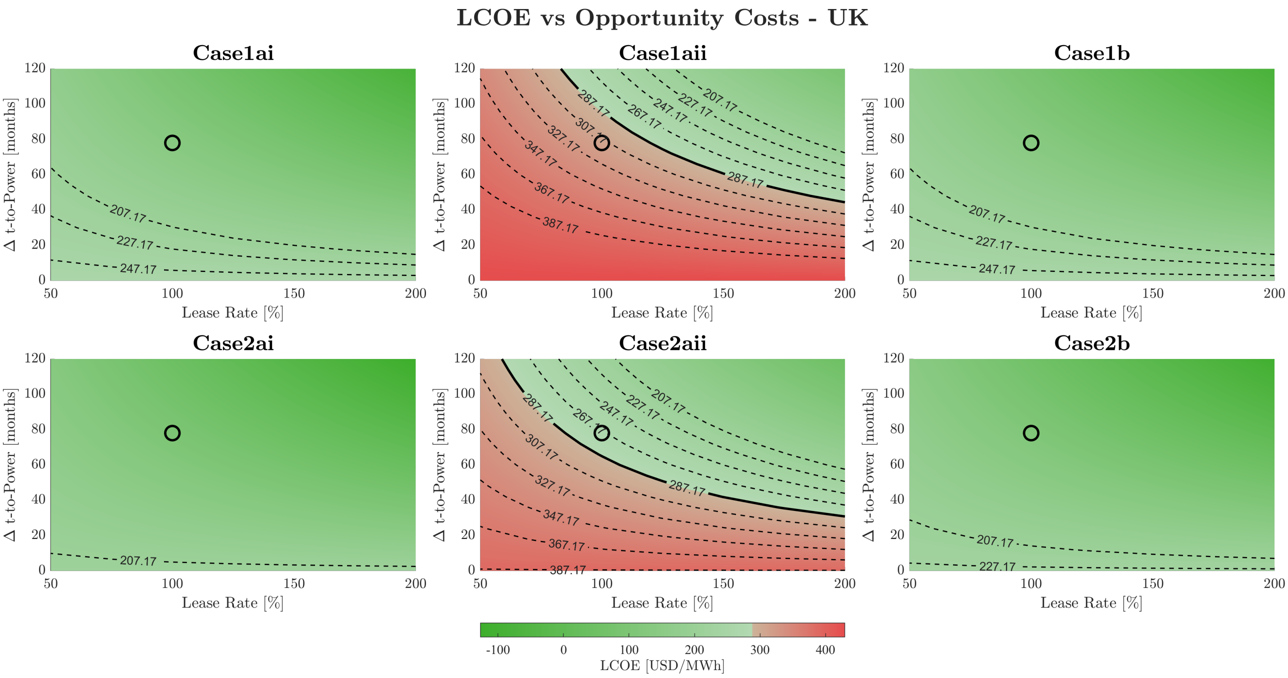

Figure D.29: LCOE opportunity costs sensitivity in the UK.

