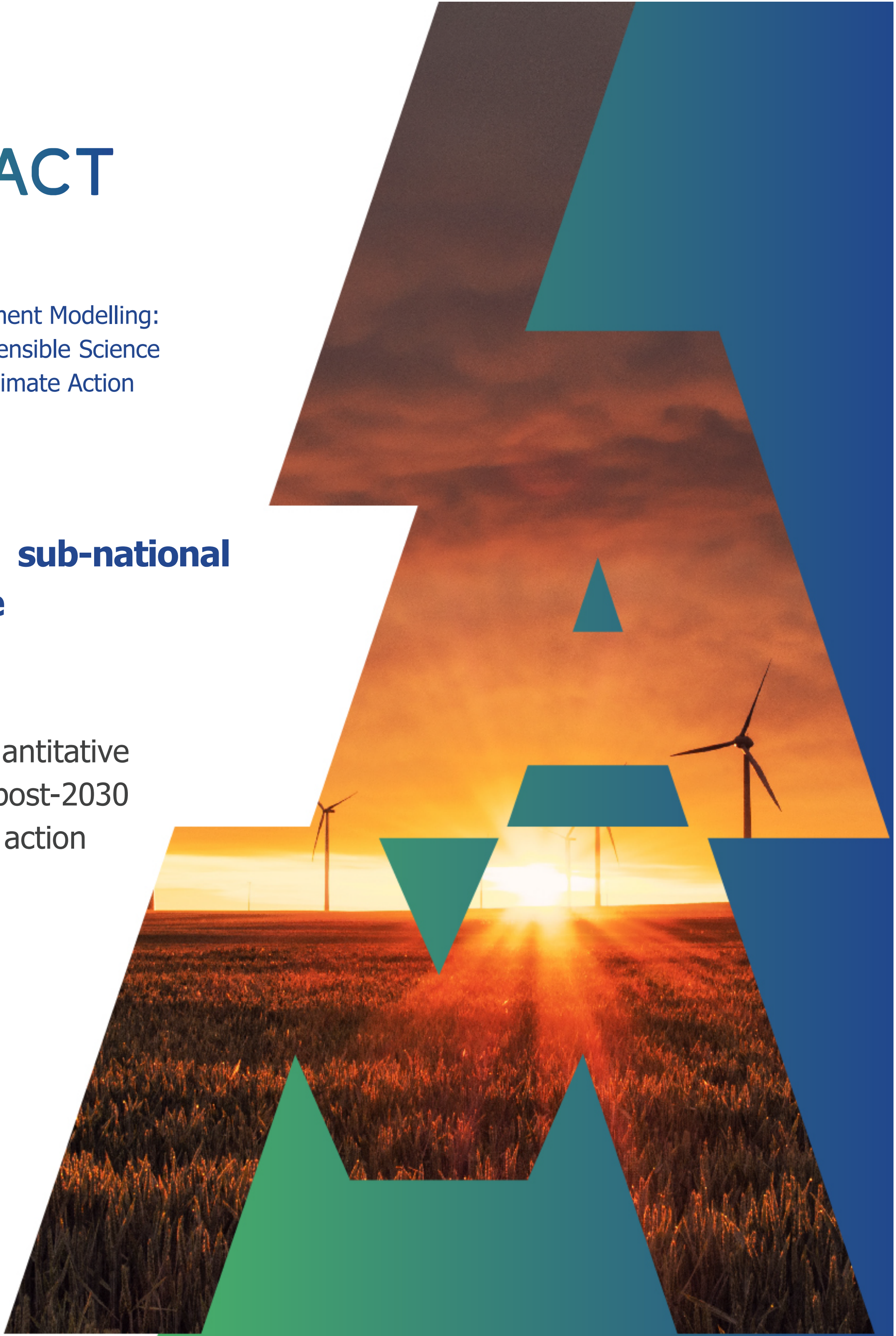
Expanding Integrated Assessment Modelling:
Comprehensive and Comprehensible Science
for Sustainable, Co-Created Climate Action

D4.10 – European sub-national deep dives – Update

WP4 – Modelling – Quantitative evidence in support of post-2030 Paris-compliant climate action

29/07/2025



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EC Summary Requirements

Changes with respect to the DoA

No changes with respect to the work described in the DoA.

Dissemination and uptake

This deliverable reports results from (i) the Grant Agreement-prescribed work on the sub-national analysis of the European electricity sector transition, especially with the focus on air pollution and health co-benefits, and (ii) the second modelling cycle of the IAM COMPACT Policy Response Mechanism (PRM), via which questions were raised and are here addressed around the topics of costs, energy security and resilience, as well as electrification. The PRM modelling cycle results will be fed back to policymakers as the last part of the PRM in the form of policy briefs. The first part overall presents an internationally novel spatial analysis on employment and skills in Europe and the regional justice implications to be published in peer-reviewed literature. The second part on cost optimal and policy prescribed decarbonisation scenarios in the EU will also be submitted for publication.

Short summary of results

This deliverable brings together four studies exploring European sub-national and sectoral perspectives on climate change mitigation, energy security and resilience, employment impacts, and policy assessment. The first study focuses on the power sector, comparing a scenario consistent with the EU's 'Fit for 55' package against a hypothetical coal phaseout. The 'Fit for 55' scenario delivers higher and more evenly distributed net employment gains at lower overall system cost, while the 'coal phaseout' scenario achieves deeper emission reductions but creates significant re-skilling challenges; these are especially acute for coal and lignite workers lacking key system and content skills needed for emerging technologies such as solar and wind. Skills required for new green jobs are relatively uniform across Europe, while the scale of re-skilling varies by region. The second study shows that well-designed, diversified renewable energy systems can be both secure and resilient, capable of meeting long-term climate goals while managing operational risks; however, if security and robustness to disruptive events are priorities, these aspects must be explicitly included in scenario design and modelling practices. The third study evaluates renewable methanol imports, finding that economic and employment benefits plateau beyond a 50% import share; it highlights the importance of diversifying supply sources and maintaining domestic production capacity to enhance energy security and system efficiency. The fourth study shows that EU and Member State policies under Fit for 55 and updated NECPs can enable deep power-sector decarbonisation by 2030 but require substantial, regionally coordinated investments in renewable generation and supporting infrastructure.

Evidence of accomplishment

This report.

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Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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Executive Summary

This deliverable brings together four studies exploring European sub-national and sectoral perspectives on climate change mitigation, energy security and resilience, employment impacts, and policy assessment. The first study focuses on the power sector, comparing a scenario consistent with the EU's 'Fit for 55' package against a hypothetical coal phaseout. The 'Fit for 55' scenario delivers higher and more evenly distributed net employment gains at lower overall system cost, while the 'coal phaseout' scenario achieves deeper emission reductions but creates significant re-skilling challenges; these are especially acute for coal and lignite workers lacking key system and content skills needed for emerging technologies such as solar and wind. Skills required for new green jobs are relatively uniform across Europe, while the scale of re-skilling varies by region. The second study shows that well-designed, diversified renewable energy systems can be both secure and resilient, capable of meeting long-term climate goals while managing operational risks; however, if security and robustness to disruptive events are priorities, these aspects must be explicitly included in scenario design and modelling practices. The third study evaluates renewable methanol imports, finding that economic and employment benefits plateau beyond a 50% import share; it highlights the importance of diversifying supply sources and maintaining domestic production capacity to enhance energy security and system efficiency. The fourth study shows that EU and Member State policies under Fit for 55 and updated NECPs can enable deep power-sector decarbonisation by 2030 but require substantial, regionally coordinated investments in renewable generation and supporting infrastructure.

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1 Introduction

This IAM COMPACT Deliverable, *D4.10 - European sub-national deep dives - Update*, presents the project's final results of Task 4.5 – A sub-national deep dive in Europe. The interim results, corresponding to Deliverable D4.9, can be found in Zenodo[1]. The work presented here is related to the European sub-national and sectoral deep dives into the energy and climate mitigation questions, using spatially explicit, national- and continent-level modelling tools. of the 1st modelling cycle Four studies have been conducted as part of Deliverable D4.10 based on the Grant Agreement and IAM COMPACT Policy Response Mechanism:

- A study focused on employment and skill with three key questions: (1) How do regional employment levels in the European electricity sector differ between current decarbonisation plans and a hypothetical EU-wide coal and lignite phaseout (2) What skill-related barriers hinder workers transitioning across electricity sector jobs, and how do these vary by region? (3) How do re-skilling needs compare to the skills required for new entrants? To answer these, we model regional employment, and skill impacts across the full electricity supply chain in Europe by 2035, using a novel spatial allocation method to link generation changes to employment shifts in resource extraction.
- An analysis of energy security, resilience, flexibility, costs, and environmental indicators in renewable energy systems in Europe using EnergyPLAN, a tool for simulation of the entire energy system including all sectors, i.e., heating, cooling, industry, transportation, as well as electricity and gas grids.
- A study that examines the trade-offs involved in ensuring a secure and affordable energy system, with a focus on different levels of reliance on domestically produced versus imported renewable methanol. Through a series of import scenarios, it analyses the associated costs of achieving energy security and affordability in Europe.
- And finally, a study that couples GCAM-Europe with EXPANSE, a detailed electricity system model which provides capacity needs, grid constraints, and storage dynamics, and derive the energy system transformations required at the EU Member State level to achieve the EU's Fit-For-55 and net zero goals and examine how these transitions differ among EU-wide targets, state-level policies, and cost-optimal pathways.

Overall, these studies already cover a breadth of deep-dive and regionalised insights into energy transition with questions on employment co-benefits of EU's pathways, energy security and resilience, green fuel imports, as well as policy assessment. This deliverable and the corresponding project task (Task 4.5) were explicitly designed to feature both Grant Agreement-prescribed work (Section 2 and 4) and research conducted in response to the Listening mechanism (PRM) of the project (Sections 3 and 5), much like several other tasks and deliverables in IAM COMPACT.

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2 Regional electricity sector employment and skills under different European policy scenarios

Authors: Alison Maguire, Alexandre Torné, Evelina Trutnevyte [UNIGE]

2.1 Summary

Supporting fossil fuel workers through low-carbon transition and ensuring a sufficient workforce for renewable energy technologies is of utmost importance. To boost climate action while maintaining a just transition in the electricity sector, we assess the regional employment implications in 2035 of two policy ambitions, the 'Fit for 55' package of the European Union (EU) and a hypothetical EU-wide coal phaseout. We account for changes in employment and associated skills from electricity generation, storage and transmission, covering the whole supply chain from resource extraction to decommissioning. We then distinguish employment transfers from employment gains to identify skill needs at a NUTS 2 regional scale. We find that net employment creation is higher and more evenly distributed under the 'Fit for 55' policy plan compared to the hypothetical EU coal phaseout. Under both policy scenarios, the skill requirements for the workers in transition (many of whom are transferring from fossil fuel technologies to low-carbon technologies) depend on the specific region, while the skillsets needed for employment gains are similar across all European regions as they are driven by employment growth in technologies that require similar skills (wind and solar power). This information can support the design of re-skilling programs, helping to ensure that regions are not left behind in the energy transition.

2.2 Introduction

European energy and climate policy efforts are expected to bring about job creation in renewable energy (Pai et al., 2021). However, decarbonisation policies have been considered insufficient (Rogelj et al., 2016) and there have been calls to boost efforts for fossil fuel phaseout (International Energy Agency, 2023; WWF et al., 2024). The electricity sector is of particular importance to climate policies as it has high greenhouse gas (GHG) emissions (Eurostat, 2024a; Sasse and Trutnevyte, 2023a), and is expected to decarbonise earlier to allow other sectors to decarbonise (European Commission, Directorate-General for Climate Action, 2020; Pietzcker et al., 2021; Sasse and Trutnevyte, 2023a). To ensure net-zero emissions by 2050 (European Commission. Directorate-General for Climate Action, 2019), it is thus important to advance electricity sector policy ambitions at an earlier date than 2050 (this is also expected to lower system costs (Victoria et al., 2020)). The global climate crisis has emphasised the concept of a just and equitable transition in employment distribution (evident in the EU Just Transition Mechanism (European Commission, 2020)), with skill requirements being an important determinant (García-García et al., 2020). This is reflected in the increasing integration of justice and equity objectives in electricity systems models (Goforth et al., 2025). Coal mining regions are likely to be severely affected (Borgonovi et al., 2023) by strongly concentrated impacts (European Commission. Directorate-General for Economic and Financial Affairs., 2022) during the transition. Historically, a faster transition from coal in Germany would most likely have resulted in a faster recovery of the mining regions (Oei et al., 2020). When comparing the coal phaseout to that of nuclear power in Germany, coal workers exhibit a low resilience for transformation due to their larger numbers, lower skills and a lack of employment mobility (Selje, 2022). Thus, the inclusion of employment distribution, mining regions and regional skill requirements is paramount when comparing policy ambitions.

With the limited historical mobility of fossil fuel workers, and their geographical situation in areas where green jobs are potentially less likely to emerge, location is an obstacle when finding employment in a decarbonised system (Lim et al., 2023). It has been shown through skill-integrated, spatial-temporal analysis that, although few coal power plant workers can easily transfer to green jobs, upstream sectors of renewable energy can alleviate job loss due to their compatible skill requirements and flexible location options (Wu et al., 2024). In Europe, there is an expected surge in construction and manufacturing jobs which will decline significantly following 2035 when

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there will be a shift towards operation and maintenance jobs (Černý et al., 2022). Although there has been increasing policy attention on regional impacts of the energy transition (Alves Dias et al., 2018; Kapetaki et al., 2020), few studies have integrated spatially explicit employment data—covering both fossil fuel and renewable technologies—with sector-wide electricity systems models to assess impacts holistically, including evolving skill needs. Demand in the labour market for renewable electricity is expected to grow rapidly for highly qualified, highly skilled, non-manual workers with the implementation of the European Green Deal (European Centre for the Development of Vocational Training., 2023). Similar findings have been presented in the US, where the lowest-skilled workforce may experience more varied gains and losses than their high-skilled counterparts (Xie et al., 2023). But as far as we are aware, a regionalised and more detailed assessment of skills does not exist yet for Europe.

In this study, we thus investigate: (1) How do regional employment levels in the European electricity sector compare in the case of current decarbonisation ambitions (European Environment Agency, 2024) and the hypothetical EU-wide phaseout of coal and lignite (European Court of Auditors, 2022)? (2) What are the key skill-related barriers for workers transitioning between jobs in the electricity sector under these different policies? How do skill demands vary across regions? (3) How do re-skilling requirements compare with the skill requirements of new workers in the electricity sector? To answer these research questions, we model the regional impacts on employment and skills in Europe in 2035, accounting for the whole supply chain from resource extraction to decommissioning across electricity generation, storage and transmission. The regional employment changes in resource extraction are linked to the changes in electricity generation using a novel spatial allocation method (with separate methods for biogas, woody biomass, coal and lignite, and oil and gas).

2.3 Methods

EXPANSE spatial electricity sector model

The European EXPANSE electricity sector model (Sasse and Trutnevyte, 2023a, 2023b, 2020, 2019; Trutnevyte et al., 2012) is a spatially and temporally detailed, technology rich, single-year optimisation model of the European electricity system in 2035 that covers 33 countries (European Union minus Cyprus and Malta and plus Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Norway, Serbia, Switzerland, and the United Kingdom). The model includes electricity generation at the level of 296 NUTS-2 regions and the electricity demand, storage, and transmission of 128 transmission grid nodes. EXPANSE balances electricity generation, storage, and transmission with inelastic electricity demand at each transmission grid node and time step. The model represents each hour of the year and optimises every sixth hour to strike a balance between computational costs and accuracy (Schyska et al., 2021).

Employment assessment

This study builds on the earlier employment assessment in EXPANSE (Sasse and Trutnevyte, 2023a, 2020), which accounts for direct employment in construction, operation and maintenance, and decommissioning of electricity generation, storage, and transmission. These jobs are calculated for the EXPANSE model outputs using employment factors (see Annex A1). The employment factors (excluding extraction) are technology-specific and are applied to the installed capacity in each NUTS 2 region (jobs/MW). Construction, operation and maintenance and decommissioning jobs are retained within the NUTS 2 region where there is capacity installed. Job losses are constrained using the current scenario, ensuring that jobs that do not exist in the current scenario cannot be removed. The nuclear decommissioning process can take 15-20 years (International Atomic Energy Agency, 2023), thus the nuclear decommissioning jobs are retained after plant closures.

In this study, the extraction jobs are calculated at the continental level by applying fuel-specific employment factors (Ram et al., 2020) (jobs/MWh) to the annual fuel use of each plants using woody biomass, biogas, waste,

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oil, natural gas, coal, and lignite. These jobs are then spatially allocated to the NUTS 2 regions of extraction through newly created spatial allocation methods specific to each technology. This allocation method thereby links the change in fuel use of each plant with the change in employment at the regions of extraction. In the current scenario, employment levels for oil, gas, coal and lignite extraction are allocated to each NUTS 2 region proportionally to existing employment in each region. That is, all oil and gas extraction jobs calculated by the model are aggregated and then distributed proportionally to the number of oil and gas extraction workers in each region (Eurostat, 2024b). The same method is conducted separately for coal and lignite mining (Alves Dias et al., 2018). The employment factors are applied to the installed capacity of the cost-optimal electricity mix in 2035 to find the number of extraction workers per technology. The change in extraction jobs due to a policy scenario is calculated at the continent level and then distributed spatially to each NUTS 2 region with separate methods for each technology. Coal and lignite extraction job changes are mapped using a risk rating (Alves Dias et al., 2018), with the highest risk regions losing the highest proportion of jobs; peat regions (Alves Dias et al., 2021) are accounted for here with the highest risk rating. Oil and gas extraction jobs are mapped using supply cost data (Black et al., 2023), with the most expensive regions losing the highest fraction of jobs. Woody biomass extraction jobs stay within the same region as the generation unless there are significant wood imports at the country level (see Annex A1).

