Clean Firm Power in Europe’s Energy Transition: Evidence, Constraints, and System Roles

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ABOUT THIS PUBLICATION

This report has been produced by Quantified Carbon (QC) on behalf of CATF to provide a review of clean firm impacts from system studies in Europe.

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Objective: Investigate how different modelling studies analyse clean firm power and compare the roles and system impacts attributed to it in Europe’s decarbonised electricity pathways.

Summary: Across models and regions, the precise choice of clean firm technology matters less than the presence of some form of dispatchable, low-carbon capacity capable of sustaining output during extended periods of low renewable generation. What the evidence shows is that system reliability hinges on the function such resources provide, not on whether that function is delivered by advanced geothermal, nuclear, CCS-enabled gas, hydrogen turbines, or long-duration storage substitutes. It is worth noting that geothermal, despite being a potentially attractive clean-firm option in some regions, is only rarely included in European modelling studies. Although the literature does not converge on a single optimal portfolio, the reviewed studies consistently show that decarbonised systems require firm, weather-independent resources to maintain adequacy, moderate system costs, and limit infrastructure burdens (overbuilt). The specific technologies, nuclear, geothermal, CCS-equipped gas or biomass, reservoir hydropower[1] or hydrogen-fired turbines, vary across countries according to political preferences and resource availability, but their system function is broadly interchangeable. Importantly, studies that incorporate realistic constraints such as sector coupling, land availability, import risks, and multi-decadal weather variability converge on a stronger and more persistent role for clean firm power. In this sense, the mix is not standardised, but the need for firm, dispatchable, low-emission capacity is a robust and recurring feature of credible European net-zero pathways. Finally, this review has mapped the modelling approaches used across the reviewed studies. A deeper understanding of the role of clean-firm power will require broader incorporation of price volatility, self-sufficiency metrics, and, in particular, higher spatial resolution, which most studies have lacked until now.

Key takeaways:

- Clean firm technologies reduce system costs of decarbonisation and price volatility in decarbonised power systems.
- Clean firm technologies reduce the total infrastructure buildout needed to decarbonise, making targets easier to achieve.

[1] Given that capacity expansion is feasible and reservoirs have seasonal storage potential.

- Systems relying heavily on imports or storage alone show greater vulnerability in stress conditions
- The *type* of firm technology varies, but the *function* it provides is consistently important
- Studies with richer system perspective (self-sufficiency, land limits, fuel risks) find higher firm capacity needs
- Modelling results show that adequacy challenges intensify during winter peaks and multi-day renewable shortfalls

Introduction

Clean firm power definition

Clean firm power refers to low- and zero-carbon electricity resources that can deliver controllable, dispatchable output for long durations, regardless of season, weather conditions, or variable renewable availability. These technologies are energy-unconstrained, meaning they are not limited by fuel scarcity over short periods (like batteries) nor by weather-driven variability (like wind and solar). Instead, they can sustain power delivery across multi-day and multi-week periods when the system most needs reliability. As shown on **Figure 1** clean firm resources span several technological classes, united by their ability to provide reliable capacity, operational flexibility, and deep emissions reductions. In general, they include:

- Capital-intensive, low-variable-cost technologies, such as nuclear power and geothermal, which offer stable, dispatchable output with near-zero fuel costs.
- Flexible thermal resources with very low or zero carbon emissions, including natural gas or coal with carbon capture and storage (gas CCS), as well as biomass, biogas, or methanation systems, often also paired with CCS to reduce lifecycle emissions.
- Combustion turbines running on clean fuels, such as hydrogen or sustainably sourced biogas, offering fast response, high flexibility, and the ability to operate during extended renewable droughts.

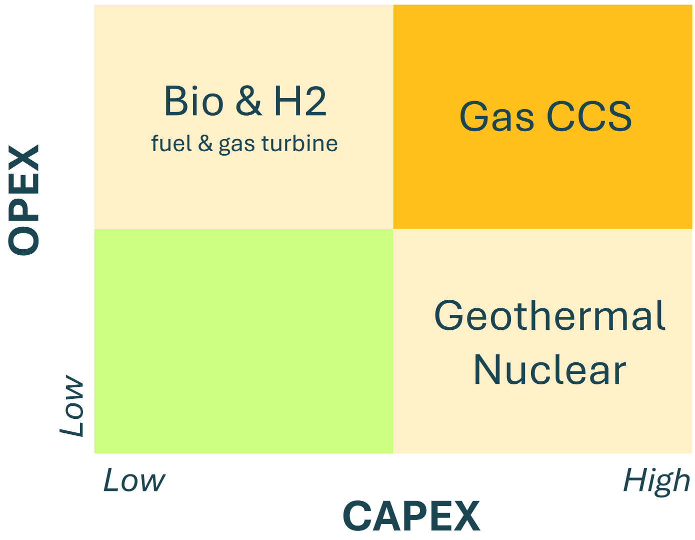

Figure 1. CAPEX–OPEX positioning of dispatchable clean power options under net-zero conditions.

These technologies differ in cost structures. Some rely on high CAPEX and very low OPEX (nuclear and geothermal both running mostly in a baseload mode), others on low CAPEX and higher OPEX (hydrogen or biogas turbines). Notably, hydro power with large reservoirs could also belong to the set of clean firm technologies listed here[2]. Yet they all share the essential characteristic of being firm: they can meet demand reliably whenever required, including during prolonged periods of low wind and solar output.

<u>Role of clean firm power</u>

As Europe enters the deep-decarbonization phase with a combination of high shares of variable renewables, strong but limited interconnection, and structural or policy limits to expanding traditional firm capacity (nuclear, gas, and reservoir hydropower), the system is approaching a point where weather-driven scarcity events, land use and transmission development speed limits, and diminishing marginal capacity value of renewables and storage become binding constraints.

These features make the question of *clean firm power* uniquely important.

First, Europe already operates with very high VRE penetration, especially in Northern and Western countries. While Zappa et al. (2019) show Europe can technically reach 100% renewables, the requirements for doing so are unrealistic and present a risky strategy. Their cost-optimal 100% RES scenarios require at least +140 GW of additional cross-border transmission above today's roughly 60 GW (an increase of ~230%) to enable continent-wide balancing of wind and solar. This corresponds to sustained deployment **of 4.4–10 GW of new transmission per year** to 2050, compared with today's pace of ~4.8 GW/year. On the flexibility side, the 100% RES system requires massive scaling of dispatchable renewable resources, including at least 8.5 EJ/year of biomass (≈4.5×

[2] Due to its limited expansion potential in Europe, it is not as focused as the other technologies in this study.

today's use) and large biogas turbine fleets, plus strong integration of electric vehicles and heat pumps through "smart flexibility" to reduce peak demand. Zappa et al. conclude that, even with optimal spatial allocation of renewables and a fully integrated European grid, the 100% RES system "**would still require significant flexible zero-carbon firm capacity**". This raises questions about the **plausibility** of achieving a 100% decarbonised power system by 2050 without material contributions from firm low-carbon technologies.