Ireland

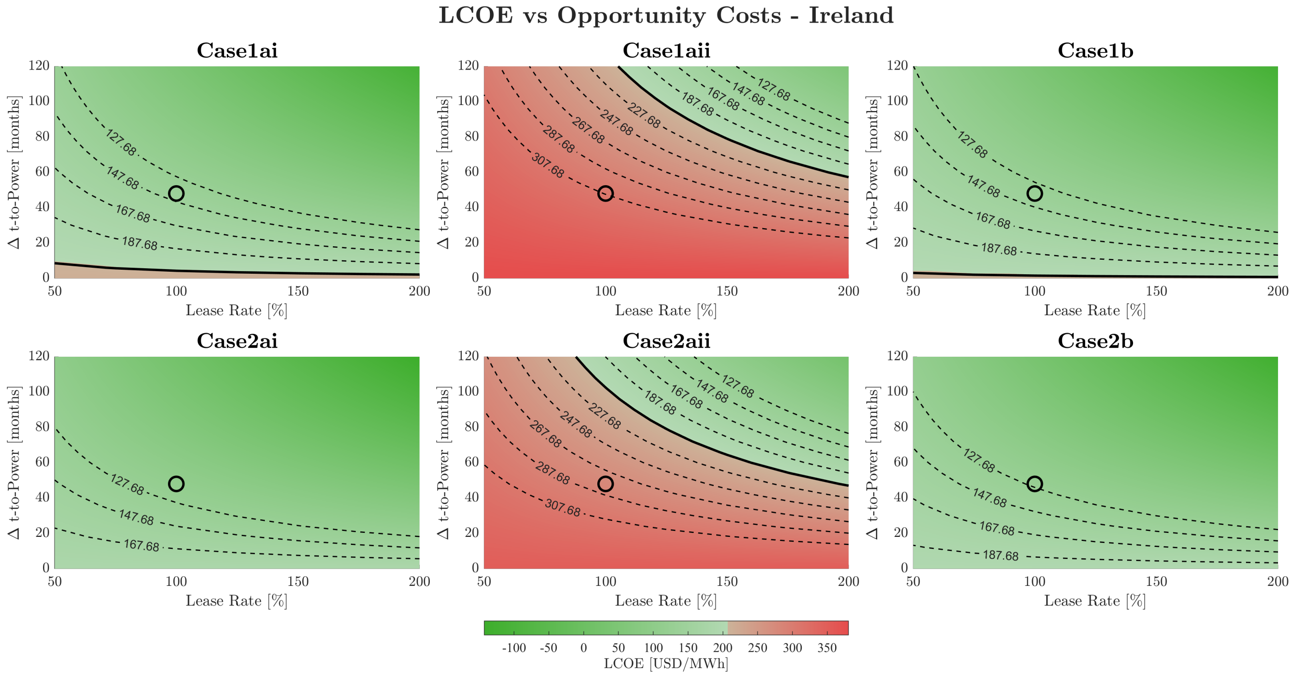

Figure D.30: LCOE opportunity costs sensitivity in Ireland.