Skills Analysis

The skills data is obtained from the O*NET database (O*NET and U.S. Department of Labor, Employment and Training Administration, 2024) where the individual skills are assigned to groups (Greenspon and Raimi, 2024; O*NET and U.S. Department of Labor, Employment and Training Administration, 2024) (social, content, resource management, complex problem solving, systems, process and technical; see Annex A1). Based on similar studies (Greenspon and Raimi, 2024; Lim et al., 2023; Soydan et al., 2024), the importance and level of each skill are combined to create a set of skill scores for each job. A list of jobs per supply chain sector group (extraction, construction, operation and maintenance, decommissioning) and technology is first created (see Annex A1). The skill scores are weighted for each technology through employment factors from each of these supply chain groups and are normalised to one for each technology (e.g. 3.8% of all skills needed for oil and gas generation jobs are in operations monitoring). As such, the skill scores from each technology are linked to the number of jobs in each region (they are calculated through the combination of employment factors and installed capacity). Skill changes are calculated on a regional basis. Re-skilling scores are the skill requirements for a worker with the opportunity to transfer jobs within the electricity sector and the same NUTS 2 region. They are calculated as the positive difference between the skills of an average job gained in the region and an average job lost.

Policy Scenarios

In this study, two policy scenarios are compared for 2035: one that is in line with the accepted EU decarbonisation policy (the 'Fit for 55' package (European Environment Agency, 2024)) and a hypothetical EU-wide phaseout of coal for electricity generation. Although other European countries are modelled, the policy constraints are applied only to those in the EU. Given the recent research on the vulnerability of coal mining regions (Alves Dias et al., 2018) and the need for a decline in coal (Diluiso et al., 2021; European Court of Auditors, 2022), coal and lignite are chosen for the technology-focused phaseout. The objective of the EU 'Fit for 55' package (European Environment Agency, 2024) is to reduce GHG emissions by 55% by 2030 compared to 1990 levels. For 2035, a constraint of an emissions target aligning with the 'Fit for 55' policy package of the EU is derived by multiplying the estimated GHG emission intensity of electricity generation required in 2030 (European Environment Agency, 2024) (110 g CO_{2eq}) with the electricity demand of 2030 (Kättlitz and Buyuk, 2024). The phaseout target is implemented as generation capacity constraints, with the upper limit for each coal and lignite generation capacity in the EU set to zero. The demand data for the modelled year 2035 is obtained from the "National Trends" scenario of the TYNDP (Kättlitz and Buyuk, 2024) and is calculated as an average between 2030 and 2040 data. For comparison, a third, current scenario is added too, using generation and storage capacity from the 2018 grid (Sasse and Trutnevyte, 2023a) while transmission capacity is allowed to increase to accommodate the demand

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of 2020 (Hörsch et al., 2018; Open Power System Data, 2020). It is assumed that no new nuclear and fossil fuel generation capacities can be built from the current scenario, except for planned expansions as of 2022 (Sasse and Trutnevyte, 2023a). It is also assumed that all nuclear generation capacities are decommissioned in Belgium and Germany by 2035 (Sasse and Trutnevyte, 2023a). Transmission capacity can increase up to four times between 2018 and 2035.

2.4 Results

Technology mixes, emissions, and costs

The two policy scenarios, both with the objective of decarbonisation, vary in terms of technology mixes, emissions and system costs (Figure 1). The smaller coal and lignite capacities across Europe under the EU phaseout coincide with larger capacities in hydrogen storage, gas power, open-field solar power, nuclear power, waste power, and hydropower compared to the 'Fit for 55' package. The cumulative European electricity sector emissions reductions are 211.2 $MtCO_{2eq}$ (EU: 228.0 $MtCO_{2eq}$) under the 'Fit for 55' scenario and 290.2 $MtCO_{2eq}$ (EU: 306.5 $MtCO_{2eq}$) under the EU coal phaseout, representing reductions of 31% and 43% respectively. The additional costs compared to the current scenario are 38.0 Billion Euro (EU: 25.0 Billion Euro) under the 'Fit for 55' package and 45.4 Billion Euro (EU: 33.2 Billion Euro) under the EU coal phaseout.

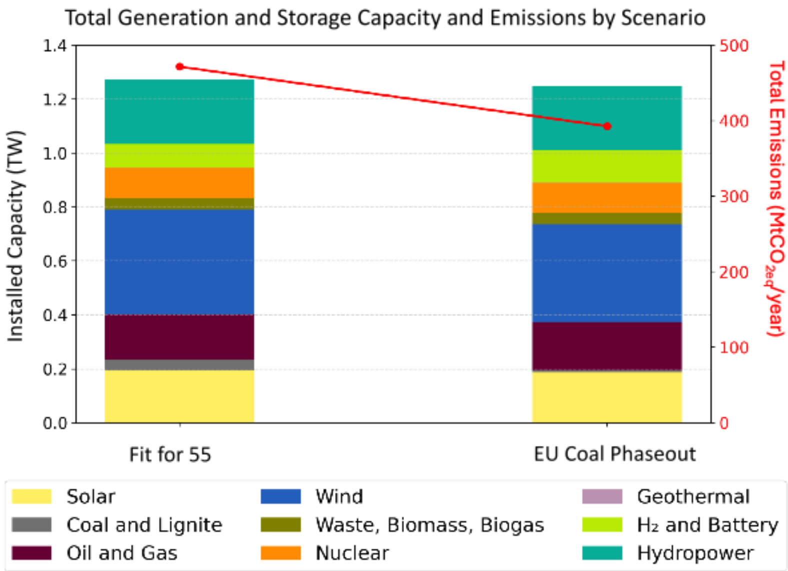

Figure 1. European generation and storage technology capacities and emissions by policy scenario in 2035.

Employment

To address inequality in opportunities across European regions, the two policy scenarios are compared in terms of employment changes overall and across NUTS-2 regions (Figure 2). As compared to the current scenario, 'Fit for 55' adds a net 236.7 thousand jobs and the coal phaseout adds 175.2 thousand jobs overall. 75% and 69% of these jobs are in the European Union respectively, while others occur in other modelled countries, such as Switzerland, Norway, United Kingdom, and the Balkan countries. More regions have net employment losses under the EU coal phaseout scenario, particularly in the coal and lignite mining regions of Germany, Poland, Czech Republic, Hungary, Romania and Bulgaria. Employment gains are highest in Northern Scotland (driven by offshore wind power) and Southern Spain (driven by onshore wind and open-field solar power). There are higher employment gains in hydrogen and waste in the case of coal phaseout, particularly in Germany. The largest increase in net employment changes is in operation and maintenance ('Fit for 55': 192.6 thousand, EU Coal

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Phaseout: 180.8 thousand), and onshore wind power creates the largest share of these jobs. As shown in Figure 2 b), the next largest increase in net employment is in construction ('Fit for 55': 94.8 thousand, EU Coal Phaseout: 87.5 thousand), with open-field solar power driving this growth. These changes are followed by those in decommissioning (Fit for 55': 26.3 thousand, EU Coal Phaseout: 23.9 thousand) and extraction ('Fit for 55': -46.7 thousand, EU Coal Phaseout: -83.1 thousand).

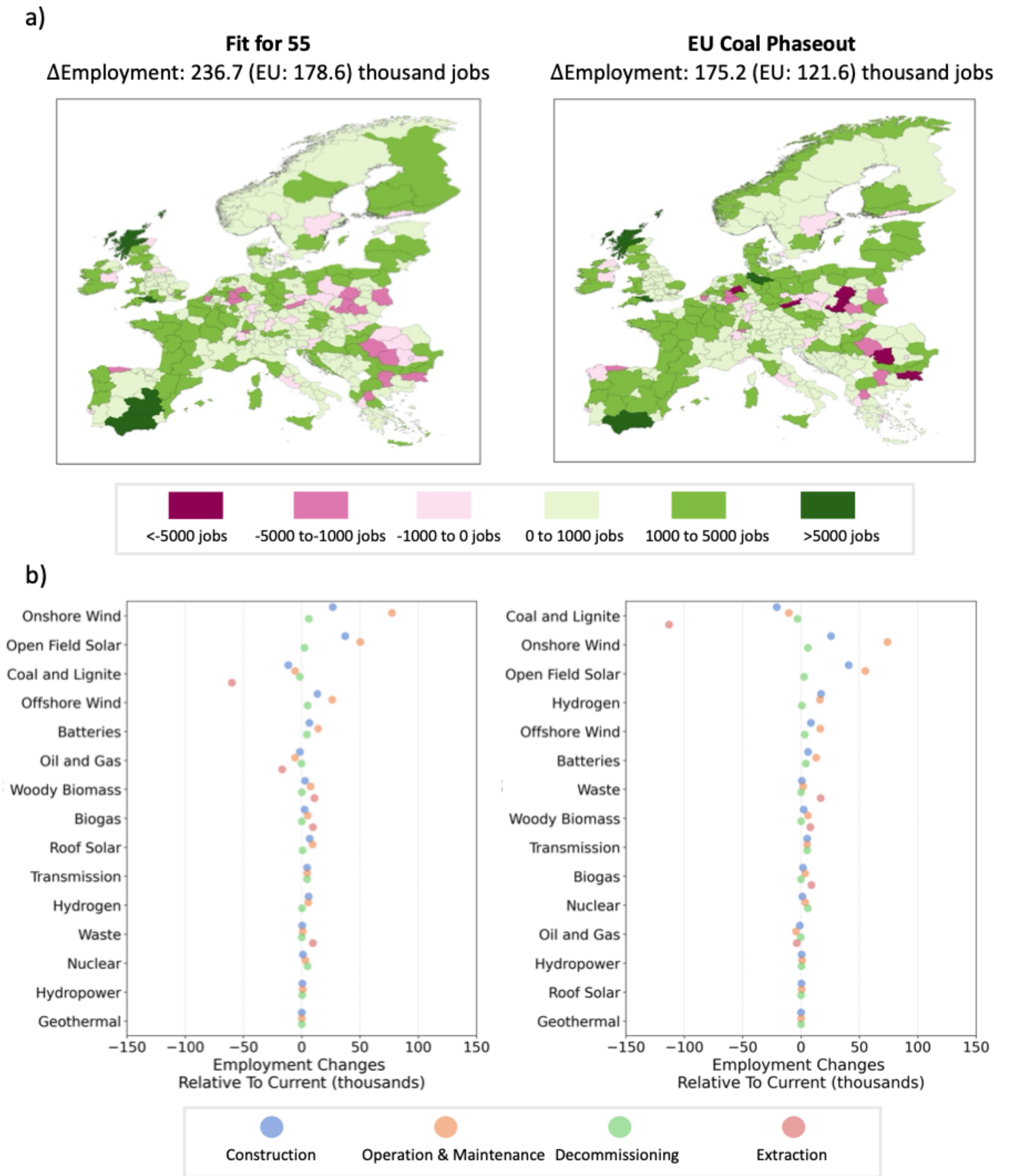

Figure 2. a) Net employment changes (number of jobs) at NUTS 2 spatial resolution from the 'Fit for 55' and EU coal phaseout policy scenarios as compared to the current scenario. The employment impacts modelled overall differ from those in the EU because EXPANSE models some European countries that are not part of the EU. b) Net technology-specific and supply chain sector-specific employment changes in number of jobs.

Regional re-skilling needs

Within the NUTS 2 regions across Europe, gross job gains and losses in the electricity sector determine the number of workers with opportunities for employment transfer. For these workers, we estimate the necessary re-skilling

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requirements (Figure 3). Throughout the results and discussion, workers experiencing employment loss who have the potential to gain employment in the electricity sector within the same NUTS 2 region are referred to as "potential employment transfers". If there are more job losses than job gains within the region, then the number of potential employment transfers is equal to the number of employment gains and vice versa. Skill scores are applied to the jobs gained and lost per technology as shown in Figure 3 c). The NUTS 2 regional re-skilling needs are the positive difference between the average skill set (skills and scores) gained in the region and the average skill set lost, scaled to the number of potential transfers. Following the workflow in Figure 3, the re-skilling needs of each region are obtained (see Annex A1). As seen in Figure 3 for the example of the EU coal phaseout scenario in Germany, Poland, the Czech Republic, Slovakia and Hungary, coal mining regions show particularly large and localised employment loss. Several coal and lignite mining regions require mostly content and systems re-skilling. The regions in Germany that require a higher share of resource management re-skilling are driven by potential transfers from nuclear power plants.

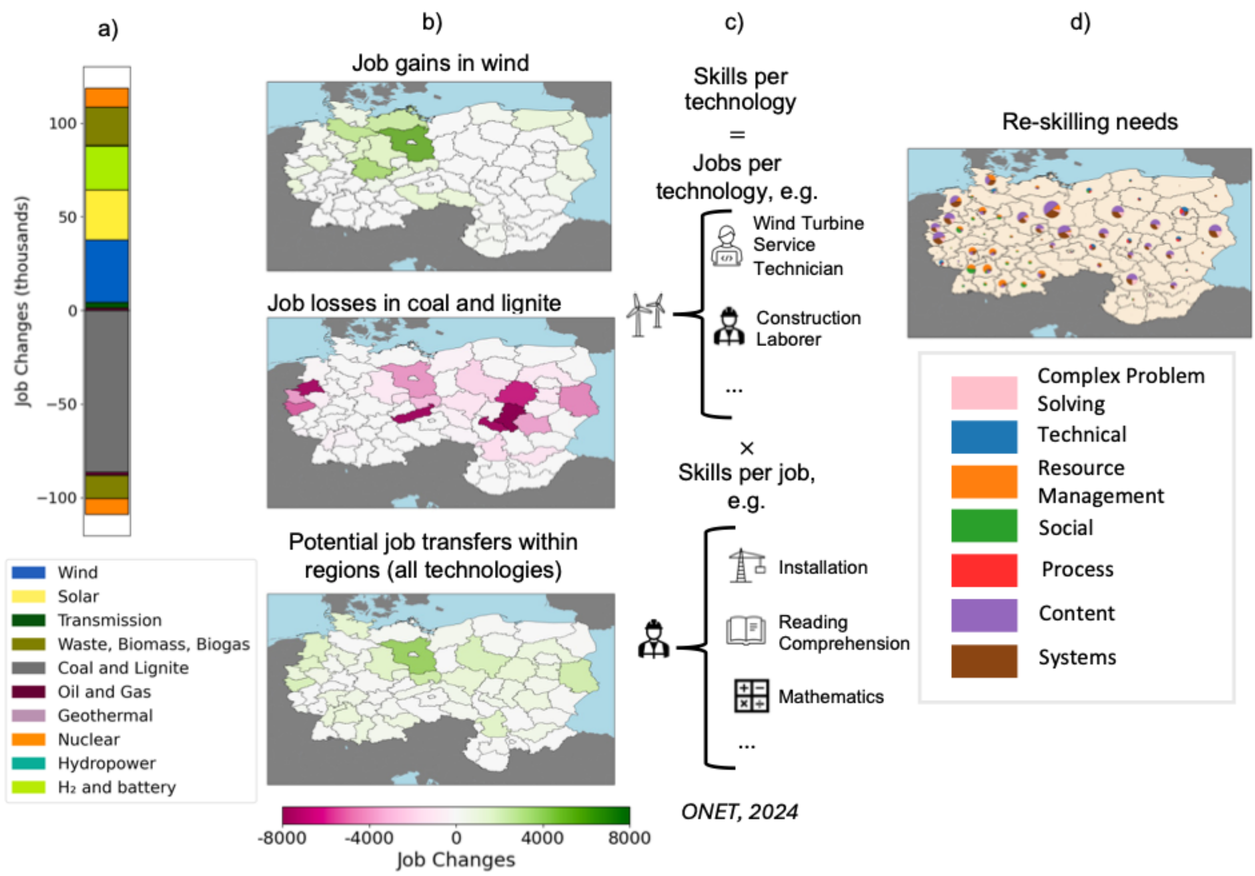

Figure 3. Schematic showing the workflow of the skills analysis for a subregion of Germany, Poland, Czech Republic, Slovakia and Hungary under the coal phaseout scenario. a) Job gains and losses per technology, b) Regional job gains, losses and potential transfers within NUTS 2 region, c) workflow from skills per job to skills per technology (see Annex A1 for the list of jobs per technology), d) net skills from job gains, job losses and re-skilling needs for each NUTS 2 region, where circle size is proportional to the number of jobs.

The loss of predominantly fossil fuel employment (Figure 5) drives a shift in the demanded skills of transitioning workers across Europe. Under both policy scenarios, countries with the largest aggregate of potential same-region employment transfers are Germany ('Fit for 55': 21.0 thousand, EU Coal Phaseout: 27.4 thousand), Spain ('Fit for 55': 8.9 thousand, EU Coal Phaseout: 7.2 thousand) and Poland ('Fit for 55': 8.1 thousand, EU Coal Phaseout: 11.4 thousand). Workers transferring from nuclear and oil and gas technologies (non-extraction) drive the demand for resource management skills in several countries. Coal, lignite, oil and gas extraction workers have low content

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and systems skills compared to other technologies and have high process and technical skills. Within most countries, potential employment transfers require additional content skills the most to fulfill the requirements of their new employment. Content skills are the foundational skills necessary for applying and gaining more specific skills, such as reading comprehension, active listening, writing, speaking, mathematics and science (O*NET and U.S. Department of Labor, Employment and Training Administration, 2024). This is also reflected across all employment gains at the continental scale, including transfers within the electricity sector, from outside the electricity sector, and newly qualified workers (Figure 5). Critical thinking, reading comprehension, active listening, speaking and writing are amongst the most needed individual skills for employment gains under both policy scenarios. In contrast, technical skills, such as operations monitoring and operations and control, appear amongst the highest skills of lost jobs, mainly driven by losses in fossil fuels extraction and nuclear power.