Second, while European interconnectors are comparatively strong, they are insufficient to absorb high-VRE stress in extreme weather years. van Zuijlen et al. (2019) explicitly highlight the limits:

> "*Transmission lines are used twice as much across all scenarios compared to the current situation. Thus outages… could pose large problems for a system that relies so heavily on continental-scale transmission*."

The concern raised by van Zuijlen et al. (2019) is not that *only* extreme-weather years produce more outages, but that in a deeply decarbonised, highly interconnected European system, the utilisation of cross-border lines increases so strongly (~2× today's use) that the system becomes structurally more exposed to transmission contingencies. This means that any transmission outage (weather-related, accidental, or operational) has larger system-wide consequences when flows are persistently high and alternatives are limited. Extreme weather years further amplify this exposure, because synchronized low-wind conditions increase the need for long-distance imports and thus push flows closer to technical limits. The practical implication is that continental transmission is a valuable enabler of high-VRE systems, but it cannot substitute fully for having some geographically distributed, dispatchable, low-carbon capacity inside each region. Otherwise, the system becomes too dependent on a small number of transmission corridors operating near congestion for long periods. An alternative to relying on such high levels of cross-border balancing is precisely what many studies recommend: maintaining some amount of clean firm capacity (e.g., nuclear, CCS-enabled gas, geothermal, long-duration hydro) within each region to reduce the risk exposure to transmission outages.

<u>Challenges to clean firm power expansion</u>

Despite clean firm power benefits, there are several challenges to its expansion.

First, Europe's ability to expand firm capacity is structurally constrained for example, nuclear is slated to be phased out in some countries like Germany, and, partially, Switzerland (Pattupara & Kannan 2016). Hydro power potential is largely saturated or limited to a few sites (Metthews, 2024). Fuels (natural gas and oil in particular) in the majority of regions have to be imported. Biomass, although often shown to play significant role in decarbonization pathways, is also subject to local scarcity, land use competition and increasingly in demand as a carbon feedstock in other sectors, including advanced biofuels, e-fuels, bioplastics, chemicals, and carbon-based materials.

Second, clean firm power technologies are often capital intensive, have long-payback periods, and may present technology development risks that prevent investment from the largest pools of capital that are risk-averse. Project bankability is ultimately needed to attract investment, but conditions may be inadequate without additional policy support or public financing mechanisms that can overcome near-term barriers to unlock long-term benefits.

Third, while the EU strongly shapes policy direction, Member States do not necessarily optimise for collective long-term system benefit. National strategies may prioritise industrial competitiveness, self-sufficiency (including fuel-supply concerns), or domestic job creation. Meanwhile, power market signals are largely short-term, not incentivising meeting long-term needs.

Therefore, clean firm power most likely need to find its place in a system shaped by high VRE shares, restricted firm capacity expansion potential, financing challenges, divergent national technology choices, and politically uneven and short-term market incentives.

This study: objective and literature review

The objective of the current study is to investigate how clean firm technologies are incorporated in existing modelling studies and examine the system-level functions they provide in Europe's decarbonised power system.

The literature review covers 16 European energy system modelling studies with varying target regions (European wide and country specific), methodological approaches, emphasis on different power system capabilities and inclusion of different firm technologies. The studies have been chosen based on their highlight of firm. This means that VRE100 studies have not been considered to the same degree[3].

Figure 2 shows how the studies cover different clean firm technologies. The technology mapping illustrates a general inclusion of nuclear, hydro, CCS (natural gas and biobased), H_2 turbines and Bio CHP but few studies consider the role of geothermal and gas turbines using other renewable fuels.

[3] The study Zappa et al. (2019) highlights potential 100% VRE pathways.

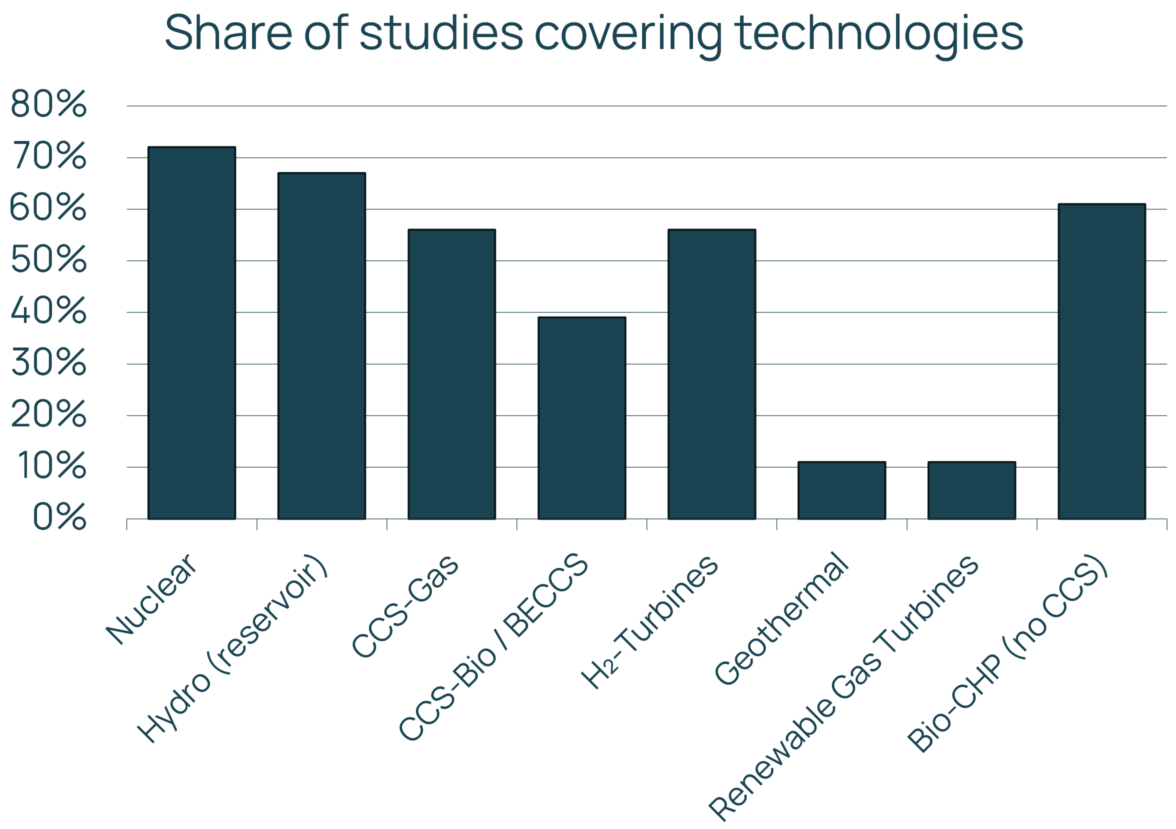

Figure 2. Share of studies covering different clean firm technologies.