Italy

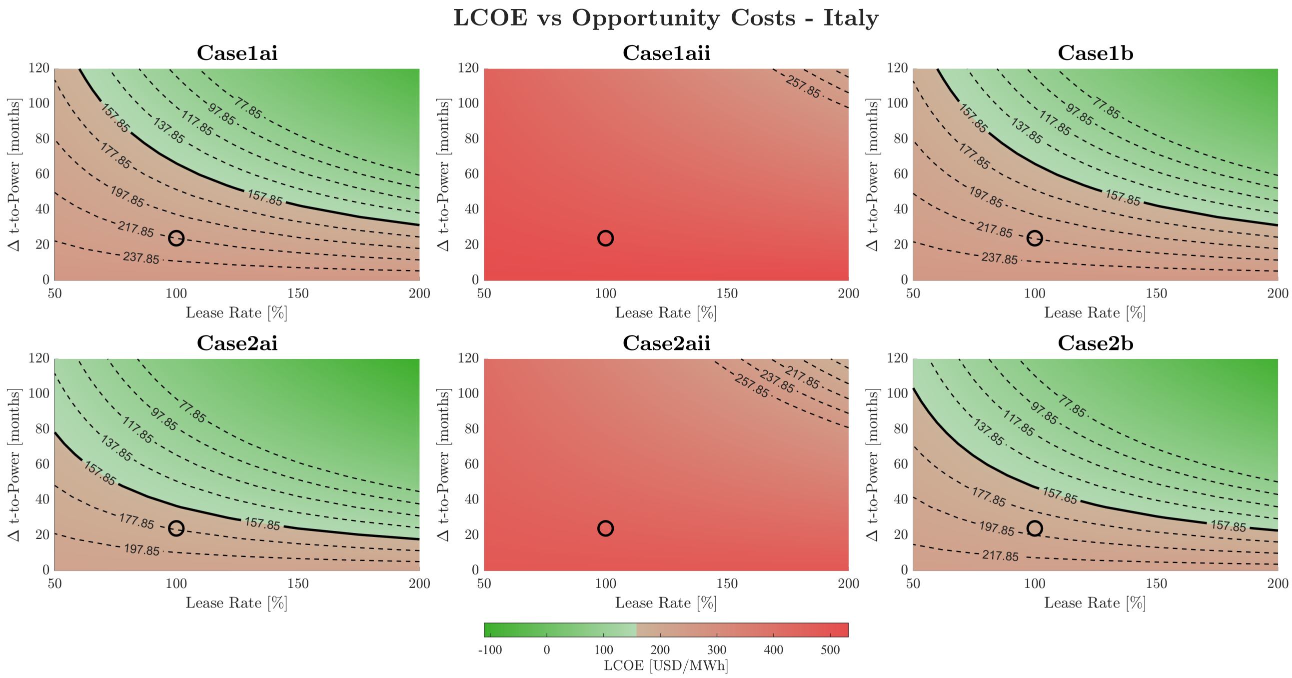

Figure D.31: LCOE opportunity costs sensitivity in Italy.

D.7 Subsidies Analysis

European Union

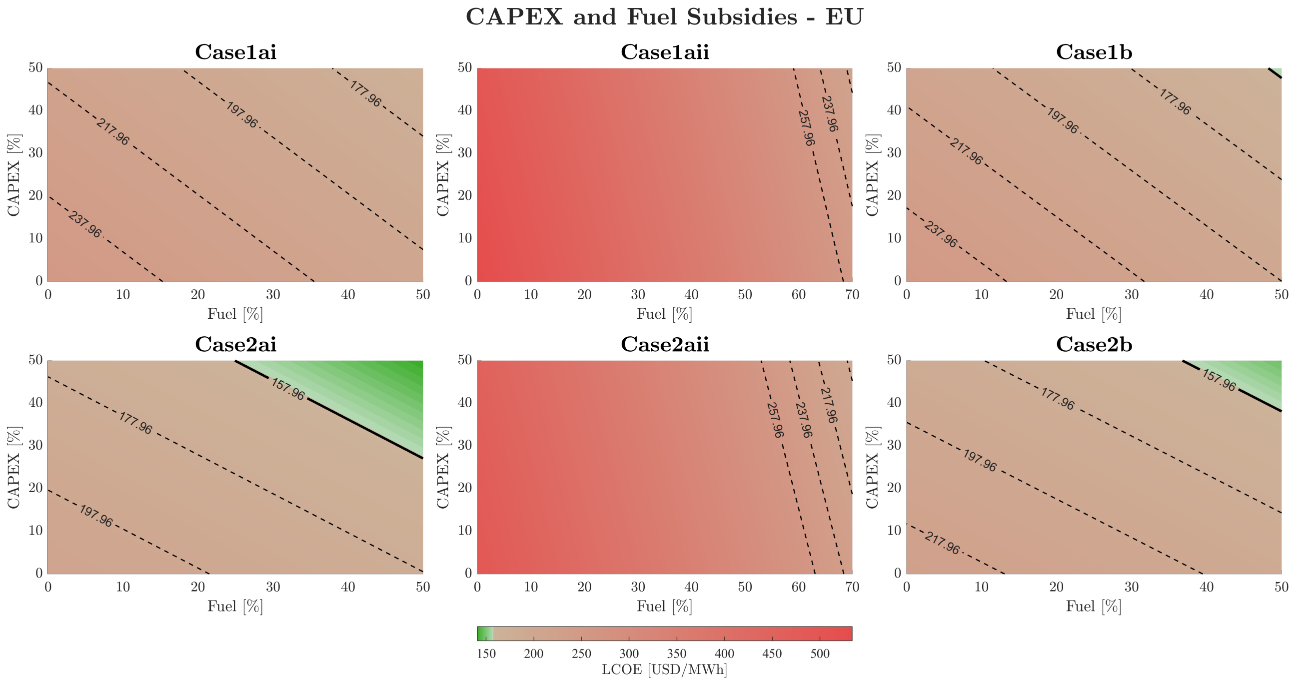

Figure D.32: LCOE variation in the EU over CAPEX and OPEX subsidies, expressed as a percentage of fuel costs.