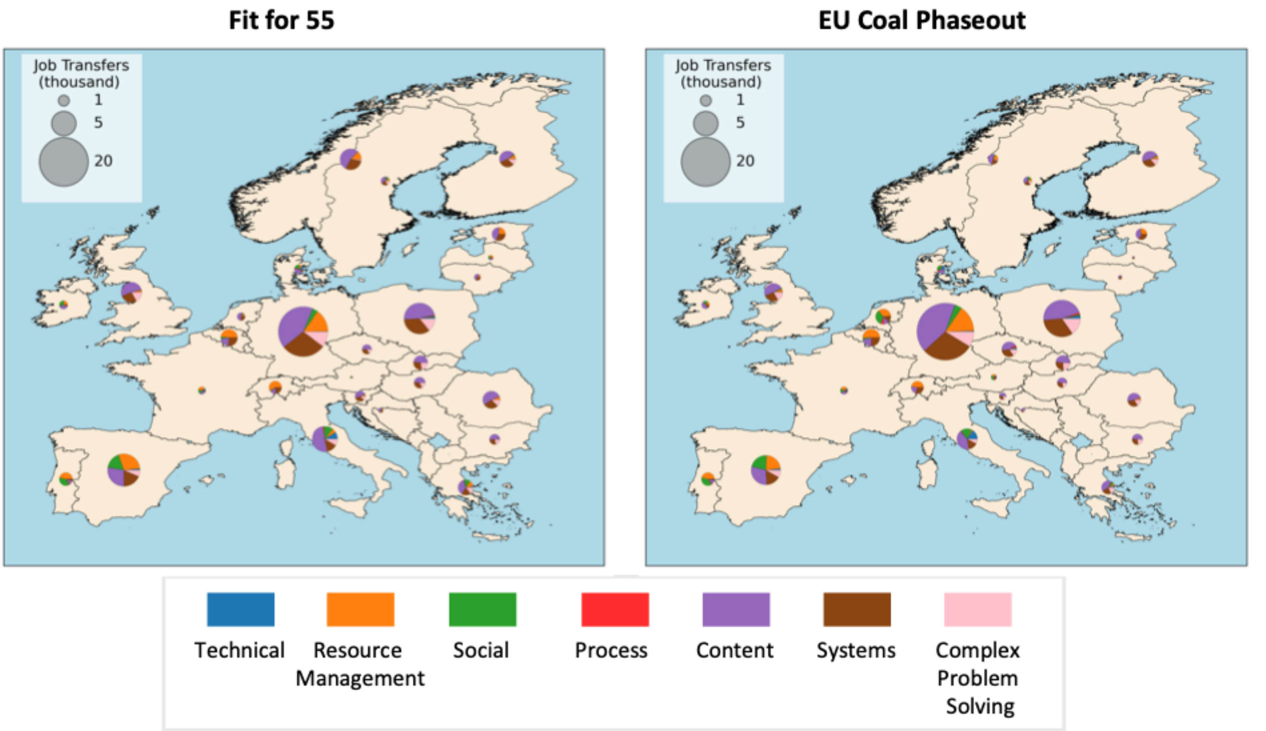

Figure 4. Re-skilling needs by 2035 showing country-level aggregates.

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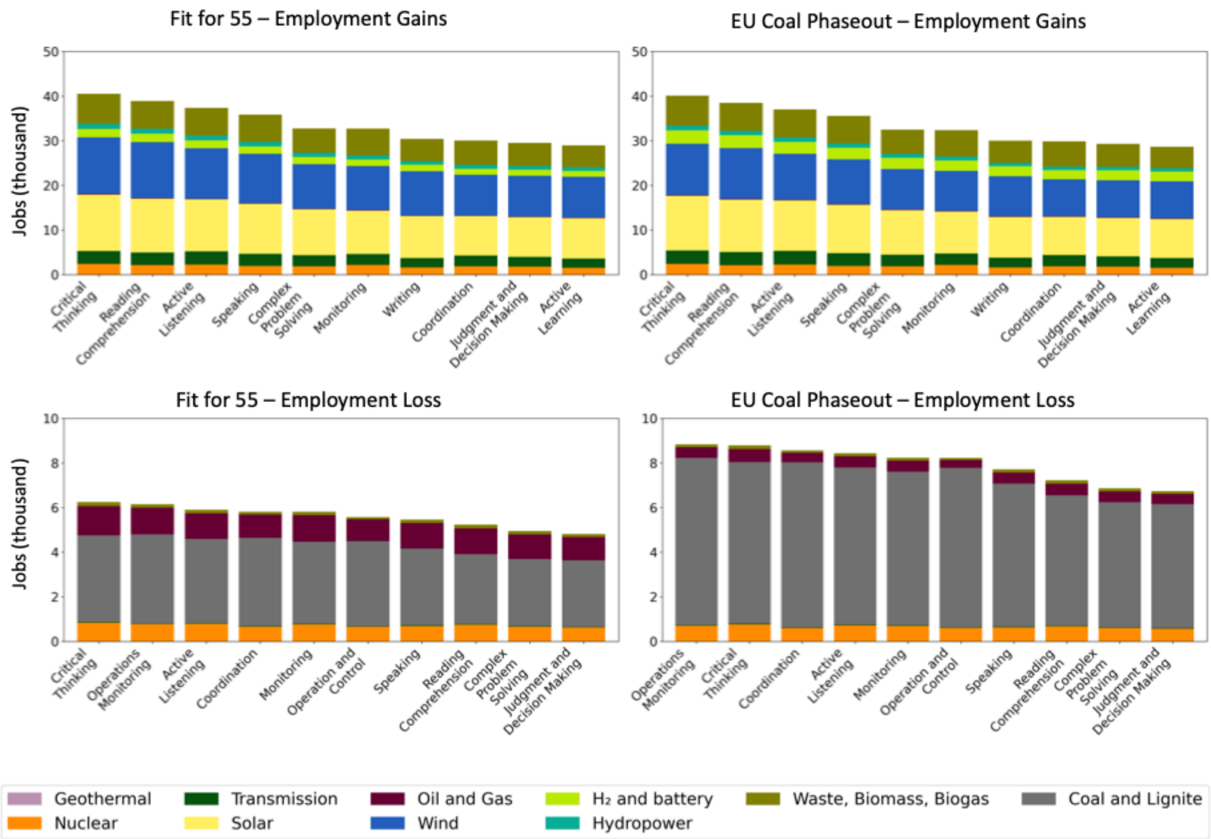

Figure 5. The most gained and lost skills by 2035, with a breakdown for each technology causing the changes.

Within each NUTS 2 region, both the positive and negative changes in employment determine the required skills for potential employment transfers creating strong regional variations in re-skilling needs. Employment gains are predominantly in solar and wind power capacities and thus drive demand for similar skills across all NUTS 2 regions in the model (see Annex A1). On the other hand, re-skilling needs for workers with the potential to transition are highly diverse across regions and depend on the technologies driving the gains and losses. Brandenburg in Germany (DE40) is the region with the largest number of potential transfers under both policy scenarios ('Fit for 55': 2.5 thousand, 'EU Coal Phaseout': 4.0 thousand). The transfers are driven by the shift from coal and lignite jobs (in extraction and generation) to jobs in onshore wind power, hydrogen and rooftop solar power, while the highest re-skilling needs are in the content group (Figure 3), such as science, writing, mathematics and reading comprehension. On the contrary, Andalusia (ES61), another region with many potential transfers (1.7 thousand under both policy scenarios) experiences a significant shift from oil, gas and coal employment (non-extraction) to employment in offshore and onshore wind power, and open-field and rooftop solar power. Wind power workers have higher resource management skills than workers in oil, gas and coal non-extraction roles driving the predominant need for skills in this group.

Nuclear power represents a significant share of gross job losses across the continent ('Fit for 55: -15.7 thousand, EU Coal Phaseout: -14.3 thousand), along with coal and lignite extraction ('Fit for 55: -59.8 thousand , EU Coal Phaseout: -113.0 thousand), non-extraction coal and lignite ('Fit for 55: -19.1 thousand, EU Coal Phaseout: -34.4 thousand), non-extraction oil and gas ('Fit for 55: -9.3 thousand, EU Coal Phaseout: -7.6 thousand), and oil and gas extraction ('Fit for 55: -16.9 thousand , EU Coal Phaseout: -3.7 thousand). However, unlike these technologies, nuclear power provides net job gains ('Fit for 55: 8.9 thousand, EU Coal Phaseout: 10.3 thousand) overall from capacity expansion in some regions. The technologies that create the largest number of gross employment gains are onshore wind power ('Fit for 55': 110.3 thousand, EU Coal Phaseout: 105.4 thousand), open-field solar power ('Fit for 55': 90.0 thousand, EU Coal Phaseout: 98.2 thousand) and offshore wind power ('Fit for 55': 44.7 thousand, EU Coal Phaseout: 27.8 thousand). Considering a nuclear worker transferring to

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onshore wind plant, the most required skills are in the resource management group. A coal and lignite extraction worker following this transition would require skills the most in the content group with the skill gaps being quantitatively larger. This example is relevant for several regions where coal and lignite extraction workers have the potential to transfer to onshore wind power in Germany, Estonia, Spain, Finland, Italy, Lithuania, Latvia, Poland, Romania, Sweden, Slovakia, and the UK. The regions where nuclear power workers have the potential to transfer to onshore wind power are in Belgium, Germany, and Spain. This analysis of specific types of workers in transition highlights the technology-specific re-skilling needs of workers in employment transition.

2.5 Discussion and conclusions

This analysis of the European electricity system under two policy scenarios (the EU 'Fit for 55' package of legislation and a hypothetical EU-wide coal phaseout) shows the tradeoff between costs, employment and GHG emissions. The EU coal phaseout results in higher system costs, more employment losses, more regional disparities in unemployment, and yet boosts GHG emissions reductions by 37% compared to the 'Fit for 55' package. Under the EU coal phaseout, the additional costs of the electricity system are 19% higher compared to the 'Fit for 55' package. A previous estimate for electricity sector employment creation driven by the 'Fit for 55' package estimated 17% increase by 2030 (Fragkiadakis et al., 2023), which is comparable with the 22% increase by 2035 from our analysis aligned with the same policy. Net employment creation is higher under the implemented 'Fit for 55' policy plan compared to the hypothetical EU coal phaseout, but the associated GHG emissions reductions are significantly higher under the EU coal phaseout. Coal phaseout also has additional benefits, such as reduction in local air pollution and improved health (Pehle et al., 2025). In combination with previous retrospective work that suggests that a timely coal phaseout in the past would have led to lower costs, less environmental damage and a faster recovery in regions (Oei et al., 2020), this study provides more insight into such ambitions at the European level.

The phaseout of coal and lignite for electricity generation would exacerbate the need for re-skilling coal and lignite workers who could transition to technologies of high growth (especially solar and wind power) across the continent. For coal and lignite extraction workers, there is an increased need for systems and content skills (as seen in Figure 3) but not social, technical or process skills in which these workers are rich. This aligns with prior findings that fossil fuel extraction workers surpass the required level of technical skills in areas of employment growth (Greenspon and Raimi, 2024). Overall, re-skilling needs for electricity sector workers who transfer jobs within the same NUTS 2 region vary greatly based on the nature of their regional energy transition. In contrast, the skill needs of employment gains, i.e. of workers who gain their first employment in the electricity sector and those transferring from other sectors, are homogeneous across European regions as they are driven by technologies requiring similar skills (solar and wind power). This study hence is useful as it identifies regional employment gains, losses and potential transfers, including the most in-demand skills for both new jobs and potential employment transfers (re-skilling). The methods can be used to identify regions that are at risk of adverse effects of the energy transition and the re-skilling support needed to ensure that these regions are not disadvantaged. This information can support the design of re-skilling programmes (e.g. through the Just Transition Mechanism (European Commission, 2020), ensuring regional equality.

This work links a European electricity sector model with an employment and skill study to identify the employment and skill-related barriers for workers transitioning between electricity sector jobs under two policy scenarios. The novelty of this work also lies in the quantification of employment impacts in the whole supply chain at a NUTS 2 regional scale. In addition, the study distinguishes the skill requirements of transitioning workers from those associated with overall employment gains in the power sector. Future work can extend the scope beyond the electricity sector and outside of Europe to allow the integration of employment data from other steps in the supply chain, such as manufacturing, or to investigate potential job transfers from the electricity sector to others. A majority of fossil fuel workers who transition to green jobs will do so without relocating (Lim et al., 2023). However, spillover effects across NUTS 2 regions could be added to the study to account for employment mobility

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between regions (including data on commuting distance (Wu et al., 2024) and precise plant locations). Uncertainties and long-term changes in employment factors could be included as employment factors are expected to decrease over time (Fragkos and Paroussos, 2018). Finally, only two policy scenarios for 2035 have been analysed here and future work could extend the analysis to a larger suite of policies and their implementation scenarios.

2.6 Acknowledgements

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3 Energy security, resilience, and flexibility in European renewable energy systems

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The study has also been published as a Policy Brief[2].

3.1 Introduction

Energy systems are undergoing a fundamental transformation driven by the transition to renewable energy (RE) and the growing integration of variable sources such as wind and solar (Lund, 2014). This shift increases the need for system integration and flexibility measures to ensure stable and efficient operation (Hansen et al., 2019). At the same time, recent global supply chain disruptions and the energy crisis have highlighted that reducing carbon emissions and optimising costs are not sufficient on their own, and that energy security and resilience must also be prioritised. These evolving priorities introduce new dimensions to energy system modelling, particularly in the evaluation of future scenarios that inform energy strategies and policy development (Monie et al., 2025).

Energy security is a multidimensional concept that draws from both social and physical sciences. While definitions vary, most emphasise the system's ability to deliver affordable, accessible, efficient, and environmentally sustainable energy services to support social stability and economic development. Sovacool (2011) identified four core dimensions, availability, affordability, efficiency, and environmental stewardship, while later frameworks have expanded this to include up to 15 dimensions (Azzuni & Breyer, 2018), reflecting the growing complexity of energy systems and the diversity of indicators used to assess them.

Closely related is the concept of energy resilience, which refers to the system's capacity to withstand, adapt to, and recover from disruptions. The International Energy Agency (IEA) defines resilience as the ability to maintain core functions during hazards while adapting and transforming in response (International Energy Agency, 2015). This includes elements such as robustness, resourcefulness, and recovery (Jasiūnas et al., 2021) and overlaps with energy security in both theory and practice.

A key strategy for enhancing both security and resilience is diversification, of energy sources, technologies, and supply chains (Kharrazi et al., 2015). The principle of "not putting all your eggs in one basket" (Grubb et al., 2006) has long underpinned energy policy, with diversification seen as a hedge against uncertainty (Månsson et al., 2014). It reduces dependence on single sources or imports, mitigates exposure to geopolitical and market risks, and enhances the system's ability to respond to external shocks such as climate impacts or regulatory changes (Sharifi & Yamagata, 2016). For example, reduced hydroelectric output due to changing precipitation patterns can threaten supply reliability, making a diverse energy mix essential for long-term stability (Molyneaux et al., 2012).

This study builds on the previous study "Enhancing Renewable Energy System Metrics: Security, Flexibility, and Sustainability" presented in report "D4.9 – European sub-national deep dives[3]", conducted during the first modelling cycle of the IAM COMPACT project. In that study, we introduced and applied the concepts of energy security, resilience, and flexibility within an energy system context. Using a multi-model approach, we evaluated national and European-scale scenarios, focusing on how system diversity, used as a proxy for security and

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resilience, can be assessed through established methods. The analysis also incorporated integrated assessment models to examine upstream supply chain dependencies, particularly the reliance on non-EU commodities in energy systems and the implications for raw material prices.

Both the current and prior study was shaped through a structured stakeholder engagement process under IAM COMPACT's Policy Response Mechanism (PRM), a co-creation framework designed to ensure policy relevance in modelling. Within the Optimal Transition theme, stakeholders from institutions such as DG ENER, ACER, and the renewable energy industry contributed to the design of scenarios, selection of key assumptions, and identification of relevant metrics. Their input helped refine the research scope and align the analysis with pressing policy needs.

Building on both the findings of the previous study and the insights from stakeholders, in the present study we further explore energy security, resilience, and flexibility in the context of European renewable energy systems. Specifically, we extend on the diversity-based evaluation approach to include the degree of decentralisation, offering a more nuanced assessment of system diversity in high-RE contexts. Secondly, we apply "shock scenario modelling" to simulate extreme disruptions in electricity production, assessing system preparedness and estimating the associated additional security costs. Lastly, we compare the flexibility of two distinct renewable-based system configurations for EU27 and the UK, focusing on their ability to integrate large shares of variable renewable electricity, measured based on critical excess electricity generation.

3.2 Methods

This methods section is structured as follows: First, we introduce EnergyPLAN, the energy system modelling tool used in this study. Next, we describe the scenarios developed and analysed, outlining key assumptions. We then present the decentralisation adjusted diversity index method, highlighting the methodological advancements made since the previous study. Then we detail the approach used to model energy system shocks, which simulates disruptive events to assess system robustness and the need and cost of additional security measures.

3.2.1 Energy system modelling tool

EnergyPLAN is a tool for simulation of the entire energy system including all sectors, i.e., heating, cooling, industry, transportation, as well as electricity and gas grids. Hourly temporal resolution allows for detailed modelling of variable renewable energy generation in addition to weekly and seasonal differences in electricity and heat demands. EnergyPLAN is a deterministic model based on analytical programming, making calculations very fast even for complex energy systems. EnergyPLAN optimises the operation of the energy system rather than the investments, which is instead done exogenously by the user.

In Figure 3-1 an overview of technologies, energy demands, and flows as represented in EnergyPLAN can be seen.

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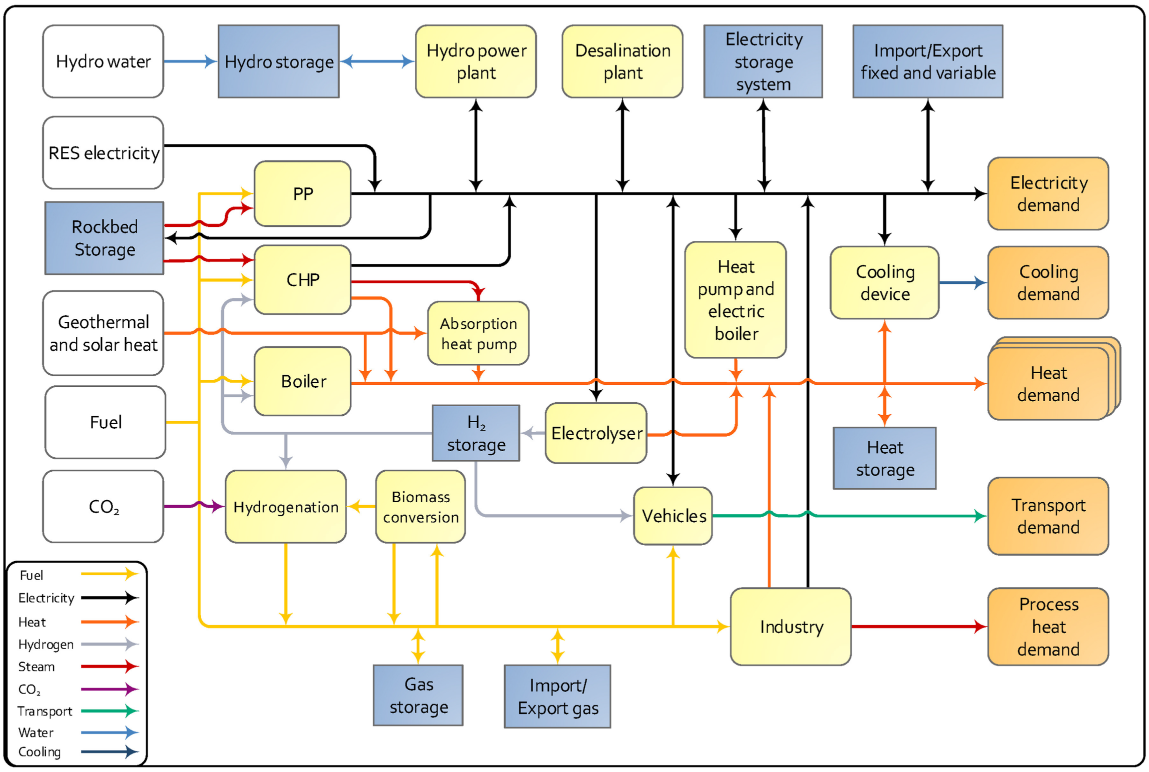

Figure 3-1: Overall technology and energy demand model for EnergyPLAN (Lund et al., 2021).