What Europe's Energy Studies Reveal About the System Role of Clean Firm Power

Europe's emerging high-renewable energy system displays several characteristic behaviours that repeatedly appear in modelling studies from the EU and UK. Although the academic and policy communities have not reached full consensus on the **extent** to which clean firm power is required, the literature provides a consistent set of insights into how firm technologies affect costs, system reliability, and integration of variable renewables under different assumptions. In the following paragraphs we will shed some light on the role of firm clean power from several angles.

Cost implications and economic role of clean firm resources

Studies repeatedly show that clean firm technologies can reduce overall system costs under deep decarbonisation, although the magnitude of cost savings depends strongly on assumptions about fuel prices, technology costs, and future electricity demand – additionally the reporting metric varies significantly between studies making often a direct comparison challenging (as shown in **Table 1**).

For the UK, Daggash (2019) finds that BECCS (Bioenergy with carbon capture and storage) and DACS (Direct air carbon capture and storage) lower the cost of decarbonisation by 37–48% relative to a system dominated by intermittent renewables. Pratama (2022) illustrates that dispatchable low-carbon technologies such as: nuclear, gas CCS, and BECCS, allow the UK and Poland to maintain system reliability cost-effectively even when significant (cost-effective) storage capacity is available, with the optimal mix depending on national-scale constraints. Studies including nuclear specifically show similarly mixed but informative results: Price (2023) concludes that new nuclear is cost-effective only under relatively low CAPEX assumptions (3520 £2010/kW), but also that nuclear's presence lowers overall system costs by reducing storage and curtailment needs. Hjelmeland (2025) reaches a complementary conclusion at the EU level, demonstrating that higher nuclear shares reduce transmission expansion, curtailment, and land use. Conversely, some studies observe that the cost-effectiveness of clean firm options depends on policy, fuel availability and emissions targets. Pietzcker (2021) shows that as EU-wide emissions targets become more stringent, gas CCS and BECCS reduce the marginal abatement cost but raise electricity prices, particularly after 2040. Meanwhile, in Finland, Koivunen (2020) finds that limiting nuclear leads to a deployment expansion of wind capacity and storage, straining the system economically and technically without adequate firm resources.

Across the literature, the technologies that qualify as "clean firm" differ in cost structure (see **Figure 1**) which means that their operational characteristics in the energy system models vary from providing more providing short power bursts (gas turbines) to baseload (nuclear and geothermal). Focusing in on clean firm power many studies conclude that high-VRE systems achieve lower overall costs when complemented by some level of clean firm capacity, as exemplified with the collected studies presented in

Table 1. Reported cost impact of high-VRE / renewables-only systems compared to mixes including clean-firm resources

Study	Reported cost metric	Reported cost difference	Region of study
Zappa et al. (2019)	Total annual power-system cost (€/yr)	Adding clean firm resources reduces cost by 25% compared to 100% VRE	Europe (~30 nodes)
Daggash et al. (2019)	Cumulative / annual decarbonisation cost	BECCS/DACS reduce the cost of decarbonisation by 37–48%	UK (single node)
van Zuijlen et al. (2019)	Total annual system cost	forcing a 70% VRES share increases total system costs by about 10% relative to the cost-optimal reference, whereas restricting CCS or nuclear increases costs by only ~5% and ~1%, respectively	Europe (~30 nodes)
Price (2023)	System level levelized cost of electricity	Adding BECCS reduces electricity cost by 5–15%; combining BECCS with long-duration storage cuts LCOE by 9–21% vs BASE	UK (9 nodes)
QC (2025b)	Total system cost, normalised to annual electricity demand	Adding nuclear reduces system cost by ~26% compared to a VRE-only system	Germany (single node)
Moen et al., (2025)	Total annual costs	"the cost landscape remains relatively flat across the different shares of nuclear energy"	Denmark (single zone)

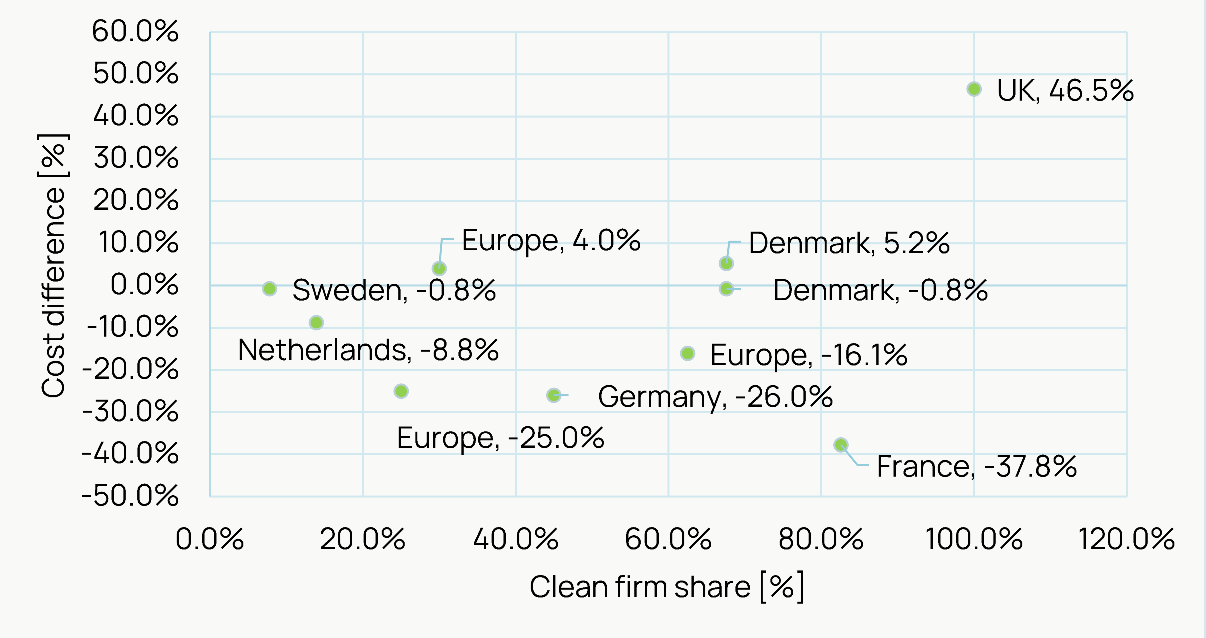

Figure 3. The "total cost difference" between the high clean firm and highest-renewables scenarios. The negative values mean the high-clean firm scenario is cheaper, positive values that it is more expensive. Data adapted from Moen et al., 2025, QC 2025b, Zappa et al., 2019, van Zuijlen 2019. The UK outlier reflects the high cost of nuclear-only system. Nuclear's high capital cost and inflexibility make a 100% nuclear pathway far more expensive than one with a diverse mix that includes renewables, storage, and other resources in addition to nuclear.