Germany

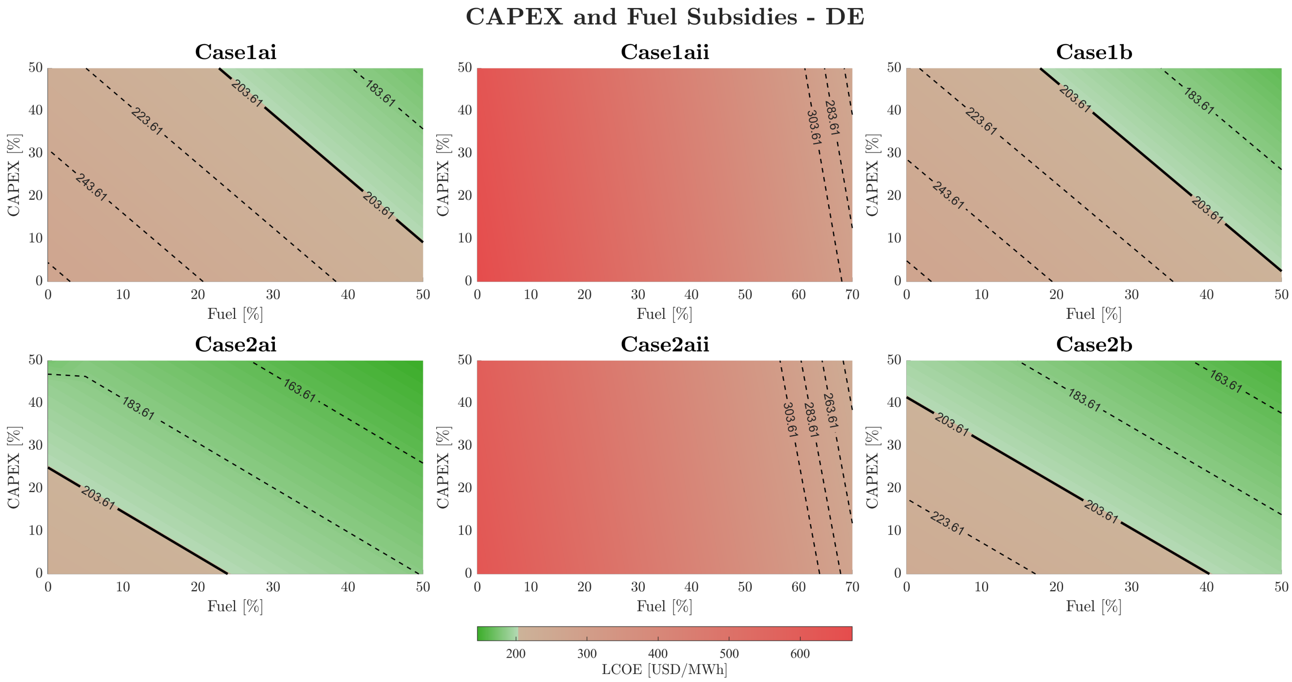

Figure D.33: LCOE variation in Germany over CAPEX and OPEX subsidies, expressed as a percentage of fuel costs.