A number of data inputs are needed to simulate an energy system in EnergyPLAN:

- Energy demands (heat, electricity, transport, industry, etc.).
- Energy generation technologies and resources (wind turbines, power plants, gas boilers etc.) and energy conversion technologies (electrolysers, gasification plants etc.).
- System characteristics (simulation and operation strategies, technical limitations such transmission capacity).
- Cost (fuel costs, fixed and variable operation and maintenance costs).

Resulting outputs are annual and hourly energy balances with annual productions, total costs including fuel consumptions, import and export of electricity (Lund et al., 2021).

EnergyPLAN has been widely applied for modelling of energy systems, with most studies focusing on the development of scenarios with shares of renewable energy integration (Mathiesen et al., 2015). Studies typically employ several indicators for system evaluation, such as primary energy supply, CO_2 emissions, system costs, and excess electricity generation (Østergaard, 2015). Excess electricity generation in this context mean electricity generated that the energy system is unable to utilise, for example by variable renewable electricity (VRE) technologies. In a physical system this electricity generation would end up being curtailed to maintain a stable electricity system, hence, this metric is relevant for evaluating an energy systems flexibility as it is a measure of how well the systems deal with large fluctuations in VRE generation.

3.2.2 Modelled energy system scenarios

The EU has put forward a long-term target to be climate-neutral by 2050 (European Commision, 2020) as part of the European Green Deal (European Commission, 2023) and in alignment with the global climate action of the Paris Agreement. In response to the Russian invasion of Ukraine, the EU has launched the REPowerEU plan (European Commission, 2022) with the aim of increasing the deployment of renewable energy, save energy, and to diversify the energy supply. Both targets call for a concretisation of potential pathways for a transition of the energy system of the EU and secondly, exploring how to evaluate these pathways. The decarbonisation of the EU's energy system entails an array of significant changes, including improvements in energy efficiency and

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energy savings, large-scale expansion of VRE capacity, and a complete conversion of transportation and industry.

In this study we evaluate two different scenarios for the future energy system of the EU27 and UK. The scenarios were first presented in Thellufsen et al. (2023), and subsequently, in the previous IAM COMPACT modelling cycle in the report *"D4.9 – European sub-national deep dives"*.

Scenarios are modelled in EnergyPLAN as an aggregated energy system, i.e., without any geographical distinction. The aggregated approach to system modelling allows for significant modelling of sector integration measures and energy technologies at an hourly temporal resolution, but also means that network, transmission, and interconnection re-strictions cannot be represented.

The transition scenarios studied are:

- **"1.5 TECH 2050":** The 1.5 TECH scenario was developed as a climate-neutral scenario and as a pathway to stay within the 1.5°C ambition of the Paris agreement. This requires significant electrification and deployment of e-fuels and hydrogen, carbon capture and storage solutions largely for bioenergy, alongside strong penetration of VRE for a decarbonised power sector.
- **"Smart Energy Europe 2050":** The Smart Energy Europe is developed as a 100% renewable energy system alternative based on the same technology catalogue as the PRIMES scenarios but designed according to Smart Energy System principles. Specifically, 1) energy efficiency first, 2) updated heating systems and expansion of district heating, 3) electrification of transport, 4) e-fuels for heavy parts of transport, 5) replacing remaining fossil fuel demands in industry and power generation with biogas and biomass.

3.2.3 Decentralisation adjusted diversity index

Diversity of an energy system is an essential parameter for energy security and can be analysed from both an energy demand and an energy supply perspective, i.e., diversity of fuels' composition, or diversity of generation technologies. This was done for European energy system scenarios in the first modelling cycle of IAM COMPACT in the study *"Enhancing Renewable Energy System Metrics: Security, Flexibility, and Sustainability"* presented in report *"D4.9 – European sub-national deep dives"*. In that study, diversity was evaluated based on the Shannon Wiener index (SWI) (Shannon, 1948).

As shown in Eq. (1), the index is calculated using the proportion *pi* of each flow or entity. A system with only one flow yields an SWI of zero, while the theoretical maximum, achieved when all flows contribute equally, increases with the number of flows (e.g., 10 flows each contributing 10%).

$$SWI = -\Sigma pi \cdot ln(pi) \qquad \text{Eq. (1)}$$

We found that the SWI, while a good starting point for evaluating security in traditional energy systems, did not capture all aspects of diversity, especially for energy systems with large shares of renewable energy. Renewable energy systems are generally based on more dispersed and decentralised energy sources, a quality that is not captured in the SWI. Traditional fossil fuel types are phased out, potentially leading to reduced fuel and technology diversity in renewable energy systems, resulting in lower SWI values. However, we find that this is offset by the increased geographical dispersion and the self-sufficient nature (i.e., not reliant on fuel imports) of VRE technologies.

To accommodate these effects, we in this study present and apply an adapted diversity index, also considering the degree of decentralisation of energy systems. This "Decentralisation adjusted diversity index" (DADI) is formulated as seen in Eq. (2).

$$DADI = -\Sigma pi \cdot ln(pi) \cdot (\log_{10} u) + 1) \qquad \text{Eq. (2)}$$

where p_i is the share of a technology as a proportion of the total installed electricity generation capacity, and u is the number of units, a new parameter introduced.

More details on the previous application of SWI for evaluation of diversity in energy systems are available in the study *"Enhancing Renewable Energy System Metrics: Security, Flexibility, and Sustainability"* presented in report

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"D4.9 – European sub-national deep dives" in IAM COMPACT. Further details on the DADI method will be available in an upcoming publication.

3.2.4 Disruptive events

This study assesses the resilience and flexibility of a renewable European energy system under sudden disruptive events that affect electricity production. Using the European energy scenarios Smart Energy Europe and 1.5 TECH, we analyse how reductions in nuclear and wind power generation impact system operation and determine the additional backup capacity required to maintain energy security during such disruptions.

Two types of disruptions are modelled:

1. **Nuclear power outages**, simulating partial or complete unavailability of European nuclear capacity.
2. **Adverse wind conditions**, representing periods of reduced wind energy generation.

The scenarios are quantified through variations in capacity factors. Table 3-1 presents the nuclear power scenarios, while Table 3-2 outlines the wind power scenarios. In both tables, the reference scenario is indicated in **bold**.

Table 3-1: Nuclear power scenarios.

Scenario	Resulting capacity factor	Production in 1.5 TECH [PWh]	Production in Smart Energy Europe [PWh]
Reference	**90%**	**0.96**	**0**
25% reduction	68%	0.72	0
50% reduction	45%	0.48	0
75% reduction	23%	0.24	0
100% reduction	0%	0	0

Table 3-2: Wind scenarios.

Scenario	Resulting capacity factor	Production in 1.5 TECH [PWh]	Production in Smart Energy Europe [PWh]
Low capacity factor onshore wind	18%	1.06	2.57
Medium capacity factor onshore wind (reference)	**32%**	**1.85**	**4.49**
High-capacity factor onshore wind	37%	2.12	5.14
Low-capacity factor offshore wind	49%	1.95	0.67
Medium capacity factor offshore wind (reference)	**54%**	**2.16**	**0.74**
High-capacity factor offshore wind	59%	2.33	0.8

To evaluate the operational impacts of these disruptions, the EnergyPLAN simulation tool is employed. It models the European energy system for both the 1.5 TECH and Smart Energy Europe scenarios, incorporating changes in electricity production due to reduced nuclear or wind capacity.

In scenarios where reduced production leads to system imbalances, additional gas turbine capacity is considered

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as a backup solution. The technical and economic parameters of the backup gas turbines are summarised in Table 3-3.

Table 3-1: Technical specifications of backup gas turbines.

Investment cost [MEUR/MW]	Fixed O&M	Lifetime [Years]	Annual Investment cost [MEUR/MW]	Efficiency	Fuel cost (EUR/MWH fuel)	Variable O&M (EUR/MWh_{el})
0.6	3%	25	0.03	0.43	24.73	4.47

3.3 Results

The primary energy consumption for the simulated 1.5 TECH and Smart Energy Europe scenarios can be seen in Figure 3-2. It is seen that the primary energy consumption is lowest in the Smart Energy Europe scenario as a result of the Energy Efficiency First Principle embedded in its design. The Smart Energy Europe scenario is based on 100% RE, whereas the 1.5 TECH scenario manages a 90% CO2 emission reduction. To achieve this, the 1.5 TECH scenario introduces additional nuclear, offshore, and onshore wind power, and PV. The Smart Energy Europe Scenario omits nuclear energy, and to a larger extent prioritises onshore wind power and energy efficiency improvements. Most of the remaining fossil fuel demand comes from the transport sector, which is not fully decarbonised in the 1.5 TECH scenario.

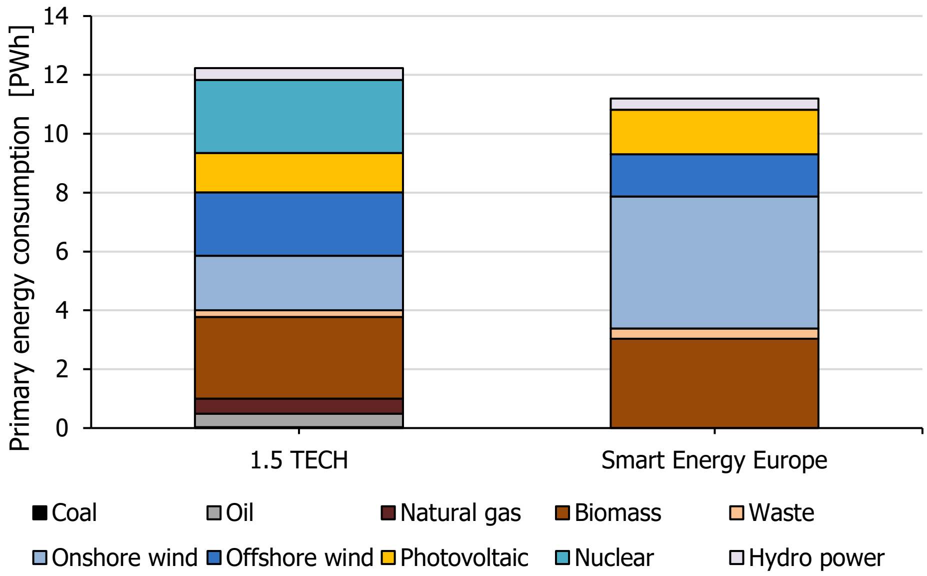

Figure 3-2: Primary energy consumption in modelled scenarios for EU27 and UK.

In Figure 3-3 total annual costs for the 1.5 TECH and Smart Energy Europe scenarios can be seen. For both scenarios investment costs are dominant, perhaps not surprisingly, given the investment heavy nature of most renewable energy technologies. Contrary to traditional energy systems with larger variable costs, arising from fuel consumption and variable operation and maintenance costs, renewable technologies generally benefit from low operation expenditures. The total costs for the 1.5 TECH scenario amount to 2162 billion EUR, assuming that the excess electricity produced cannot be exported and would need to be curtailed. If it could be exported, this would reduce the annual costs by 84 billion EUR, resulting in a total cost of 2078 billion EUR. The Smart Energy Europe scenario has a slightly lower total annual cost of 1975 billion EUR, without considering electricity exports. Electricity exports would further reduce this by 65 billion EUR to 1910 billion EUR.

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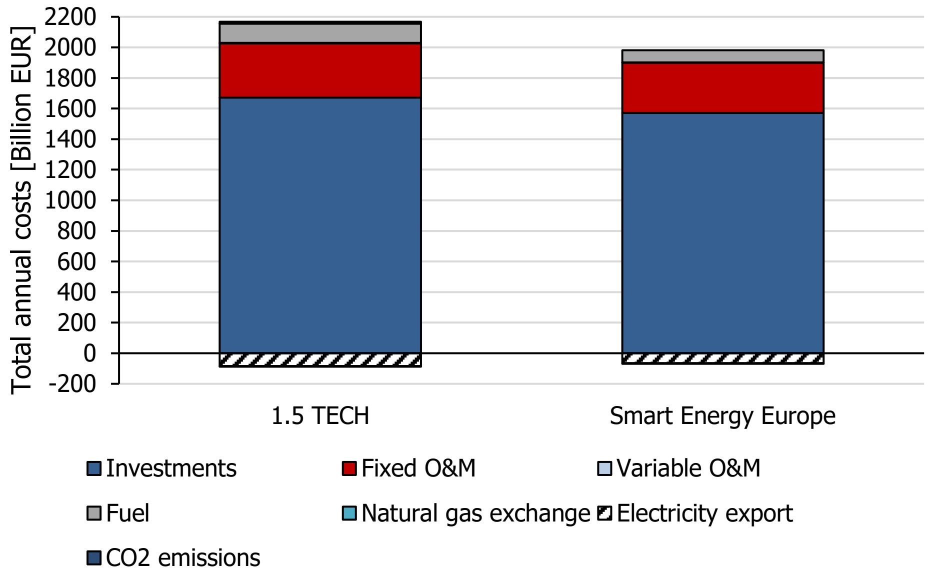

Figure 3-3: Total annual energy system costs in modelled scenarios for EU27 and UK.

3.3.1 Energy system security through diversity

The following analysis applies the decentralisation adjusted diversity index to the context of two energy systems with a high degree of renewable energy for EU27 and UK, focusing on the diversity of the electricity generation sector.

The electricity generation capacities for the modelled EU scenarios can be seen in Figure 3-4. The combined electricity generation capacity in the Smart Energy Europe scenarios is higher due to a larger share of VRE technologies, primarily in the form of onshore wind power. Both scenarios include a similar power plant capacity of 540 GW and 500 GW for 1.5 TECH and Smart Energy Europe, respectively. Furthermore, the 1.5 TECH scenario maintains some nuclear power capacity as a stable baseload generation technology, while the Smart Energy Europe scenario includes a comparable capacity of combined heat and power (CHP) plants.

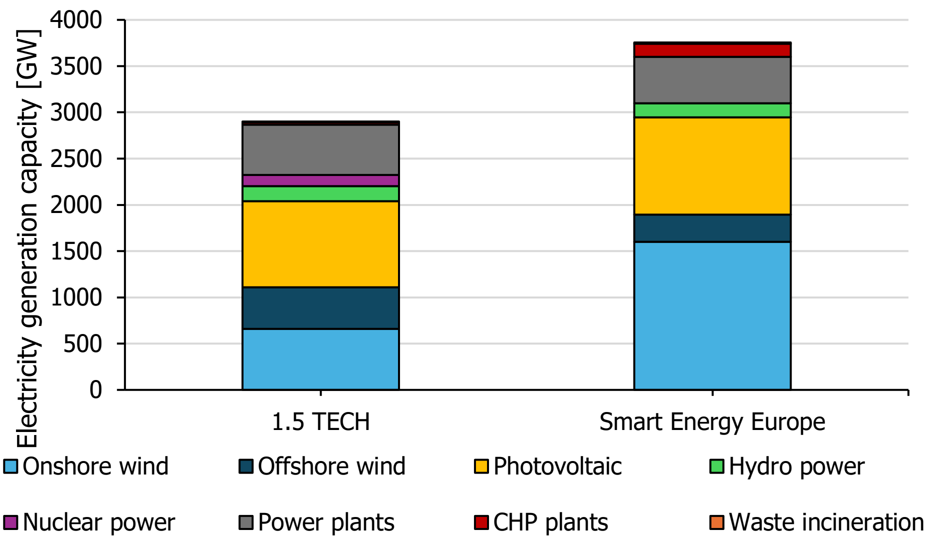

Figure 3-4: Installed electricity generation capacity in 1.5 TECH and Smart Energy Europe scenarios.

The proposed method for evaluating diversity considering also a systems' degree of decentralisation incorporates a new parameter – the number of *units* present in the energy system. A unit in this regard represents a physical

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entity, e.g., a power plant, or an offshore wind farm. The number of units can, naturally, be included as the actual physically installed quantity, if available in e.g., national or regional statistics. Alternatively, and typically more feasible for large energy systems such as national or European systems, based on average assumptions of unit sizes. This is also the case for the current study, for which the assumed average unit sizes can be seen in Table 3-4.

Table 3-2: Assumed average unit sizes applied, based on the Technology Catalogue for electricity and heating technologies published by the Danish Energy Agency (2025).

Technology	Average unit size [MW]
Onshore wind	120
Offshore wind	600
Photovoltaic	100
Hydro power	200
Nuclear power	900
Power plants (natural gas)	250
Power plant (biomass)	300
CHP plants (natural gas)	250
CHP plants (biomass)	300
Waste incineration	35

The resulting SWI and DADI values, along with total electricity generation capacity and the number of generation units, are presented in Table 3-5. It is important to note that SWI and DADI are based on different formulas and should not be compared directly in absolute terms. The Smart Energy Europe scenario features a larger total generation capacity and a higher number of units. While a greater number of units generally benefits the DADI, reflecting increased decentralisation, the contribution diminishes when a single technology dominates. Figure 3-5 shows the specific diversity index contributions by technology type.

Table 3-3: Installed generation capacity, electricity generating units, and diversity index values for 1.5 TECH and Smart Energy Europe.