From Baseload Thinking to Adequacy-Oriented Planning

A particularly important clarification emerges when the Chalmers system analysis is read alongside the synthesis by Weidlich et al. (2025). The Chalmers (Göransson et al., 2025) report demonstrates that highly renewable power systems continue to require firm capacity to ensure adequacy during prolonged scarcity events, highlighting the importance of flexibility and security rather than continuous energy provision. Building on this system-level insight, Weidlich et al. explicitly show that meeting these firm capacity requirements does not imply a need for new baseload generation: instead, a limited amount of residual-load power plants with very low utilisation is sufficient and cost-effective. This distinction reinforces the conclusion that firm system function matters more than baseload energy share. Furthermore, the Chalmers study performs a comprehensive cost-optimisation of the Swedish power system. It is one of the few efforts that integrates detailed grid simulations, selected system services required to maintain within-hour operational safety (including grid strength and active/reactive power provision), and high spatial resolution, while explicitly evaluating the role of firm power with a particular focus on nuclear energy.

Reliability and resource adequacy

A recurring insight across European studies is that firm clean resources materially influence the ability of the system to maintain reliability during periods of low renewable availability. Models that explicitly simulate multiple historical weather years or that examine extreme events consistently show that high-renewable systems without firm capacity struggle to meet demand during multi-day periods of low wind and solar generation. Price (2023) demonstrates this clearly for the UK, showing that when new nuclear is removed from the system, costs increase sharply during "extreme low-wind periods" and the model must rely on substantial long-duration storage to maintain adequacy – such periods are further visualised in **Figure 4** for Sweden (left panel) but while taking into account the European context (right panel). Similarly, van Zuijlen (2019), using 30 years of historical weather[4], finds that portfolios including roughly 10–20% clean firm capacity produce the "least-cost" outcomes once reliability constraints are enforced. The QC-DE (2025a) and QC-PL (2024) studies, both utilising full-year hourly representation across 33–35 weather years, show that systems relying exclusively on variable renewables and batteries experience structural shortages under adverse weather conditions, whereas systems including nuclear, hydrogen turbines, or CCS-equipped plants maintain adequacy with far lower overbuild requirements. The need for firm capacity is particularly visible in winter, when electrified heating and hydrogen production further elevate peak demand. Moen (2025) illustrates this for Denmark, showing that systems containing nuclear or dispatchable bio/waste CHP require less storage and less grid reinforcement than highly renewable configurations. Although it is technically possible to build extremely large amounts of storage and renewable overcapacity, as Child (2019) emphasizes, such systems exhibit high curtailment and depend strongly on continental balancing to remain feasible.

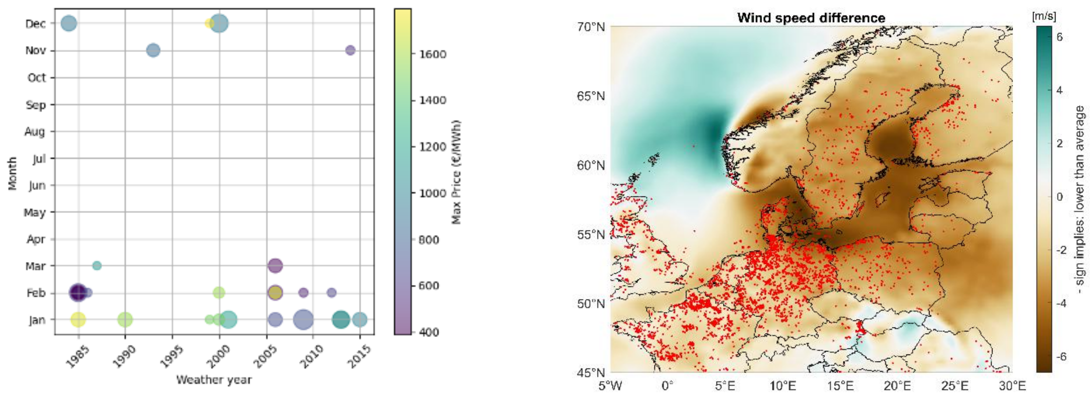

Figure 4. Electricity prices reflect periods of stress well in the power systems. Left panel shows the mean price (colour) in the Swedish (zones SE1-4) power system (Quantified Carbon (2025c)) across different weather years and calendar month with the longest period lasting almost 10 consecutive days, while the right panel is an almost continent wide wind energy drought particularly noticeable in the Baltic Region and Central Europe lasting from 25th of January to 1st of February of historical weather in 2009 (Quantified Carbon 2025d).

VRES integration & lowering infrastructure buildout needs to achieve targets

Another consistent pattern in the literature is that firm clean technologies play a significant role in integrating large shares of variable renewables. By providing

[4] Notably, it is relevant to consider the impact of climate change on extreme weather conditions in energy system planning. Kapica et al. (2025), a study not included in this review, investigates this aspect.

dispatchable power during scarcity periods, firm resources reduce curtailment and limit the need for long-duration storage. van Zuijlen (2019) highlights that firm capacity reduces the need for “excessive storage and overcapacity,” allowing VRE to operate more efficiently. Price (2023) similarly shows that flexible nuclear substantially lowers curtailment and reduces the residual demand peaks that would otherwise need to be met by high-cost storage or imports. Child (2019), while advocating a 100% renewable system for Europe, nonetheless finds curtailment rates above 10% in multiple regions when firm resources are excluded. This implies a structural reliance on both large-scale grids and synthetic fuels in such scenarios.

Firm resources also reduce the infrastructure necessary to achieve decarbonisation targets, making them more plausible to achieve. Moen (2025) finds that firm-capable portfolios require less storage, lower transmission expansion, and modest renewable overbuild. Ek Fälth (2020) quantifies the land-use implications, showing that introducing nuclear in Europe reduces required land use for VRE by roughly half. Hjelmeland (2025) reaches a similar conclusion, noting that higher nuclear shares decrease curtailment and reduce the need for extensive transmission build-out. Where hydro reservoirs already exist, as in the Nordics, dispatchable hydro plays the firm role for seasonal balancing, reducing dependence on additional clean firm technologies (Koivunen 2020; Kan 2020). Across many studies, systems that exclude firm resources compensate through significantly greater requirements for storage, hydrogen production, or transmission, all of which increase system costs and operational complexity. **Figure 5** demonstrates the dynamics on installed capacity of VRE and flexible resources with an example of the German power system contrasting two scenarios, one with and one without nuclear power[5].