United Kingdom

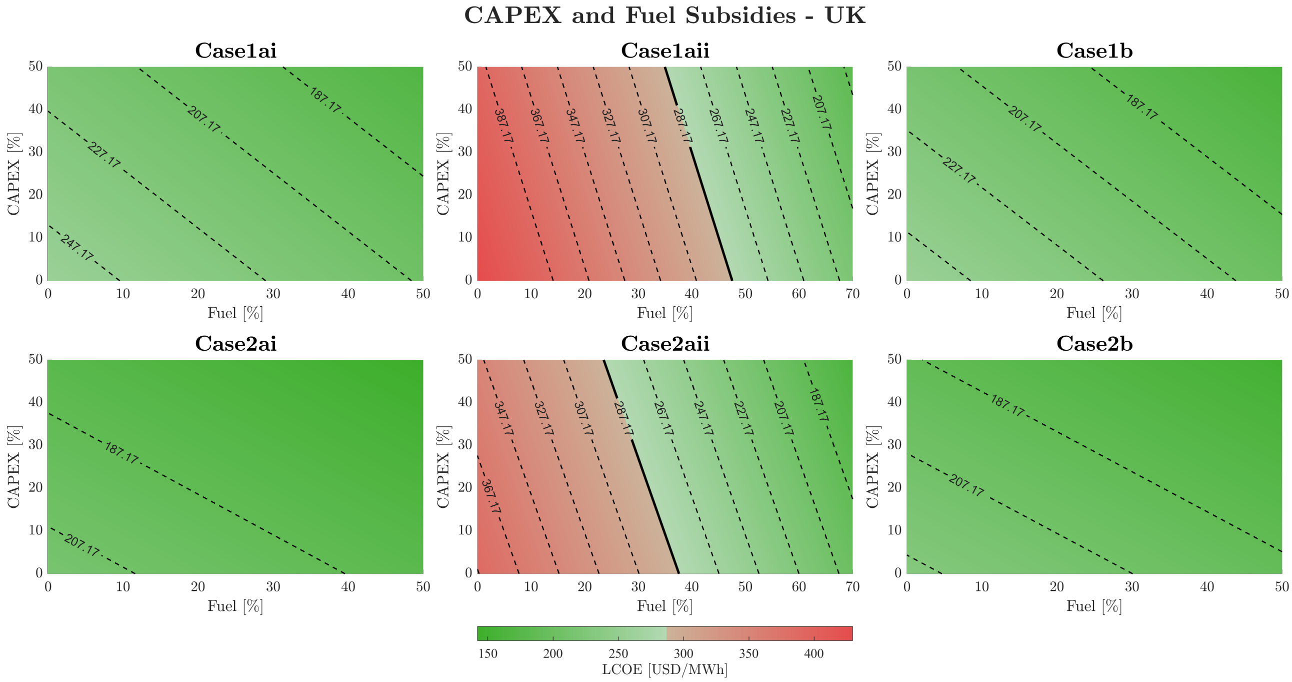

Figure D.34: LCOE variation in the UK over CAPEX and OPEX subsidies, expressed as a percentage of fuel costs.