	1.5 TECH	Smart Energy Europe
Electricity generation capacity [TW]	2.90	3.76
Number of electricity generating units	18966	28064
Shannon-Wiener diversity index (SWI) value	1.79	1.46
Decentralisation adjusted diversity index (DADI) value	7.54	6.60

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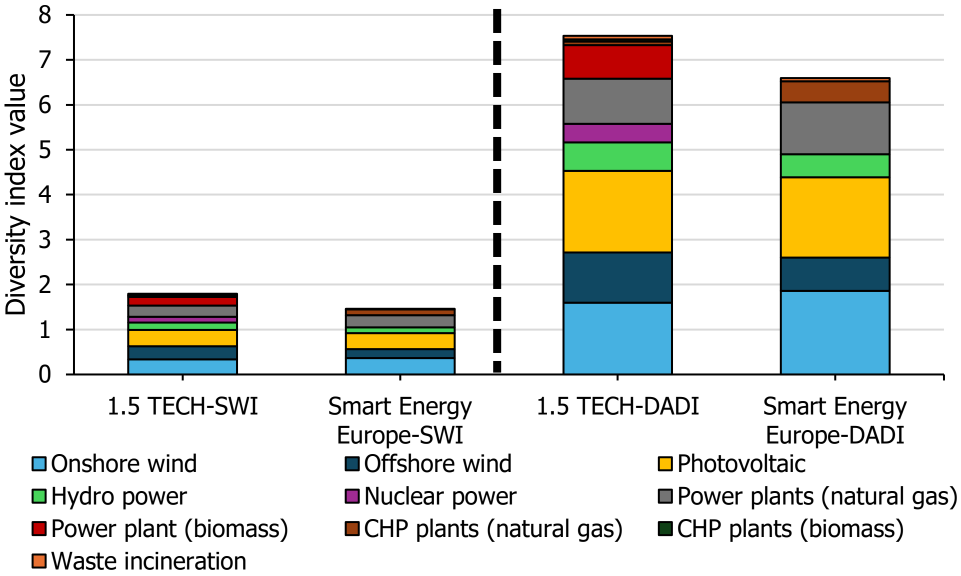

Figure 1-5: Diversity index value contribution per technology for 1.5 TECH and Smart Energy Europe.

The high unit count in Smart Energy Europe is primarily due to extensive onshore wind capacity, as was illustrated in Figure 3-4. However, further expansion of this already dominant technology provides limited gains in diversity due to the logarithmic nature of the index. This effect is even more pronounced in the SWI, which does not account for decentralisation and therefore underrepresents technologies like wind and PV.

In contrast, the 1.5 TECH scenario achieves higher SWI and DADI values due to a more balanced distribution of technologies, particularly among onshore wind, offshore wind, and PV. It also includes additional generation types, such as nuclear and CHP plants using both biogas, and solid biomass, which, despite relatively low capacity, enhance technological and fuel diversity. Smart Energy Europe excludes nuclear and relies solely on biogas-fuelled dispatchable units, reducing diversity.

Neither scenario was designed with diversity metrics in mind; both were developed to meet long-term climate targets and designed based on economic optimisation criteria. Nonetheless, this evaluation highlights important considerations for future modelling efforts.

In both scenarios, dispatchable technologies, though limited in capacity, contribute significantly to diversity. This suggests that maintaining or expanding such technologies may support system robustness, even with low annual utilisation. Diversifying fuel types for backup capacity and balancing VRE technologies can further enhance diversity. Finally, incorporating decentralisation into diversity assessments, as done in this study, provides a more accurate reflection of renewable energy systems. Traditional indices may overestimate diversity in fossil-based systems and undervalue the structural benefits of VRE, underscoring the need for advanced metrics like DADI in future evaluations.

3.3.2 Modelling energy system disruption responses

The following analysis evaluates how energy systems with large shares of renewable energy respond to extremely disruptive events and technical and economic implications of such system shocks.

In Table 3-6 and Table 3-7 some of the notable results from the simulation of the 1.5 TECH and Smart Energy Europe scenario respectively, in terms of system impacts from the modelled disruptions to nuclear power and adverse wind power conditions can be seen. Note that no nuclear power is included in the Smart Energy Europe scenario, hence only the wind power scenarios are modelled.

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Table 3-4: Resulting total annual cost, needed backup capacity, and security cost from disruption scenarios in 1.5 TECH scenario.

Nuclear power capacity factor reductions			
Nuclear power	Annual cost of existing system [B EUR]	Backup capacity need [GW]	Additional security cost [B EUR]
Reference	**2162**	**0**	**0**
25% reduction	2168	64	3.36
50% reduction	2177	121	6.35
75% reduction	2189	174	9.13
100% reduction	2202	222	12.27
Wind power capacity factor reductions			
Wind (onshore and offshore)	Annual cost of existing system [B EUR]	Backup capacity need [GW]	Additional security cost [B EUR]
Low capacity factors	2218	164	26.68
Medium capacity factors	**2162**	**0**	**0**
High capacity factors	2152	0	0
Nuclear power capacity factor reductions combined with low wind power capacity factors			
Nuclear and wind	Annual cost of existing system [B EUR]	Backup capacity need [GW]	Additional security cost [B EUR]
Reference	**2162**	**0**	**0**
25% reduction	2245	208	11.53
50% reduction	2261	249	13.68
75% reduction	2278	288	16.35
100% reduction	2295	326	18.96

Table 3-5: Resulting total annual cost, needed backup capacity, and security cost from disruption scenarios in Smart Energy Europe scenario.

Wind	Annual cost of existing system [B EUR]	Backup capacity need [GW]	Additional security cost [B EUR]
Low capacity factors	2071	14.27	26.68
Medium capacity factors	**1975**	**0**	**0**
High capacity factors	1965	0	0

In the reference scenarios (both 1.5 TECH and Smart Energy Europe) the total installed power plant capacity in Europe is approximately 500 GW. Under extreme disruption conditions, where key electricity producers such as nuclear and wind are significantly underperforming, an additional 300–400 GW of reserve capacity may be required to maintain system reliability. This reserve capacity could be provided through various means, including electricity imports, installation of peak-load power plants, or demand curtailment. For the purposes of this study, it is assumed that the required reserve is met by installing additional peak-load power plants, ensuring that electricity demand is covered in all hours of the year.

The simulations in EnergyPLAN demonstrated that the need for additional backup capacity is evident in extreme disruption scenarios:

- In 1.5 TECH, a full nuclear outage requires 222 GW of additional gas turbine capacity, operating only 0.5% of the time. If low wind conditions coincide, the requirement increases to 326 GW, with operation time rising to 0.8% of the year.

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- In Smart Energy Europe, the worst-case wind scenario necessitates 414 GW of additional gas turbines, operating 2% of the time.

These findings highlight that while the operating hours of backup capacity are minimal, the installed capacity requirement is substantial. For context, the current installed power plant capacity in Europe is approximately 500 GW, meaning that extreme disruptions could necessitate an additional 300–400 GW of reserve capacity, if no other measures and system adaptations (e.g., demand curtailment) are implemented.
Figures 3-6, 3-7 and 3-8 illustrate the annual additional security cost relative to the total annual investment cost for the electricity system for the 1.5 TECH scenario, while Figure 3-9 shows the same results for the Smart Energy Europe scenario.

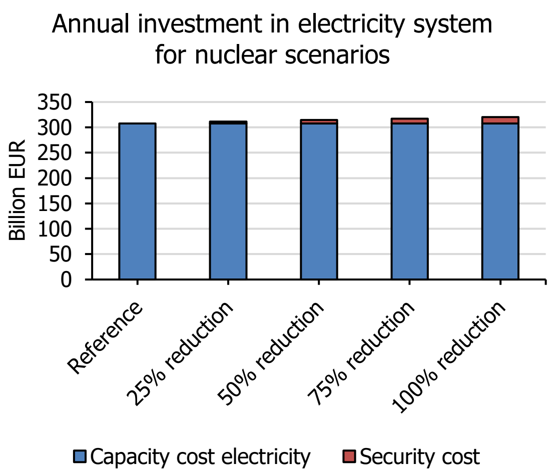

Figure 3-6: Additional security cost compared to investment costs in the electricity sector in 1.5 TECH.

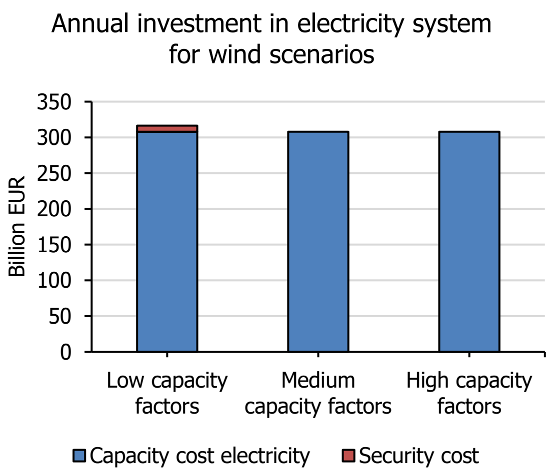

Figure 3-7: Additional security cost compared to investment costs in the electricity sector in 1.5 TECH.

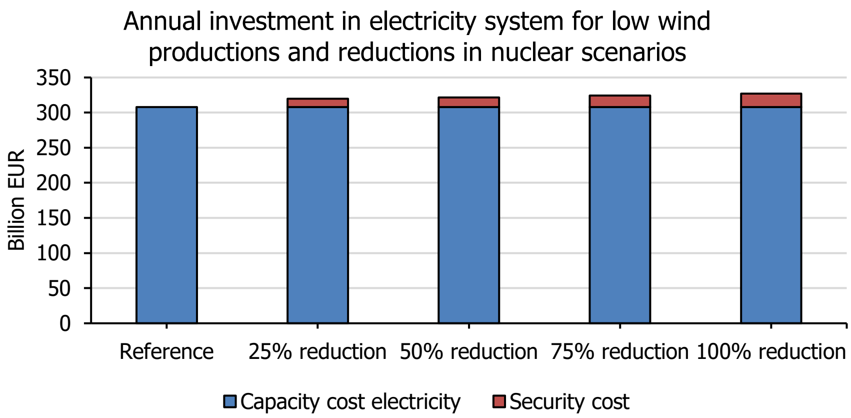

Figure 3-8: Additional security cost compared to investment costs in the electricity sector in 1.5 TECH.

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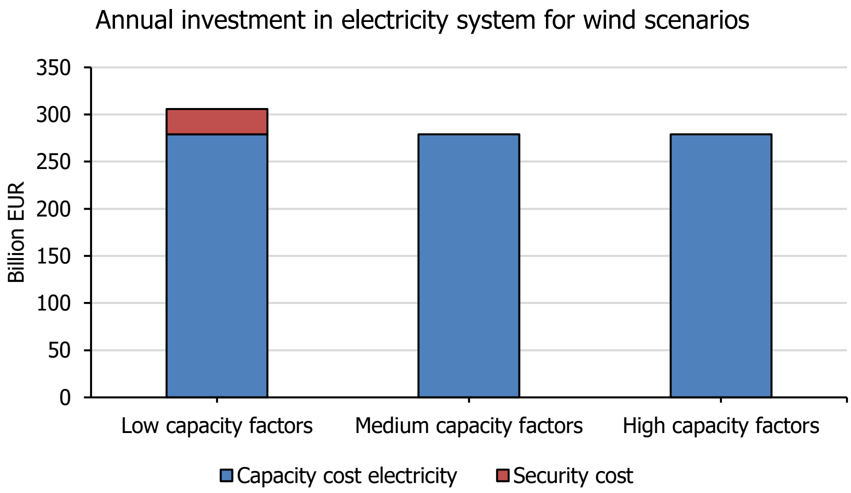

Figure 3-9: Additional security costs compared to investment costs in the electricity sector in Smart Energy Europe.

The "security cost" constitutes the costs related to investment of additional backup gas power plants, and the additional fuel consumption and O&M costs incurred by these. The majority of the costs are connected to the investment in additional capacity, and secondly fixed O&M costs primarily due to the operating hours being so few that fuel and variable O&M costs are negligible.

The analysis shows that most disruptions can be managed using existing system investments, with increased fuel consumption from dispatchable sources compensating for lost nuclear or wind output. However, this shift may lead to higher CO_2 emissions, particularly if fossil gas is used in backup turbines.

To mitigate this, we recommend maintaining existing dispatchable power plant capacity, or implementing new capacity if existing capacity is not present, prioritising biogas for backup generation. If this is not feasible, fossil gas may be required, albeit with environmental trade-offs.

It is important to note that the analysis does not assess the frequency of such extreme events. If these disruptions are rare, alternative strategies, such as demand-side flexibility, electricity imports, or temporary curtailment, may offer more cost-effective solutions than large-scale backup investments.

Additionally, renewable energy production may exceed reference assumptions in favourable wind years. In such cases, the system could achieve up to 60 million tonnes lower CO_2 emissions than projected in the reference Smart Energy Europe scenario, which in a long-term perspective, can be used to off-set the additional costs of security.

3.3.3 Curtailment and excess electricity

In the context of renewable energy systems for Europe by 2050, it is relevant to also evaluate the extent of excess electricity production, particularly from variable renewable energy sources such as wind and solar. Excess electricity occurs when generation exceeds demand and cannot be absorbed by the system. This surplus may need to be curtailed (e.g., by reducing wind or solar output) or, alternatively, managed through flexible system operations such as load-following nuclear power (i.e., operating at reduced capacity factors). While electricity exports outside the European system could also serve as a balancing mechanism, this option is not considered in the present analysis.

This analysis focuses specifically on how variations in wind power production affect the level of curtailment and how this compares to total electricity generation for the two scenarios evaluate as part of this study: the 1.5 TECH scenario and the Smart Energy Europe scenario.

Figure 3-10 illustrates the share of curtailment, referred to as Critical Excess Electricity Production (CEEP), as a percentage of total electricity production across different wind production scenarios.

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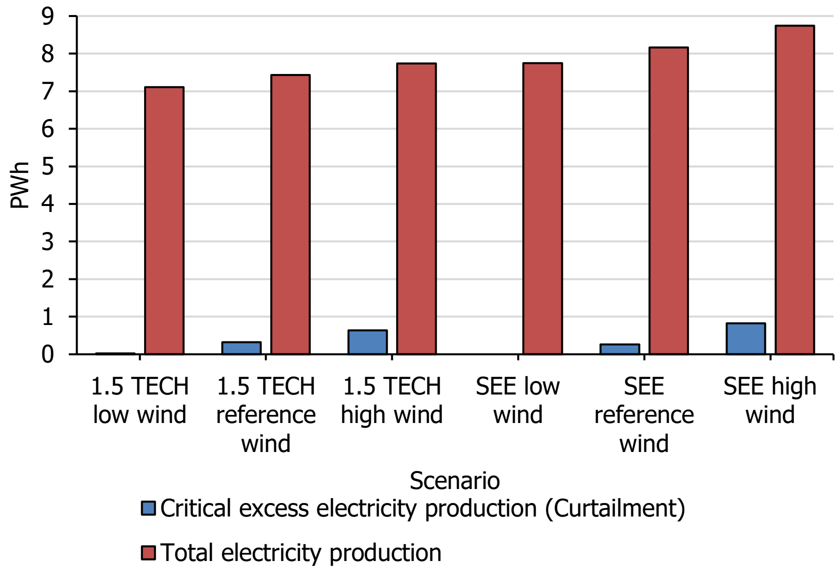

Figure 3-10: Comparison of critical excess electricity production (CEEP) with the total electricity production when varying wind across the two system designs.

The results show that:

- In both scenarios, CEEP remains below 10% of total electricity production, even under high wind output conditions.
- In the reference scenarios, where renewable capacity is designed to match system needs, curtailment is limited to just 3–4% of total production.
- These findings suggest that both systems can integrate high shares of wind power without requiring excessive curtailment or significant reductions in nuclear capacity factors.

This indicates that energy efficient energy systems are achievable, even with high levels of variable renewable energy. The relatively low levels of curtailment in the reference scenarios reflect well-balanced system configurations that effectively align generation capacity with demand and flexibility options.

While curtailment is often viewed as a sign of inefficiency, the modest levels observed here imply that appropriate sizing of renewable capacity and flexible backup and implementation of adequate integration measures and technologies, such as PtX, power-to-heating and large scale-thermal storage, electric vehicles and smart charging, can minimise energy waste and maintain high system efficiency.

3.4 Conclusion

This study has examined the energy security, resilience, and flexibility of two climate-neutral European energy system scenarios, a 1.5 TECH scenario developed by the European Commission and a Smart Energy Europe scenario, developed by Aalborg University. Demonstrating that not only is achieving this possible, but it is also technically and economically feasible.

We propose and apply an advancement to the traditional Shannon-Wiener diversity index, emphasising that future energy systems based on large shares of variable renewable electricity are misrepresented in previous diversity index approaches. The analysis of diversity metrics revealed that a more balanced mix of technologies and fuels, as seen in the 1.5 TECH scenario, enhances system diversity and resilience. The inclusion of decentralisation in the diversity assessment (via the DADI index) provided a more accurate reflection of modern renewable systems, highlighting the structural benefits of distributed generation.

The results of a "shock analysis" - a modelling of extremely disruptive events to the energy system, show that

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both systems can accommodate significant reductions in nuclear or wind power production with limited operational disruptions, primarily through increased fuel use if combined with additional backup capacity. The actual operational hours of this backup capacity are limited even in the most extreme disruptive scenarios, though the necessary installed capacity is substantial. This underlines a need for political prioritisation on the degree of security to pursue, and for further exploration of alternative solutions to managing extreme system disruption in addition to additional backup power plants, such as demand curtailment, securing imports, or additional storage capacities.

Analysing the experienced level of variable renewable electricity curtailment in these renewable energy scenarios, revealed that curtailment levels remained modest across scenarios, suggesting that high shares of variable renewable energy can be integrated without excessive energy waste or the need for extensive residential load-following, assuming that flexible electricity consumers such as smart charging EVs, district heating, and PtX are present in the system. However, the findings also underscore the importance of maintaining a diverse portfolio of dispatchable technologies and fuel sources to support system robustness, both from a diversity perspective and as a backup mechanism in the case of extreme disruptive events.

Overall, the study demonstrates that with thoughtful system design and strategic diversification, renewable-based energy systems can be both secure and resilient, and capable of meeting long-term climate goals while managing operational risks. However, if security, diversification, and robustness to extreme disruptive events are key societal priorities, these need to be explicitly incorporated in energy system scenario design and modelling practices.