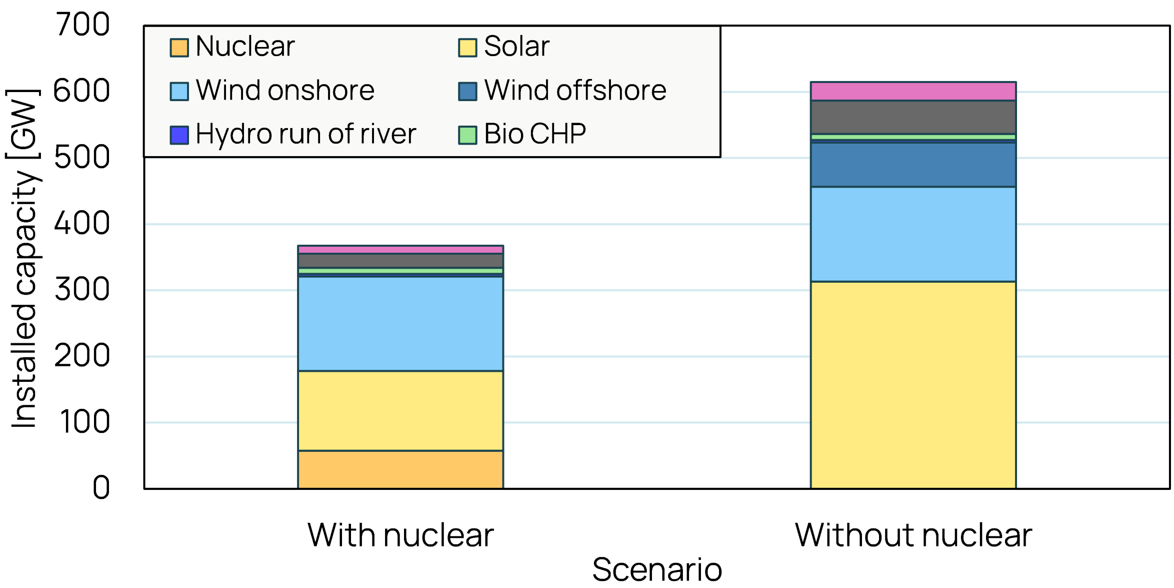

Figure 5. Decarbonised German power systems with (left) and without (right) nuclear power. Source: Quantified Carbon (2025b)

[5] Recent study by Rockefeller Foundation also highlights this dynamics.

European diversity and political constraints

The role of clean firm capacity varies markedly across European countries due to differences in political constraints, resource endowments, and national energy strategies. Countries pursuing nuclear phase-outs, such as Germany and Switzerland, face specific challenges. Hjelmeland (2025) shows that removing nuclear increases storage, transmission, and renewable overcapacity needs in EU-wide systems. Likewise, Pattupara and Kannan (2016) find that Switzerland becomes more reliant on imports and faces higher decarbonisation costs when nuclear is phased out. Conversely, Sweden and Finland illustrate how the continued use of nuclear and reservoir hydropower reduces system strain; Kan (2020) finds nuclear significantly improves Swedish system economics and export opportunities, while Koivunen (2020) emphasises that hydro and nuclear together stabilise Finland's winter adequacy and reduce curtailment. For some countries, natural-gas-based firm power remains an attractive option, but fuel import dependence raises both economic and security concerns. Pietzcker (2021) and QC-PL (2024) highlight uncertainty in the long-term cost and availability of gas and hydrogen, a concern reinforced by QC-DE (2025a), which stresses that interconnection alone is insufficient to balance VRE variability during stress periods. Matthews (2024) underscores that UK hydro potential is limited and that biomass imports are controversial, reinforcing the need for firm low-carbon alternatives.

Interconnectors play an important but constrained role. Although many models assume extensive cross-border trade, several studies caution against relying too heavily on continental-scale smoothing. van Zuijlen (2019) notes that systems focusing regional coordination with a strategy to expand interconnections significantly are vulnerable to transmission outages, while Child (2019) emphasises that even very strong interconnection cannot fully offset continent-wide weather shortages. QC-DE (2025a) and QC-PL (2024) further observe that national energy strategies often prioritise energy sovereignty, a factor that may limit the political appetite for deep reliance on imports of electricity or hydrogen.

A study by Carbon Free Europe (2022) (**Figure 6**) indicates a significant spatial variation in preferred firm technologies across various countries with gas power playing a dominant role followed up by nuclear. Collectively, these studies show that the role of clean firm power in Europe is shaped not only by techno-economic factors but also by political choices and national resource constraints. Countries with hydro reservoirs or ongoing nuclear programmes have ways to handle adequacy challenges, while those without such assets may need to rely more on CCS-based thermal generation, bio-based firm fuels, or hydrogen turbines.

Finally, it is worth noting that geothermal, despite being a potentially attractive clean-firm option in some regions, is only included in one of the reviewed modelling studies. This is believed to be largely due to limited resource assessments and fewer techno-economic datasets, rather than lack of system relevance.