Ireland

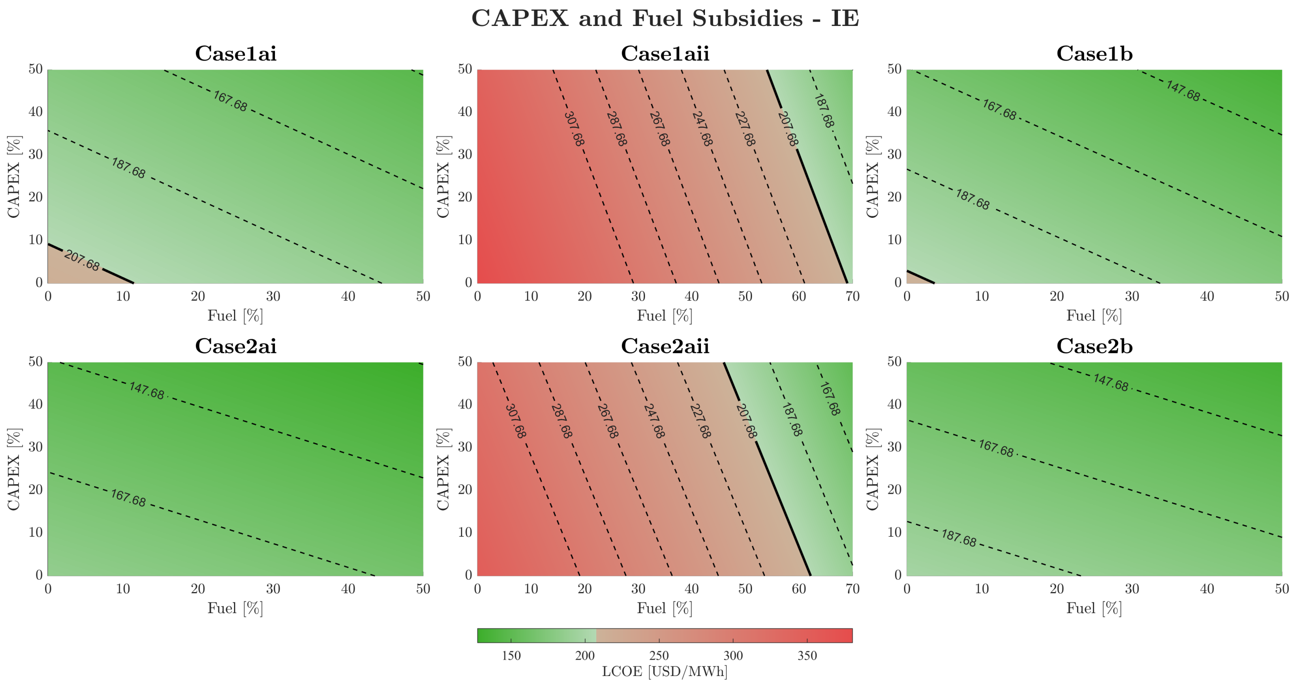

Figure D.35: LCOE variation in Ireland over CAPEX and OPEX subsidies, expressed as a percentage of fuel costs.

Italy

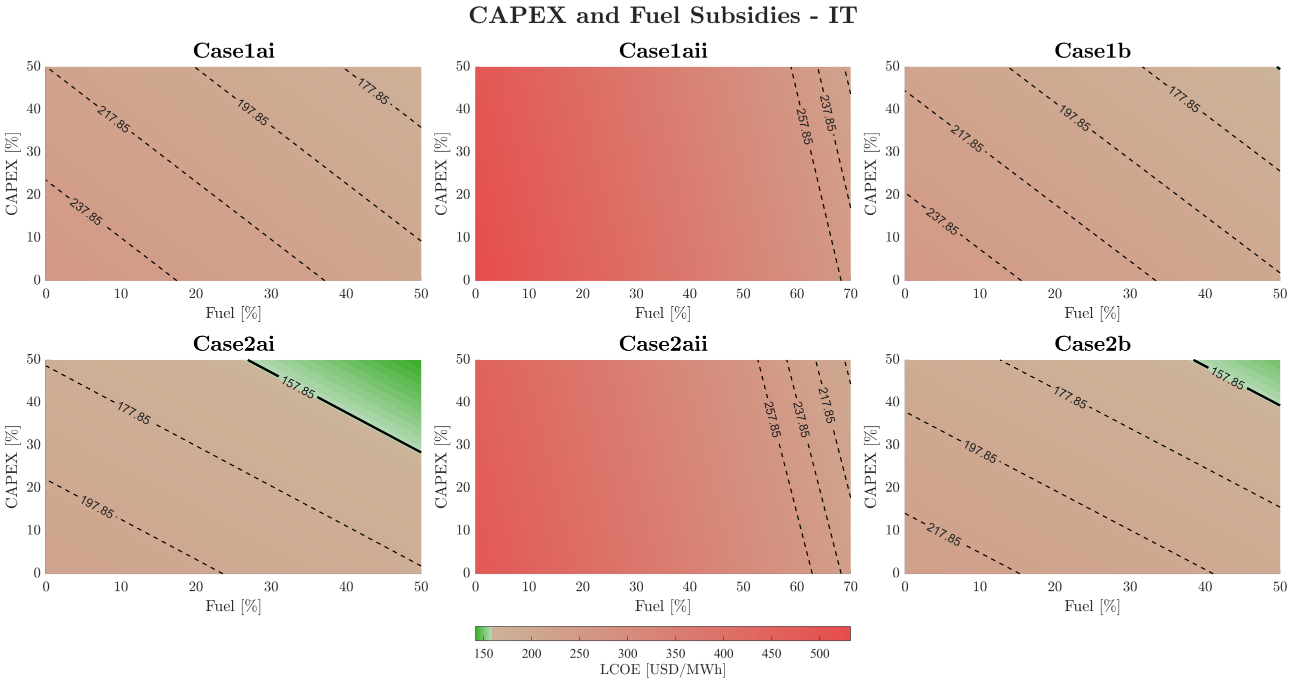

Figure D.36: LCOE variation in Italy over CAPEX and OPEX subsidies, expressed as a percentage of fuel costs.