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4 Energy independence and green fuel import

Authors: Meng Yuan, Rasmus Magni Johannsen, Jakob Zinck Thellufsen [AAU]

4.1 Introduction

The European Union aims to become climate-neutral by 2050 to alleviate the negative effects of greenhouse gas emissions. A joint effort from member states will be required to overcome the challenges in hard-to-abate sectors to achieve this overall goal. The aviation and shipping sectors, which heavily rely on hydrocarbons, are eager to seek green and affordable solutions. Renewable methanol, including both bio-methanol (produced from biomass) and e-methanol (from CO2 capture and green hydrogen), is considered as one of the key chemical products for producing sustainable aviation fuels and powering the shipping industry (IRENA AND METHANOL INSTITUTE, 2021).

The existing scenarios (Kountouris et al., 2024; Thellufsen, Lund, Sorknæs, et al., 2023) proves that Europe can achieve self-sufficiency by 2050 by utilising local renewable energy resources and their derivatives. However, recent literatures (Moritz et al., 2023; Schorn et al., 2021; Wang et al., 2023) also shows that other regions (e.g., Australia, the Middle East, Chile, etc.) also enjoy significant potential to produce hydrogen and other renewable fuels inexpensively, and Europe can benefit from imports from these regions. Similar to the traditional coal- and gas-based methanol market, renewable methanol in principle also has the potential to become an international commodity in the global market via the existing infrastructures (Galimova et al., 2023). Compared to hydrogen, methanol has a distinct and important advantage of lower shipping costs (Schorn et al., 2021). On the other hand, energy security is also a high priority for the EU, given the increasing uncertainty in the geopolitical situation. In this context, balancing the trade-off between energy security and the potential economic benefits of imports becomes a critical question to be answered.

This study explores the trade-offs associated with achieving a secure and affordable energy system, focusing on the varying degrees of dependence on domestic production of renewable methanol versus imports. By implementing a series of methanol import scenarios, this study investigates the costs associated with achieving a secure and affordable European energy system at various levels.

4.2 Methods

This section introduces the EnergyPLAN tool applied for energy system modelling, the reference scenario and a range of alternative renewable fuel import scenarios created in this study.

EnergyPLAN – Advanced energy system analysis tool

The advanced hourly energy system analysis simulation model EnergyPLAN (Lund et al., 2021). This tool was introduced also in Section 3.2.1, and hence, in the following, we will only detail specific model and scenario adaptations implemented for this study.

Reference scenario – updated Smart Energy Europe scenario

The "Smart Energy Europe scenario" created in EnergyPLAN by Thellufsen et al. (2023) is used as the basis for the reference scenario. The Smart Energy Europe scenario aims to achieve a self-sufficient, sector-coupled, 100% renewable-based, carbon-neutral European energy system in the year of 2050. In this scenario, all energy demand is covered by locally available energy sources, which means the reference scenario represents the highest level of energy security in terms of fuel independence from the rest of the world. Further details of this scenario can be found in study by Thellufsen et al. (2023), Section 3.2.2 of the present study, and the Section 3.4.1 of the IAM COMPACT report D4.9 – European sub-national deep dives.

To provide concrete insights for a better understanding on the potential economic consequences, the cost and technical specifics of key technologies related to renewable methanol production are updated to the latest

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available data. The updated technologies are listed below:

- Renewable electricity generators, including onshore wind, offshore wind, PV
- Renewable methanol synthesis process, including both biomass hydrogenation and CO_2 hydrogenation
- Carbon capture. Assuming 50% post-combustion point sources capture and 50% solid adsorption direct air capture.
- Green hydrogen production through electrolysers
- Hydrogen storage

Alternative scenarios – renewable methanol import

A range of alternative scenarios, from complete self-sufficiency (reference scenario with zero import) to full reliance on renewable methanol imports (100% import, including both bio-methanol and e-methanol), are designed to investigate the general patterns of the European energy system responses to the varying degrees of dependence on domestic renewable methanol versus imports. An interval of 10% import is implemented, i.e., scenarios with 0, 10%, 20%, ...,90%, 100% of renewable methanol import are investigated. The system configurations, including the key parameters of wind and solar capacity, electrolysis, hydrogen storage as well as carbon capture capacities, are optimised to achieve a balance in electricity curtailment and overall costs.

4.3 Results

Based on the results of the scenarios, the marginal production cost of renewable methanol in EU and the consequences of energy imports for the overall European energy systems can also identified based on comparisons to the reference scenario. The marginal production cost is calculated by the system cost reduction compared to the reference scenario divided by the amount of methanol import.

Figure 4-1 illustrates the results of marginal production cost of renewable methanol in Europe. The cost forecasts by IRENA and the Methanol Institute serve as benchmarks for this study. With anticipated technological maturity, the production costs of bio-methanol and e-methanol are expected to range between 10.3-38.2 EUR/GJ and 11.3-28.5 EUR/GJ, respectively, for mature processes in 2030-2050. This range accounts for different levels of costs associated with biomass feedstock and CO2 capture pathways (e.g., point sources vs. direct air capture). 4-1 shows the marginal production cost of renewable methanol declines from 27.3 EUR/GJ (at 10% import) with an increase in methanol imports up to approximately 50% of the total methanol demand. Beyond this point, the cost stabilises at around 24.6 EUR/GJ, representing approximately a 9% reduction. These findings suggest that the European energy system would economically benefit from importing renewable methanol from other regions, provided the import costs remain below the marginal production cost curve (as indicated in the dark area in 4-1). On the contrary, costs above the curve (shown in the orange area) would not be economically favourable from EU's perspective.

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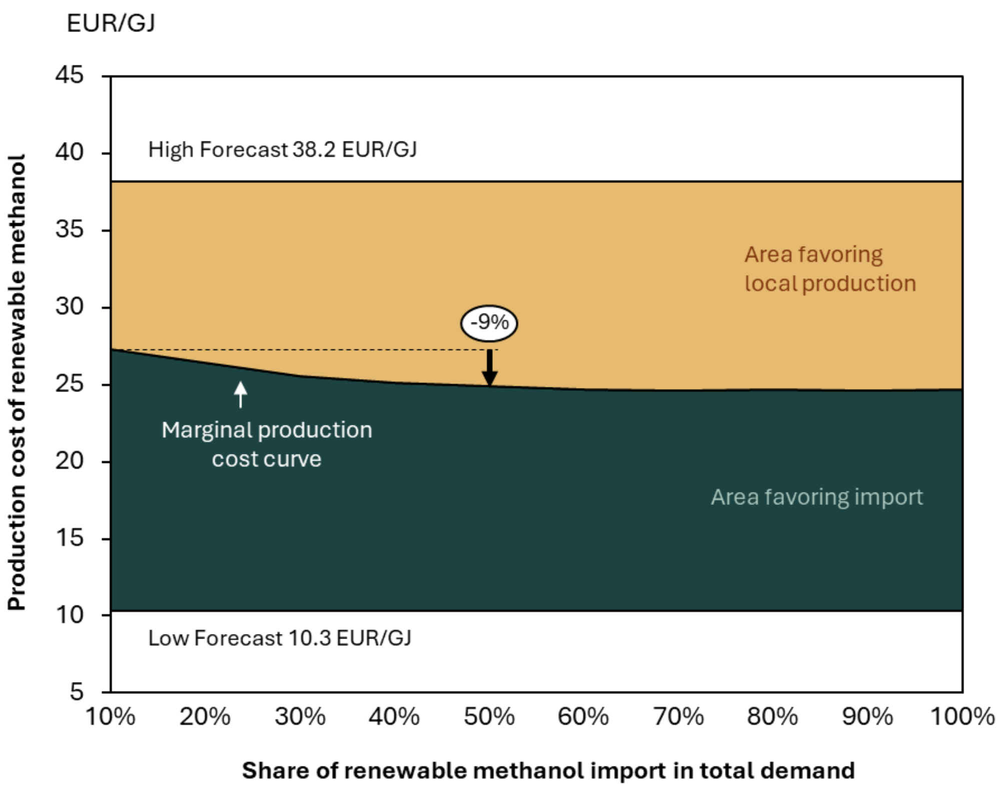

Figure 4-1 Landscape of renewable methanol import in Europe based on the results of this study. Cost forecast sources from (IRENA AND METHANOL INSTITUTE, 2021)**.**

Figure 4-2 and Figure 4-3 present the results of electricity curtailment and the primary energy consumption of the entire European energy system under different methanol import scenarios. With an increase in renewable methanol imports, a significant rise in excess electricity is foreseen in the system, while the primary energy consumption declines due to reduced local production. Electricity curtailment increases from 3.2% of the total electricity production in the reference scenario with zero imports to 11.5% in the 100% import scenario. This is primarily a result of reduced electrolysis capacity which functioned as an important flexible electricity consumer. Variable renewable electricity capacity is also reduced based on an optimisation of total system cost; hence the curtailment increases of electricity increases as methanol import increases. It can be difficult to track the energy efficiency for methanol production in other regions, however, from the perspective of system balance in the EU, it may be beneficial to keep some domestic methanol production to avoid redundant overcapacity and large curtailment of variable renewable electricity.

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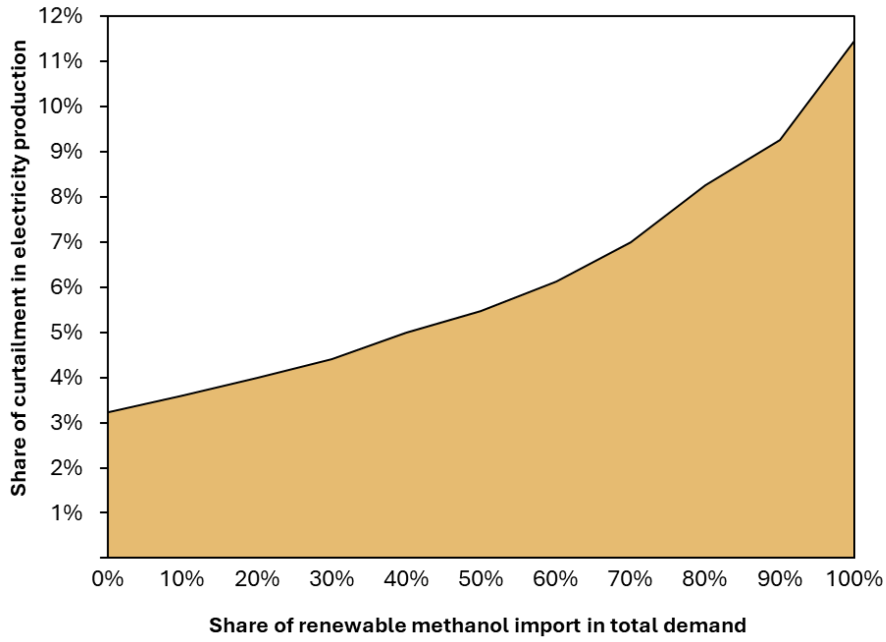

Figure 4-2 The increase of electricity curtailment per increased share of renewable methanol imports in Europe.

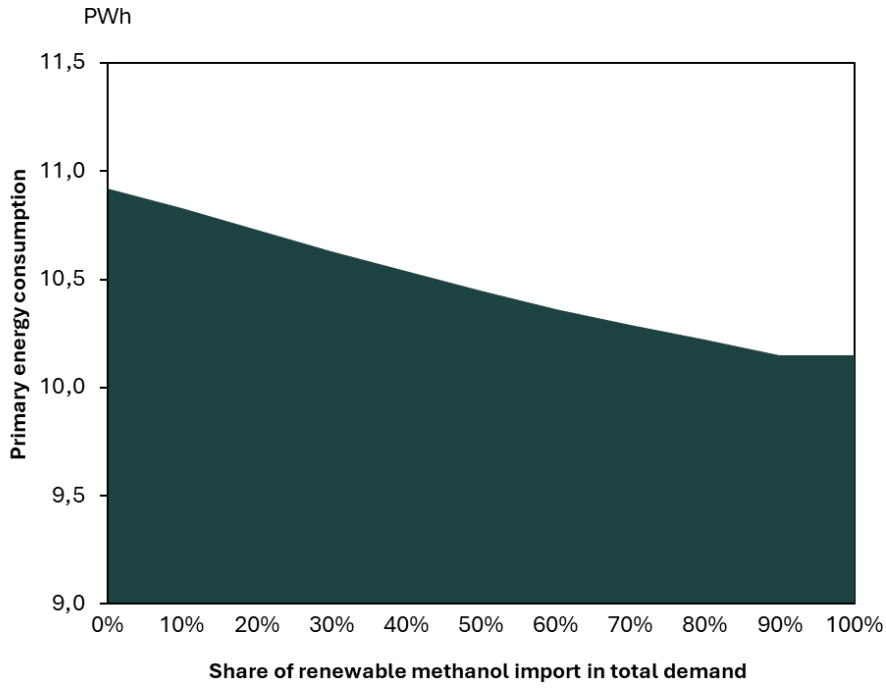

Figure 4-3 The decline of primary energy consumption per increased share of renewable methanol imports in Europe.

4.4 Conclusion and policy implications

This study highlights the strategic importance of the trade-offs of importing renewable methanol in supporting the EU's ambition to achieve climate neutrality by 2050. It is found that it can be beneficial to exploit economic opportunities through methanol imports, however, it is also important to maintain an acceptable level of energy security. By evaluating a range of methanol import scenarios, the results show the largest marginal benefit comes from less than 50% of renewable methanol import. However, beyond this threshold, the benefits plateau, and

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challenges such as increased electricity curtailment and reduced domestic energy activity become more obvious.

Similarly to fossil fuel trading, Europe should also aim to diversify its import sources for e-fuels and biofuels from a variety of countries to avoid over-dependence on any single country, which can pose risks to energy security. This is also aligned with the key pillars in REPowerEU.

Another important perspective related to the trade-off issue comes from job creation. By reducing renewable energy capacity and domestic renewable fuel production in Europe, and instead increasing methanol imports, the EU could likely lose some job opportunities and worsen the trade balance. This might offset some of the economic benefits gained from importing renewable fuels from other regions. The socio-economic impacts can be investigated further in our future study.

Considering the factors mentioned above, it is crucial for policymakers to understand both technical and economic trade-offs related to renewable fuel imports so that strategies based on thorough evaluation can be developed, effectively balancing these trade-offs and energy security concerns.

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5 Comparing cost-optimal to policy-driven scenarios for a decarbonised European energy system

Authors: Natasha Frilingou [NTUA]; Dirk-Jan Van de Ven, Jon Sampedro, Russell Horowitz, Clàudia Rodés-Bachs, Rhodes [BC3]; Alexandre Torné, Evelina Trutnevyte [UNIGE]

5.1 Background about the process

In the context of IAM COMPACT's Policy Response Mechanism, we have held several dedicated workshops with experts and stakeholders with the aim to co-create modelling studies and co-design scenarios. The present study has been formulated by our Policy Steering Groups and is part of the theme "Modelling the Clean Industrial Deal" [4] focusing on the infrastructure investments needed to enable a clean European economy. The workshop brought together a diverse group of stakeholders, including IAM developers, representatives from EU policy institutions, industry experts from energy-intensive sectors, environmental NGOs, and research organisations working at the interface of science and policy, to discuss how the updated National Energy and Climate Plans (NECPs) compare to a cost-optimal pathways for reaching EU climate targets, considering grid infrastructure, offshore development, cross-border connections, and generation-transmission cost balance.

Discussions focused on EU infrastructure and its role in enabling a decarbonised electricity system, on key indicators of competitiveness and resilience among others, and on the need to address critical uncertainties of the net-zero transition. Participants highlighted a range of indicators considered most relevant for assessing the expected impacts of a decarbonised power system, including metrics such as energy prices, system costs, investment needs, and carbon budgets. Environmental indicators like air quality were also noted, alongside electricity-specific measures such as household energy bills, temporal electricity price volatility, network tariffs, natural gas availability and origin as a metric of energy security, and disaggregated cost breakdowns for transmission and storage infrastructure. Social indicators, such as the share of prosumers, levels of energy poverty linked to electricity prices and household consumption, and broader societal benefits of power system integration, were also considered essential. The latter indicators were more relevant to Study 11 "Towards a just transition: the distributional effects of EU environmental policies", part of Deliverable *D5.3 - Climate action social & distributional impacts – Update*.

One of the key outcomes of the workshop was a shared commitment to an iterative and collaborative model development process. Participants agreed on the importance of continuous stakeholder engagement, whereby model results are presented for validation and refinement, ensuring that scenarios are grounded in both empirical evidence and the evolving policy context. This iterative process aims to improve the usability and legitimacy of model-based insights for decision-making at both national and EU levels. By facilitating structured dialogue between modelling teams and policy stakeholders, the workshop underscored the essential role of stakeholder engagement in enhancing the scientific robustness, policy relevance, and real-world applicability of IAMs.

5.2 Introduction

The transition to a low-carbon economy in the European Union (EU) requires a balance between collective ambition and national priorities. The European Commission introduced the European Green Deal in December 2019 (European Commission, 2019) with the aim of transitioning Europe's economy towards climate neutrality by

[4] https://iam-compact.eu/news-events/core-working-group-workshop-modelling-clean-industrial-deal

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2050, followed by the European Climate Law in 2021 (European Parliament, 2021), making the EU's commitment to achieve net-zero greenhouse gas emissions by 2050 and to reduce emissions by at least 55% by 2030 compared to 1990 levels legally binding. In 2023, the EU adopted the Fit-for-55 package, a comprehensive set of legislative measures including the EU Emissions Trading System (ETS) Directive, the Effort Sharing Regulation (ESR), the Renewable Energy Directive, the Energy Efficiency Directive, and the Land Use, Land Use Change and Forestry (LULUCF) Regulation, aimed at achieving the 2030 climate target (Kelleher & Daly, 2025). The main policy documents detailing how Member States will each contribute to achieving the EU's 2030 2030 energy and climate policy goals are the National Energy and Climate Plans (NECPs) (European Commission, 2025b). NEPCs were first finalised in 2020 but required an update to align with the more ambitious EU targets. The draft updated NECPs were published in 2023, and, following an EU-wide and country-specific assessment, had to be finalised by 2024. As of May 2025, 24 national plans have been submitted, along with an updated EU-wide assessment of finalised NECPs (excluding Estonia, Belgium, and Poland). This assessment found that the EU is on track to reach the 2030 targets of reducing net GHG emissions by at least 55% compared to 1990 and increasing the renewable energy share to at least 42.5% with the aspiration to achieve 45% (European Commission, 2025a). An ambition gap however remains, particularly for the 2030 energy efficiency objectives for both primary and final energy use. Overall, the expected reduction rate of CO_2 emissions is unprecedented and challenging (Rosenowid, 2022).