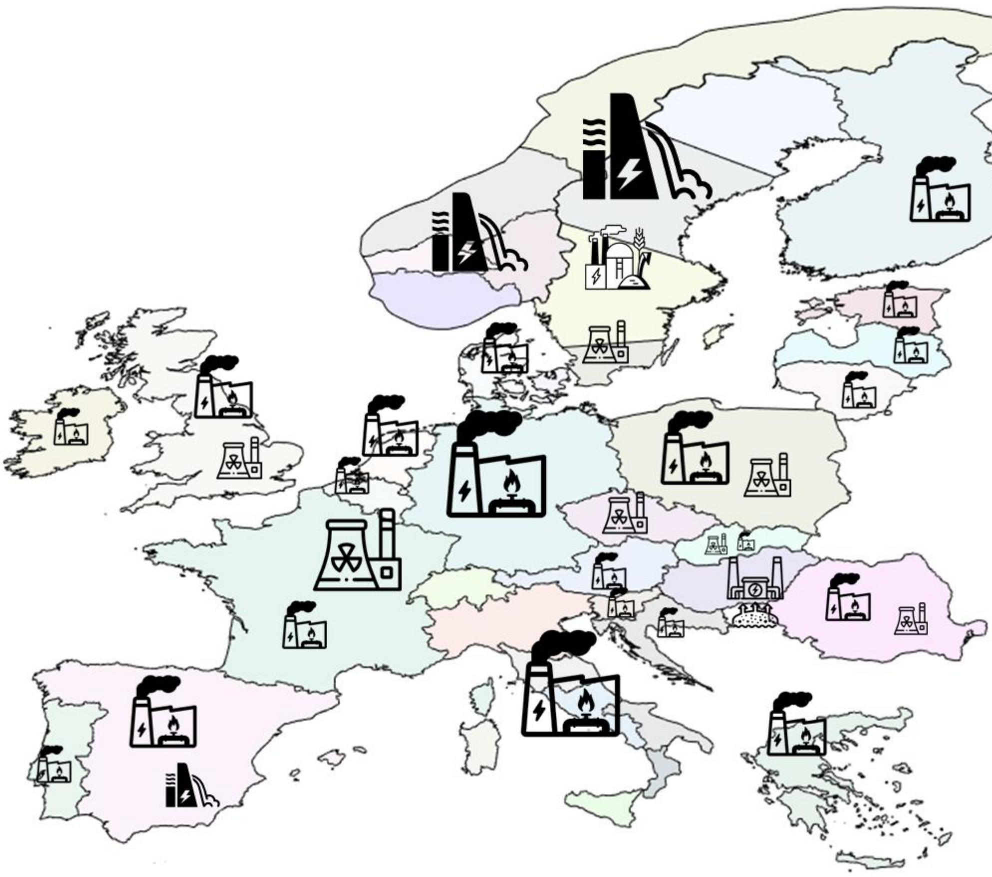

Figure 6. Dominant firm technologies in each country as per the study by CFE in the year 2050.

What Comparative Evidence Suggests About the Modelling of Clean Firm Power in Europe

The broad set of studies examined in this report exhibit considerable diversity in scope, modelling assumptions, and methodological depth, yet a number of structural patterns emerge when these works are viewed together. The comparison table (Appendix

Table **2**) highlights ten recurring modelling methodological characteristics[6] across the literature that meaningfully influence how clean firm power is valued or overlooked. Figure 7 presents an illustration of how different modelling assumptions drive increased or reduced role for clean firm technologies, providing a first understanding on why different studies could arrive at different conclusions regarding the role of clean firm capacity in future European power systems.

[6] See Appendix

Table **2** for definition of modelling methodological characteristics.

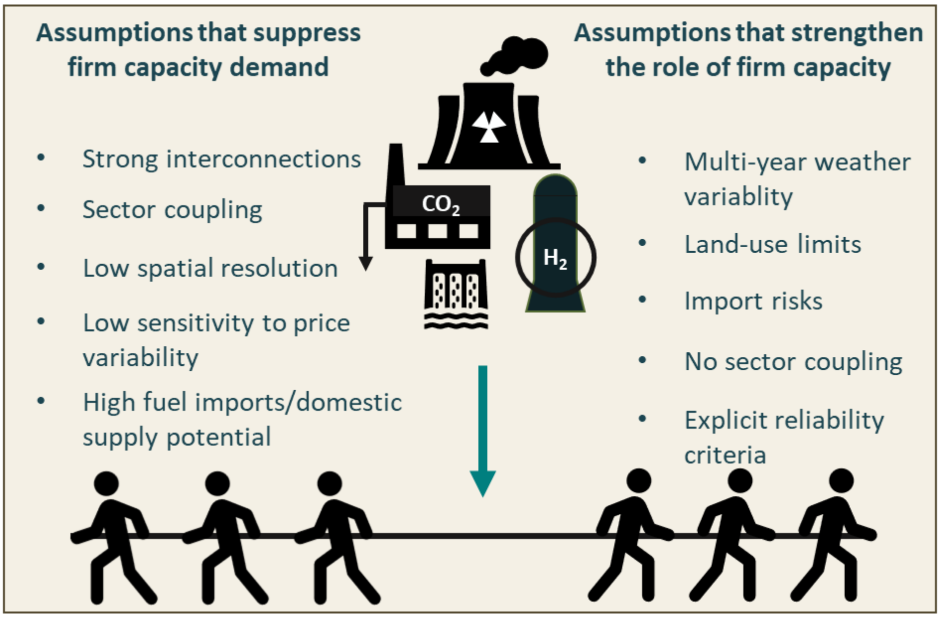

Figure 7 List of modelling assumptions (non-exhaustive) that reduce or increase the need for firm clean capacity in decarbonised power systems. Assumptions on the left generally suppress firm capacity demand by enabling high renewable integration, while those on the right reveal system stress and strengthen the role of firm, dispatchable resources.

Figure 8 depicts modelling aspects emphasized throughout the studies, which highlights that interconnector expansion, cost-related sensitivities, and various demand scenarios are most commonly integrated study design features. This contrasts with price volatility, self-sufficiency and high spatial resolution which are aspects hardly considered among the references. In the middle range, 34%-53% coverage, methodological characteristics sector coupling, security of fuel imports, land-use trade-offs and resource adequacy are found. We go through each of the modelling aspects and their employment throughout the studies below.

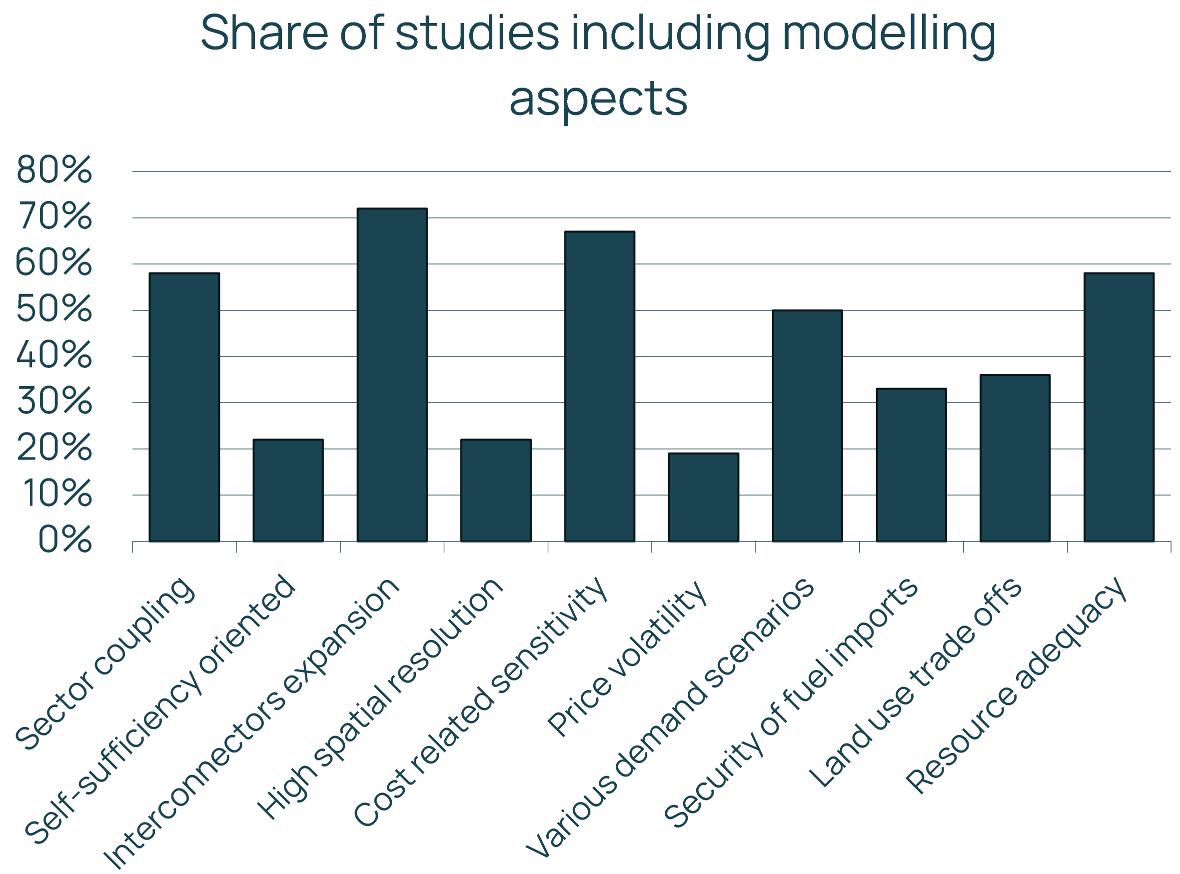

Figure 8. Share of studies including various modelling aspects.

Roughly half the studies model sector coupling. Works such as Moen (2025), (2025a), QC-PL (2024), or CFE (2024) integrate heat, hydrogen, and transport into their electricity modelling. Other studies treat the system as electricity-only, sometimes with electric vehicles added at the margin. The role of clean firm could largely depend on whether the model allows for endogenous capacity expansion of multiple sectors alongside transmission or defines it exogenously. However, generally strengthened sector coupling drive a lower role for clean firm. For instance, capacity expansion on hydrogen production and transmission alongside the power sector could enable a lot of system flexibility without clean firm.

A cross-study pattern is the near-universal assumption of cooperation rather than self-sufficiency. Numerous pan-European models (van Zuijlen 2019; Zappa 2019; Pietzcker 2021; Price 2023; CFE 2024) rely on continental balancing or make imports available to varying degrees. While such cooperation is a central feature of the European market design, it creates a methodological asymmetry: firm capacity needs appear smaller in models that implicitly assume reliable imports, yet this may not hold during geopolitically stressed periods or continent-wide VRE scarcity events. Models that rely on imports (e.g., Zappa 2019; Price 2023) tend to report lower domestic firm capacity requirements compared to studies that constrain cross-border flows (Koivunen 2020; QC-PL 2024). The above also strongly relates to the transmission expansion, which is enabled in most models, what further suppresses the apparent need for domestic firm power. Studies such as Zappa (2019), Price (2023), and allow large interconnector buildout, and this effectively substitutes infrastructure for firm generation. Although transmission expansion is an important flexibility asset, high reliance on it raises vulnerability when large portions of the continent face similar weather conditions. The van Zuijlen (2019) analysis is explicit on this point, arguing that heavy dependence on cross-border flows increases the consequences of transmission faults during scarcity events. Notably, large dependency on transmission infrastructure could also represents a vulnerability to pace of implementation and could risk feasibility of transition pathways.

Avery prominent trend is the low spatial resolution in many models. Except for Price (2023), which incorporates 9-nodes in UK, most studies use a single national node. While computationally convenient, such simplification smooths out local scarcity events, masks congestion, and hides internal transmission needs. Future studies on the role of clean-firm resources should incorporate higher spatial granularity. This not only captures their potential to dampen local price spikes and support load centres but also exposes their complementary value in providing flexibility nearer to consumers and easing constraints on lower-voltage networks.

The fifth pattern relates to cost sensitivity, which is uneven across the literature. Several studies conduct robust sensitivity sweeps: including Moen (2025), Price (2023), QC-DE (2025a), and QC-PL (2024), while others apply fixed cost assumptions with little variation (e.g., Kan 2020; Koivunen 2020). Fixed assumptions predetermine outcomes and reduce the robustness of conclusions concerning the optimal share of nuclear or CCS-equipped gas, as cost-competitiveness can shift materially under plausible parameter ranges. Going beyond pure cost optimization is a relevant consideration as highlighted in Quantified Carbon (2025e).

Sixth, electricity price volatility is rarely analysed, with QC-DE/PL and LFS-FI being notable exceptions. Because firm clean technologies dampen scarcity-driven price spikes and contribute to a more predictable market capable of sustaining decarbonisation investments, omitting volatility modelling obscures a major part of their system value. When volatility is not incorporated, this stabilising effect remains invisible.

Another recurrent feature is the limited representation of demand uncertainty. Most papers assume a single deterministic demand trajectory without alternative electrification scenarios. Exceptions include Price (2023), and Hjelmeland (2025). Deterministic demand shapes the system to idealised conditions and fails to capture possible future shocks in hydrogen demand or accelerated heat pump uptake, both of which increase the relevance of firm dispatchable capacity.

Fuel import security is also rarely examined explicitly. Although QC-DE and QC-PL quantify import volumes, most studies assume perfect availability of natural gas, biomass, or hydrogen. This assumption diminishes the perceived strategic value of domestic firm capacity. Similarly, land-use constraints are weakly modelled in most studies, while QC-DE, QC-PL, and Ek Fälth (2020) show that incorporating spatial constraints significantly alters the optimal portfolio and reduces the feasible scale of VRE deployment.

Finally, resource adequacy evaluated based on weather-year robustness varies between studies. Some use a single weather year, some use a few representative days, and others (van Zuijlen 2019; QC-DE; QC-PL; Price 2023) evaluate 30 or more historical weather years. It is precisely in such multi-year analyses that the importance of clean firm power becomes most visible: during unfavourable drought years in van Zuijlen (2019), firm resources such as nuclear, hydro reservoirs or hydrogen turbines become essential, although it is important to remark that they are also being affected.

Taken together, the comparison Appendix

Table 2 (Appendix) therefore suggests that many modelling frameworks struggle to incorporate wide set of modelling aspects that could mean a general undervalue of firm clean capacity. Studies that incorporate a more complete set of real-world constraints, such as QC-DE, QC-PL, van Zuijlen (2019), Price (2023), and Moen (2025), tend to converge on the finding that substantial volumes of firm clean capacity improve reliability, reduce system costs, stabilise prices, or reduce infrastructure burdens in high-VRE systems.