Individual studies have been published to explore the impact of reaching NECP targets in e.g., Greece's energy system (Karamaneas et al., 2023), and its power sector (Kleanthis et al., 2025), Ukraine's power sector (Sotnyk et al., 2025), UK's heating sector (Scamman et al., 2020), and Spain's energy system (Parrado-Hernando et al., 2022), or have focused on assessing NEPCs in terms of sufficiency e.g., in Hungary (Munkácsy et al., 2024), and in the EU (Zell-Ziegler et al., 2021), or compared NECP targets with alternative reference scenarios (Greaves et al., 2022). Several modelling studies have analysed the impacts of the Fit-for-55 package and net-zero targets of individual EU countries (Aryanpur et al., 2024; Millot et al., 2020; Scheepers et al., 2022; Shahzad et al., 2024) or specific sectors (Ali et al., 2024; Ovaere & Proost, 2022; Upadhyay et al., 2025), but few studies have analysed the entire policy package of the European Green Deal for the entire bloc (Mikropoulos et al., 2025; Tsiropoulos et al., 2020; Victoria et al., 2020) or for each individual Member State (Boitier et al., 2023). Most studies have focused on parts of the policy package, i.e., ETS prices (Pietzcker et al., 2021; Zhao et al., 2018) or renewable electricity generation requirements (Fleschutz et al., 2021; Janota et al., 2022; Johannsen et al., 2023; Shirizadeh & Quirion, 2022). Comparing the bottom-up trajectories outlined in individual NECPs with the top-down goals of Fit-for-55 could thus reveal how each Member State contributes to the collective responsibility of reaching EU-wide targets, their sectoral burden-sharing, and the implications for equitable effort-sharing among Member States. Our study fills a critical gap in the literature, by validating the individual plans vis-à-vis EU-level policy goals and in an integrated way, modelling wider energy and electricity system implications of achieving EU's 2030 targets.

Despite progress in climate policy modelling, few existing tools can capture both the geographic diversity of national climate strategies and the technical detail required for sector-specific transformation, particularly in electricity. Integrated assessment models (IAMs) have been widely criticised for their limited spatial and sectoral resolution (Koasidis et al., 2023), reliance on simplified policy assumptions, and an overarching focus on cost-optimisation under idealised conditions, which often fail to reflect real-world complexities, and extensive reliance on negative-emission technologies such as BECCS (Gambhir et al., 2019; Rubiano Rivadeneira & Carton, 2022). Many IAMs operate at aggregated regional or continental levels, which obscures national heterogeneity in energy infrastructure, governance, resource availability, and socio-economic conditions (Aryanpur et al., 2021). On the other hand, national energy models, while offering high sectoral and policy detail, typically lack the ability to account for cross-border interactions, regional market integration, and EU-wide spillover effects, critical factors in assessing packages like Fit-for-55 and the coherence of National Energy and Climate Plans (NECPs) (Mertens et al., 2020). Their limited scope constrains their usefulness for evaluating how national actions align with collective EU targets, or for analysing infrastructure needs, such as cross-border electricity flows and shared resource constraints. Although European countries independently establish and manage their national targets, they are deeply interdependent due to the integrated electricity grid and the shared EU ETS.

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In this context, the use of GCAM-Europe, an expansion of the well-established IAM Global Change Analysis Model (GCAM) (Calvin et al., 2019) with Member State-level granularity, represents a significant step forward. Unlike traditional IAMs that operate at regional or supra-national levels (Nikas et al., 2018), GCAM-Europe can reflect national differences in energy systems, emissions profiles, resource availability, and policy ambitions, allowing for more policy-relevant and actionable insights at the country level. Despite significant improvements in the spatial resolution, electricity flows and load segmentation (see **Methods**), which capture temporal variation in electricity demand and supply more accurately, the model still operates in 5-year time-steps, which may hinder the accurate estimation the optimal level of variable renewable generation (Gong et al., 2023). Given the critical importance of electrification and sector coupling in mitigation scenarios (IEA, 2023) , there is a growing need for IAMs to expand their scope and level of detail to effectively support energy transition and climate policy development (Krawczyk & Braun, 2025; Trutnevyte et al., 2019), and for mitigation scenarios to include non-IAM pathways (Gambhir et al., 2022). The power sector remains a major emitter in the EU, accounting for 19% of CO_2 emissions (Eurostat, 2023), and is expected to be the first sector to decarbonise, to allow other sectors reach net-zero emissions before 2050 (Sasse & Trutnevyte, 2023a). Accurately reflecting the power sector transformation over long time horizons, and the variability of renewable energy, which are strongly dependent on national- and local-scale grid systems (Fujimori et al., 2019), is crucial for the robust assessments of investment needs. Bridging this temporal resolution gap has been attempted through soft-linking IAMs with spatially-detailed electricity system models (Brinkerink et al., 2022; Chang et al., 2021; Nikas et al., 2024; Pavičević et al., 2020). Here, we couple GCAM-Europe with EXPANSE (Sasse & Trutnevyte, 2023b), a detailed electricity system model that captures regional electricity generation and storage dynamics, as well as grid constraints. We derive the energy and electricity system transformations required at the EU Member State level to achieve the EU's Fit-For-55 and net zero goals and examine how these transformations differ if meeting GHG emission targets at EU- or state-level, and either considering climate policies or just under cost-optimal pathways. This scenario design aims to explore the implications of non-coordination to achieve climate targets, and of proposed climate policies.

5.3 Methods

NECP analysis

We analysed 27 NECPs, 24 of which were final, and 3 (Belgium, Estonia, and Poland) still in draft to extract individual Member States targets on emissions, renewable shares in final energy consumption, energy efficiency, as well as stated coal phase out policies. When available, projections with additional measures (WAM) provided in the NECPs were used. If the WAM projections were missing, the projections with existing measures (WEM) provided in the NECP were used instead. We crossed-checked the resulting targets with data from Ember (Ember, 2025) which include the stated targets of Member States in NECP documents covering greenhouse gas emissions, final energy demand, electricity generation and installed electricity generation capacity.

Scenario design

In this study, we explore four alternative climate policy scenarios alongside a benchmark baseline, each representing a distinct trajectory toward meeting the EU's GHG emission reduction targets and broader climate objectives. These scenarios, detailed in Table 2, allow us to assess the implications of different policy designs. To isolate the relative price effects of climate policy, all scenarios, including the EU_NOPOLICY baseline, incorporate existing Member State-specific energy taxes (on electricity, gas, and transport fuels) as of 2024, and hold them constant through 2030. Regions outside the EU are assumed to follow NDC and long-term targets.

Table 5-1: Description of modelled scenarios

Scenario	Description
NO_POLICY	We assume the absence of any climate policy. While several cross-sectoral policies and objectives are currently in place at both the EU level and within individual

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	Member States, this theoretical scenario serves as a benchmark. It enables comparison with alternative pathways to assess the impact of various climate policy interventions.
NECP_POLICY	The scenario reflects a detailed representation of the existing Fit-For-55 policy portfolio, including EU-wide targets for the EU-ETS (1 and 2), vehicle emission standards, country-specific coal phase-out strategies, renewable energy as a % share of final energy (Table A1) and energy efficiency as a maximum final energy use (Table A2) targets as defined in country-specific NECPs
NECP_FREE	In this scenario, Member States achieves the same level of CO_2 emissions mitigation as in the NECP_POLICY scenario. However, in this case, emissions reductions are accomplished through emissions constraints without considering the current climate policies, allowing the models to select the cost-optimal pathway for reducing emissions.
FF55_POLICY	This scenario is similar to the NECP_POLICY scenario, but instead of applying NECP-specific targets, EU-wide targets for 2030 in line with Fit-For-F55 are applied for renewables (42.5% of final energy) and energy efficiency (11.7% reduction in final energy w.r.t. 2020) and net-zero for 2050, allowing the model to optimally allocate efforts for these targets over the different Member States.
FF55_FREE	In this scenario, the EU achieves the same level of CO_2 emissions mitigation as in the FF55_POLICY scenario. However, in this case, EU emissions reductions are accomplished through emissions constraints without considering the current climate policies, allowing the models to select the cost-optimal pathway for reducing emissions.

Together, these scenarios represent a range of plausible policy narratives that contrast prescriptive regulatory approaches with more flexible, least-cost mitigation strategies. While all scenarios are calibrated to achieve the same total reduction in CO_2 emissions at the EU level by 2030 in GCAM-Europe, they differ significantly in how mitigation responsibilities are distributed across sectors and Member States. To ensure consistency with official projections, population and GDP assumptions are harmonised with the 2024 edition of the EU Ageing Report (European Commission, 2024 reflecting expected demographic and economic trends across Member States.

At the EU level, climate policy instruments incorporated in the FF55_POLICY scenario include:

- EU Emissions Trading System (ETS): This cap-and-trade mechanism covers power generation and large industrial emitters, setting a declining carbon cap to reduce emissions cost-effectively.
- ETS2: A new emissions trading system for buildings and road transport, assumed to introduce a carbon price of €45/tCO2 (in 2020 prices) by 2030.
- Vehicle emissions standards: These are modelled to tighten gradually over time, culminating in near-zero emissions from new vehicles by 2035, in line with the EU regulation phasing out the sale of internal combustion engine (ICE) vehicles.

Country-specific policies reflect national contributions under the National Energy and Climate Plans (NECPs) and include:

- Energy Efficiency Directive targets, requiring a reduction of final energy consumption to 764 million tonnes of oil equivalent (Mtoe) by 2030 at the EU level.
- Renewable Energy Directive objectives, mandating that 42.5% of final energy consumption be met through renewable sources by 2030.

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- National coal phase-out plans, which specify timelines for retiring coal-based electricity generation in individual Member States.
- After 2030, we assume policies remain constant, and use economy-wide carbon price towards net-zero in 2050 (or earlier for specific countries)

These differentiated policy frameworks allow for a comparative analysis of the trade-offs between coordination, flexibility, and equity in the pursuit of the EU's climate goals.

Models used

GCAM-Europe

GCAM-Europe[5] is an expansion of the Global Change Analysis Model (GCAM), a well-reputed IAM widely used in global scenario analysis (Calvin et al., 2019). The model is designed to analyse alternative "what-if" type scenarios within a single computational platform. GCAM-Europe includes technology-rich representations of the economy, energy sector, land use, and water linked to a global climate model that can be used to explore climate change mitigation policies, including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. Regional population and labour productivity growth assumptions drive the energy, land-use and water systems employing numerous technology options to produce, transform, and provide energy services, as well as to produce agricultural and forest products and to determine land use and land cover. A full description of the GCAM model can be found in the online documentation[6].

GCAM-Europe's geographical disaggregation is highly-detailed for the European continent. While core GCAM divides the European continent in five different regions, namely EU-12, EU-15, Europe Eastern, Europe-non-EU, and European Free Trade Association (EFTA), in GCAM-Europe all European countries are disaggregated into individual model regions (Figure 5-1). Having this level of detail enables us to explore the country-level effects of European policy packages or transformational strategies, as well as the potential international effects (e.g., carbon leakage).

[5] BC3, 2025. GCAM-Europe (Version 7.2.0). https://github.com/bc3LC-GCAMEurope/gcam-core. Basque Centre for Climate Change. https://doi.org/10.5281/zenodo.15655567 .

[6] https://github.com/JGCRI/gcam-doc

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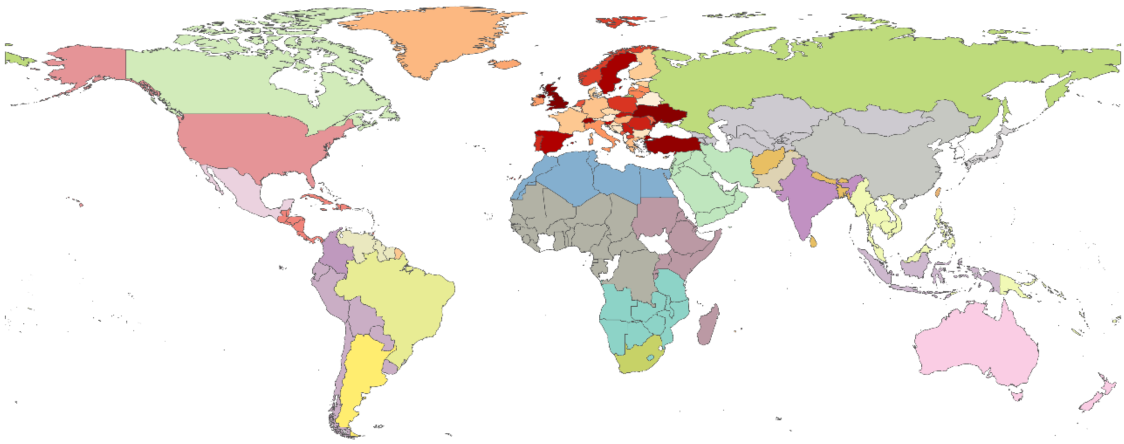

Figure 5-1: Regional disaggregation in GCAM-Europe. Orange-to-red represent the regional groups that are explicitly disaggregated for this model (from 5 regions to 39 countries). All other colours represent the 27 regional groups that were part of the original model and are also part of GCAM-Europe.

GCAM-Europe replaces the default international data sources for newly defined European countries with Europe-specific datasets wherever possible, prioritising sources such as Eurostat for energy statistics. In cases where country-level data are unavailable in these European sources, GCAM-Europe defaults to broader international datasets, primarily the IEA.

The model expands sectoral and technological detail, particularly in the buildings sector, with new end-use demand categories, including hot water, cooking, and various household appliances, and the integration of emerging technologies such as heat pumps. Additionally, residential energy demand is disaggregated by consumer groups using country-specific data where available, improving the granularity of household energy use representation. In the industrial sector, GCAM-Europe incorporates a European Single Market, enabling the simulation of intra-European trade in selected industrial goods. The electricity sector is modelled as an integrated grid system structured around grid regions, load segments, and inter-segment storage (see Figure 5-2). This design supports a more realistic depiction of electricity flows and flexibility both within and across regions. Load segmentation is aligned with the ENTSO-E "National Trends" scenario (ENTSOE, 2024), allowing for a refined temporal resolution of demand and supply. This structure also enables the assessment of storage technologies in balancing electricity across time segments and geographies. Each grid region and cluster operate a distinct electricity market, with electricity prices varying based on time-of-day demand patterns, typically lowest during off-peak hours and highest during peak periods. Price differentials between clusters and regions incentivise investments in storage and cross-regional electricity trade.

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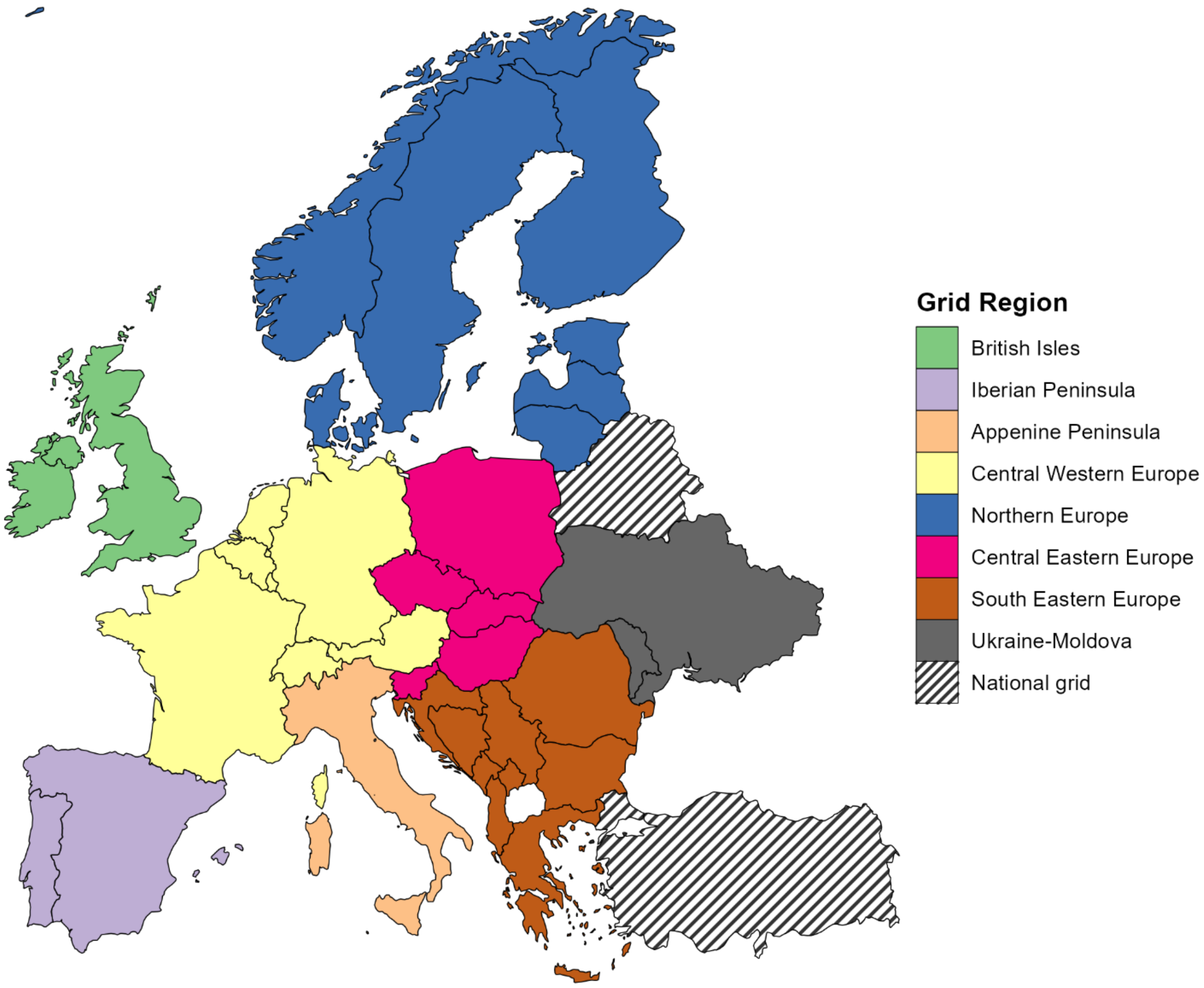

Figure 5-2: Electricity grid regions in GCAM-Europe.