For future modelling studies, the review highlights the lack of consideration for price volatility and self-sufficiency, and especially high spatial resolution, that deserves a larger focus to increase the understanding of their potential impact to guide energy system planning.

Concluding remarks

This study has investigated how clean firm technologies are incorporated in existing modelling studies and what system-level functions they provide in Europe's decarbonised power system by means of a literature review across 16 European energy system modelling studies.

Even without consensus on the optimal portfolio of technologies, a clear and durable pattern emerges across the better-resolved studies in this review: clean firm technologies consistently play a stabilising and cost-reducing role in Europe's decarbonised energy systems. Studies show this especially when a more holistic representation of realistic system constraints is incorporated, like limited availability of land for VRE expansion, uncertainties over future fuel imports, and the pronounced variability of multi-decadal weather patterns. van Zuijlen (2019), Price (2023), QC-DE (2025a), and QC-PL (2024) show that high-VRE systems only remain reliable and affordable when complemented by firm low-carbon options, whether nuclear, geothermal, biomass CHP, gas CCS, or hydrogen-fired turbines. Notably, across the 16 studies reviewed geothermal as a clean firm technology was only considered in one, highlighting reason to further integrate this potential resource in future energy system studies.

Taken together, this cross-study evidence indicates that firm clean power is not a universal prescription, but it becomes increasingly indispensable as European systems move toward deep electrification, tighter emission limits, and more volatile weather conditions. In this sense, clean firm resources act less as optional add-ons and more as a critical complementary backbone that ensures adequacy, moderates system costs, and anchors the resilience of a highly renewable, deeply decarbonised European energy system.

Finally, this review has mapped the modelling approaches used across the reviewed studies. A deeper understanding of the role of clean-firm power will require broader incorporation of price volatility, self-sufficiency metrics, and, in particular, higher spatial resolution, which most studies have lacked until now.

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Appendix

Table 2 Comparative assessment of modelling assumptions across studies and their potential implications for firm clean technologies.

Aspect/ reference	Daggash, 2019	Hjelmeland, 2025	Kan, 2020	Moen, 20225	Pattupara & Kannan,	van Zuijlen, 2019	Zappa, 2019	Price, 2023	Pietzcker, 2021	Koivunen, 2020	Matthews, 2024	Child, 2019	QC DE	QC PL	CFE PL	LFS FI	Weidlich, 2025	Göransson, 2025	Coverage
Sector coupling	-	-	+/-	+	-	+	-	+	-	+/-	+	+/-	+/-	+/-	+	+	+	+	58%
Self-sufficiency oriented	-	+	-	-	-	-	-	-	-	+/-	+/-	+	+/-	+/-	-	-	-	-	22%
Interconnectors expansion	+	-	+	+	+	+	+	+	+	-	+/-	+	-	-	+	+	+	+/-	72%
High spatial resolution	-	-	+	-	-	-	-	+	-	-	-	-	-	-	-	+/-	+/-	+	22%
Cost sensitivity	+	+	+	+	-	+	+	+	+	-	-	-	+	+	+	-	+	-	67%
Price volatility	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	-	-	+/-	19%
Various demand scenarios	-	+/-	+	+	+/-	+	+/-	+/-	+/-	-	+	-	-	-	+	+	-	+/-	50%
Fuel supply security	+/-	-	-	+/-	+/-	+/-	-	+	-	+/-	+/-	-	+/-	+/-	-	+/-	+/-	-	33%
Land use trade offs	+/-	-	+/-	+/-	-	+/-	+/-	+/-	-	-	+/-	+/-	+	+/-	-	+	-	-	36%
Resource adequacy	-	+	-	+	-	+	+	+	-	+/-	+/-	-	+	+	-	+/-	+	+	58%
Coverage	30%	35%	50%	60%	20%	60%	40%	70%	25%	20%	45%	30%	55%	50%	50%	55%	50%	45%	

Legend: **Sector coupling** indicates if the model integrates heat, transport, hydrogen or industry and interactions between them. **Self-sufficiency oriented** shows if the system is designed to meet its own demand rather than depends to an extent on imports. **Interconnectors expansion** specifies if cross-border transmission capacity can be added or reinforced in the modelling. **High spatial resolution** refers to models that represent the power system with multiple regions or nodes instead of a single aggregate (several nodes per country). **Cost-related sensitivity** captures studies that test robustness by varying CAPEX, OPEX, or fuel-price assumptions. **Price volatility** describes models that analyse hourly price fluctuations instead of only average system costs. **Various demand scenarios** applies to studies exploring multiple future demand pathways or levels of electrification. **Security of fuel imports** Covers assessments that account for risks linked to reliance on imported fuels like gas, biomass, or hydrogen. **Land-use trade-offs** Highlights studies that include constraints on siting and available land for renewable deployment but also compares scenarios depending on energy mix. **Resource adequacy** Denotes work that evaluates system reliability under challenging or stress-case operating conditions. **”+”** – deeply studied in the report; **”+”/-“** – not exhaustively covered; **“-“** – not covered.

Table 3 Clean Firm Technologies Included in Each Study (+included/tested, - absent)

Firm clean technology/ reference	Daggash, 2019	Hjelmeland, 2025	Kan, 2020	Moen, 20225	Pattupara & Kannan, 2016	van Zuijlen, 2019	Zappa, 2019	Price, 2023	Pietzcker, 2021	Koivunen, 2020	Matthews, 2024	Child, 2019	QC DE	QC PL	CFE PL	LFS FI	Weidlich, 2025	Göransson, 2025	Coverage
Nuclear	-	+	+	+	-	+	-	+	-	+	+	-	+	+	+	+	+	+	69%
Hydro (reservoir)	-	-	+	-	+	+	+	-	+	+	+	+	+	-	-	+	+	+	63%
CCS-Gas	+	-	-	-	+	+	-	+	+	-	+	-	+	+	+	-	+	-	56%
CCS-Bio / BECCS	+	-	-	-	-	-	-	+	+	-	-	-	+	+	+	-	-	-	44%
H_2-Turbines	-	-	-	-	-	+	-	+	+	-	+	-	+	+	+	+	+	+	50%
Geothermal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	+	-	6%
Renewable Gas Turbines	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	-	-	13%
Bio-CHP (no CCS)	+	-	+	+	+	+	-	-	-	+	+	-	+	+	+	+	-	-	69%
Coverage	38%	13%	38%	25%	38%	63%	25%	50%	50%	38%	75%	25%	75%	63%	75%	50%	63%	25%	