GCAM-Europe introduces a trade framework that mirrors the structure of the European Economic Area (EEA) and the internal single market among EU member states, Norway, and Iceland. In the standard GCAM model, trade in commodities such as energy, food, and selected industrial products (e.g., steel and ammonia) is governed by Armington-style assumptions, which define the degree of substitutability between domestic and imported goods within and across regions through a logit sharing function. Imports are from a single global pool that draws from all regions and is also governed by a logit (Zhao et al., 2022).

In the GCAM-Europe extension, EEA countries are modelled as a unified trading bloc in global markets. An additional intra-EEA trade layer, also based on Armington specifications, captures trade flows within the bloc. While trade costs between the EEA and non-EEA regions remain aligned with standard GCAM assumptions, intra-EEA trade is assigned reduced costs to reflect the lower barriers characteristic of the internal market. This refined structure enhances the realism of European trade dynamics and provides a foundation for incorporating future common trade instruments, such as the Carbon Border Adjustment Mechanism (CBAM).

EXPANSE

EXPANSE is a comprehensive spatially explicit technology-rich optimisation model of the European electricity system in 2035 (Nikas et al., 2024; Sasse & Trutnevyte, 2020, 2023b; Section 2 of this deliverable. It includes 33 countries (EU without Cyprus and Malta, plus Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Norway, Serbia, Switzerland, and the UK) and considers electricity generation, storage, and transmission. The model operates at a spatially explicit level, with 296 NUTS-2 regions for electricity generation and 128 grid nodes

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for demand, storage, and transmission (Sasse & Trutnevyte, 2023b).

EXPANSE been used to assess regional benefits and vulnerabilities linked to a low-carbon transition of the European electricity sector (Sasse & Trutnevyte, 2023a), investigate air pollution and associated health co-benefits of low-carbon electricity supply scenarios in Europe (Pehle et al., 2025), analyse employment and skill implications (Section 2 of this deliverable), understand options for reducing the reliance on Russian gas together with other models (Nikas et al., 2024), and evaluate the regional interdependencies of cost-effectively implementing European electricity sector targets for renewable electricity and greenhouse gas emissions (Sasse & Trutnevyte, 2023b). The model's technology portfolio covers a broad range of electricity generation options, including conventional sources, such as coal- and gas-fired power plants and nuclear power, as well as renewables like hydropower, solar photovoltaics (PV), wind turbines, along with supporting storage, and transmission infrastructure.

In this study, the EXPANSE model minimises total system costs, which include annualised investment costs and marginal costs of electricity generation, storage, and transmission infrastructure, to find optimal regional capacities in 2035. Investment and operation and maintenance cost assumptions stem from long-term estimates for the year 2035 and include changes in costs from technological learning. Prices of natural gas and other fossil fuels in 2035, as well as carbon prices modelled as a fuel tax come from GCAM-Europe. A weighted average cost of capital (WACC) of 3% is assumed for all technologies and regions. Input data, assumptions, and the mathematical formulation of EXPANSE are available in the Annex A2. To accommodate more ambitious emission reduction and renewable generation targets, in this study we allow further flexibility by limiting the expansion of transmission lines capacity to three times the current instead of two and allow flexible fossil fuel-based technologies and firm renewables to operate at the full range of their capacity instead of at least at 40% of their nominal capacity.

A comparison of GCAM-Europe and EXPANSE can be seen Table 5-2.

Table 5-2: Comparison between the coupled models GCAM-Europe and EXPANSE

Model information	Model name and version	GCAM-Europe v7.2.0	EXPANSE
	Model type	Intergated Assessement Model (IAM)	Power sector model (PSM)
Scope and resolution	Spatial scope	Entire globe	Europe
	Temporal resolution	5 year time steps	Single year, 1 to 6 hours resolution
	Modelling period	2015 - 2050	2035
	Regional resolution	27 geopolitical regions & 39 European countries	33 European countries, 296 NUTS-2 regions (generation), 128 transmission grid nodes (demand and storage)
	Climate policy options	Carbon or GHG prices, emission constraints, climate constraints, production or land constrains, protected lands	Carbon prices, emission constraints, production constraints, cost and technical constraints
Power sector dynamics	Endogenous hourly dispatch	No	Yes

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	Price elasticity of demand	Yes	Not in the default version
	Capital cost of technology	Exogenous	Exogenous
	Vintage tracking of capital stock	Yes	No
	Transmission assumption	Multi-node grid structure	High voltage alternative and direct current transmission lines between 128 grid nodes
	Negative emission technologies	CCS, BECCS, DAC	Not available
Model code and data specification	Programming language	C++	Python
	Input data openess	Partially open data	Partially open data
	Source code openess	Open	Open

Model linking

For each modelled scenario, we run GCAM-Europe in 5-year intervals from 2015 to 2050, generating outputs such as country-level electricity demand, required emission reductions, and renewable electricity shares consistent with EU or national targets. These results are used as constraints for the EXPANSE model, which we use to analyse the EU electricity system in 2035, specifically generation, storage, and transmission capacity needs, associated investments, and electricity prices. Carbon prices are taken from GCAM-Europe and used as fuel tax. EXPANSE does not include negative emission technologies, contrary to GCAM-Europe; thus, meeting EU targets would require the electricity system configuration described by EXPANSE, plus the level of CCS provided by GCAM-Europe. Inputs, outputs, and linkages between GCAM-Europe and EXPANSE are shown in Figure 5-3.

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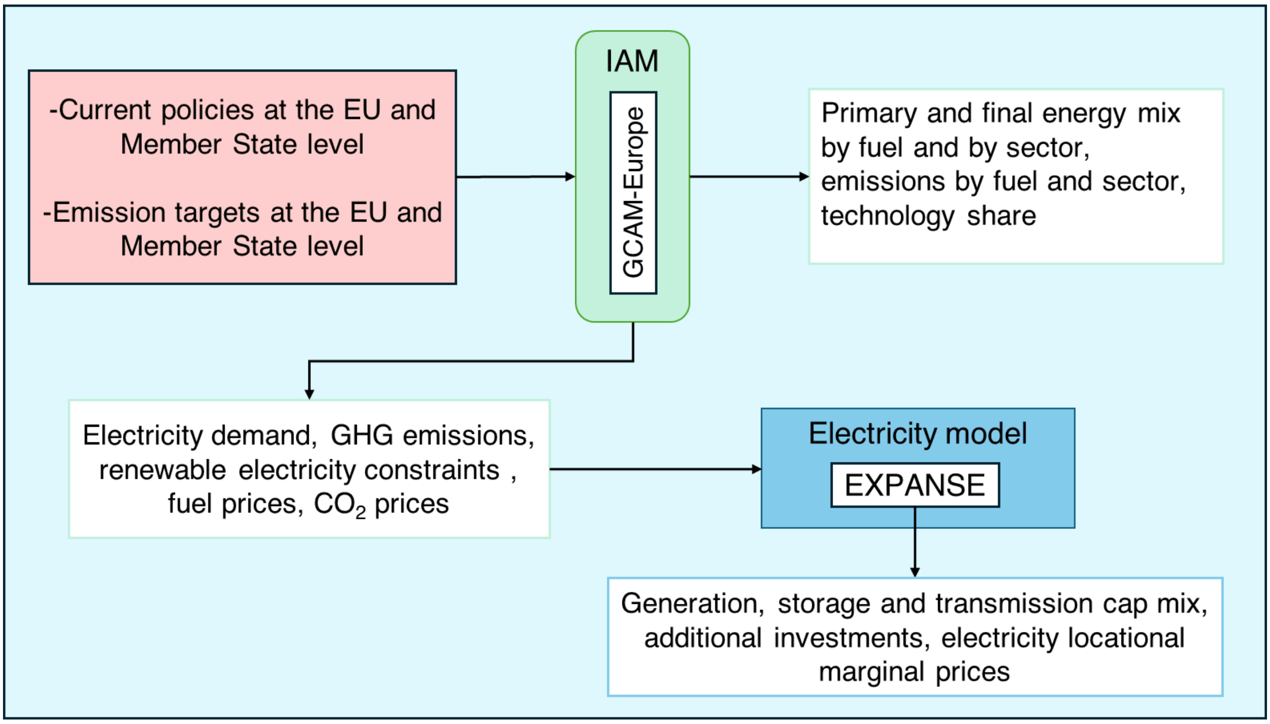

Figure 5-3: Inputs, outputs, and model connections

5.4 Results

Emissions

Current EU and national climate policies, represented by the *NECP_POLICY* and *FF55_POLICY* scenarios, are projected to significantly reduce CO_2 emissions by 2030 (***Figure 5-1***). GCAM-Europe results show that fossil CO_2 emissions across the EU-27 decline steeply from 2015 to 2030 in all policy and cost-optimal pathways, with the electricity sector delivering the largest share of reductions, followed by significant decreases in buildings and transport. All four scenarios achieve emissions reductions of more than 1 Gt CO_2 by 2030 compared to 2015 levels and reach the Fit for 55 emission target of 55% reduction compared to 1990, with only minor differences between the policy-driven and free variants. The POLICY scenarios reflect additional constraints, such as minimum renewable shares, efficiency measures, and carbon pricing, which lead to slightly different sectoral contributions compared to the FREE scenarios, mainly higher emission cuts in electricity rather than transport. By 2050, emissions in all scenarios are reduced by ~94% compared to 1990; the electricity sector approaches carbon neutrality, having the highest share of emission cuts from 2030 onwards in cost-optimal scenarios. Industrial emissions in the EU are projected to fall by over 130% in 2050, requiring deep transformation of industrial processes and widespread deployment of carbon capture and storage (CCS). The right panel highlights how reductions are shared across Member States: Germany, France, and Italy contribute the largest absolute declines, while Spain, Poland, and other mid-sized emitters also play major roles. Overall, the results illustrate that the EU's Fit-for-55 and updated NECP targets are broadly consistent with cost-optimal decarbonisation, while revealing regional and sectoral diversity in how these reductions are achieved.

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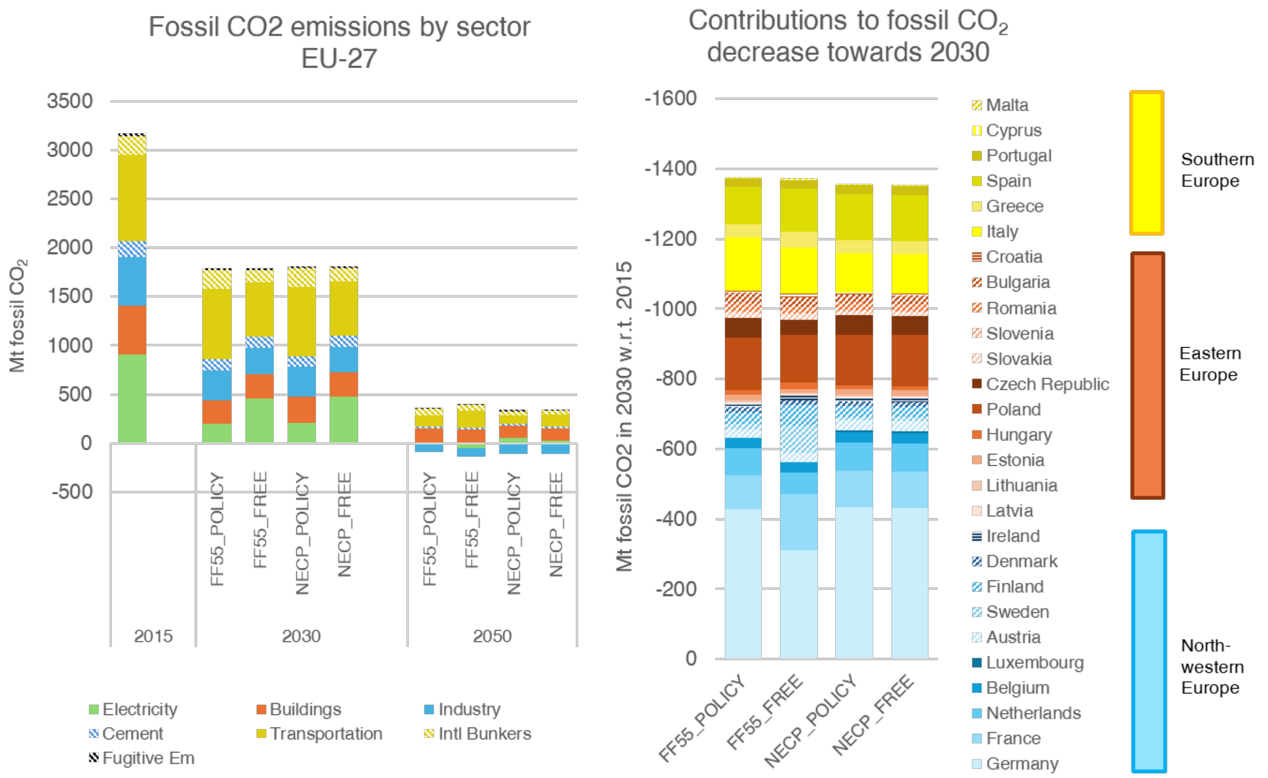

Figure 5- 1: CO_2 emissions by period, region, and scenario ($MTCO_2$). The left panel shows the emissions at the EU level by sector and scenario, while the right panel shows emissions EU Member States by scenario

Energy Efficiency

Figure 5-5 highlights how climate policy scenarios affect the composition and volume of final energy use across the EU and its Member States. At the EU level, all scenarios achieve a notable reduction in final energy use by 2030 compared to 2015, primarily through decreases in fossil fuel consumption, especially liquids and gas, while electricity becomes increasingly important, and hydrogen begins to emerge by 2050. The more prescriptive energy efficiency scenario (FF55_POLICY) leads to the lowest final energy use by 2030, reflecting the stringent 11.7% EU-wide efficiency target. This is confirmed in the right-hand panel, where Germany, France, and Italy are the largest contributors to energy savings, followed by Spain and the Netherlands. Interestingly, the cost-optimal (FREE) variants of both FF5 and NECP show slightly higher energy use, indicating that future policies are pushing the system beyond what is purely cost-optimal, especially in more ambitious countries. These results suggest that existing EU and national policy frameworks are effective in driving efficiency improvements, and that large Member States play a key role in meeting the EU's aggregate targets.

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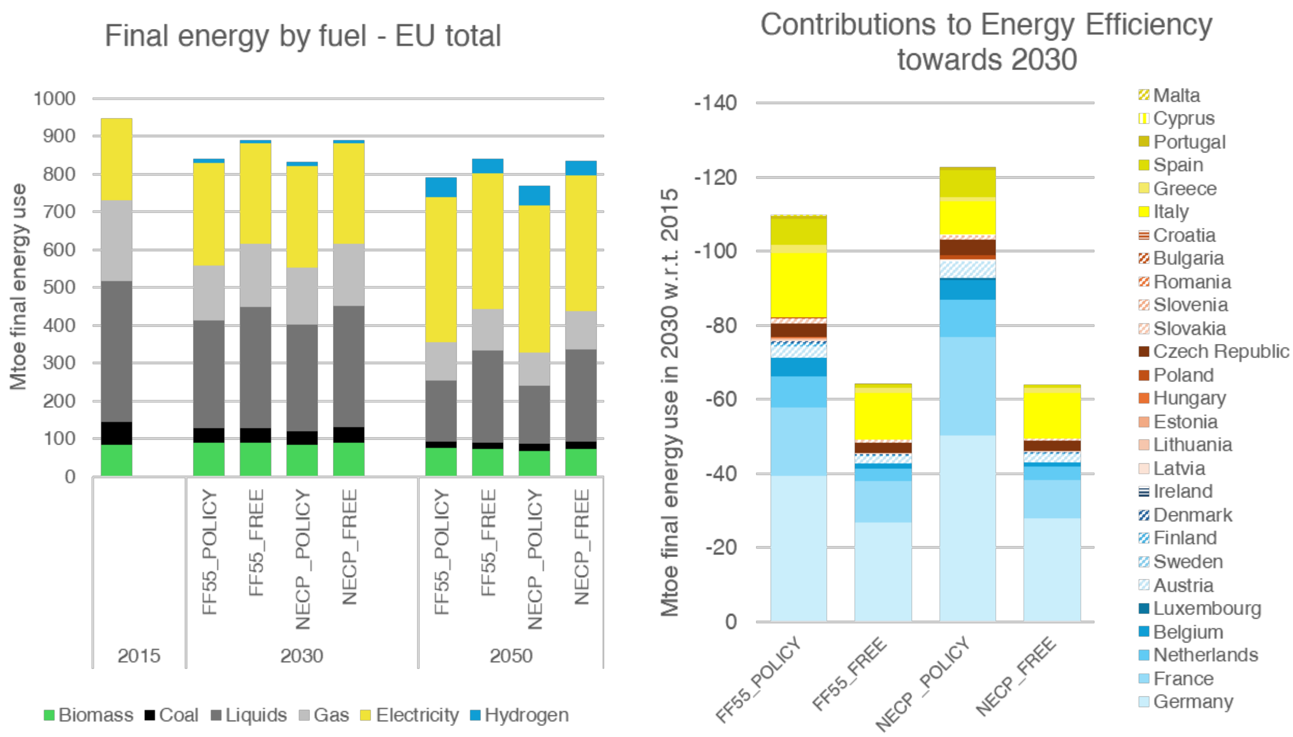

Figure 5-4: Final energy by fuel at the EU level in 2015, 2030, and 2050 (left) and final energy use by Member State in 2030 for all scenarios

Renewable Energy

The growth of renewable energy across the EU and Member States highlights the strong expansion under all scenarios. At the EU level, renewable final energy use nearly doubles from 2015 to 2030 in both EU_FF55 and NECP_POLICY scenarios, with renewable electricity and biofuels driving the bulk of this increase. By 2030, the renewable share of final energy use almost reaches the 42.5% target in the FF55_POLICY scenario and approaches similar levels in the other scenario variants, particularly under the cost-optimal FF55_FREE and NECP_FREE pathways (nearly 40%). This indicates that EU-wide renewables targets are broadly in line with least-cost trajectories. The right-hand panel shows that Germany, France, and Italy contribute most to the EU-wide increase in renewables, followed by Spain, the Netherlands, and Sweden. Southern and Eastern Member States, including Greece, Portugal, Romania, and Poland, also demonstrate notable contributions. These results confirm that EU and national policies effectively stimulate renewable deployment, while allowing for flexibility in how Member States contribute based on their domestic potential and system cost-efficiency.

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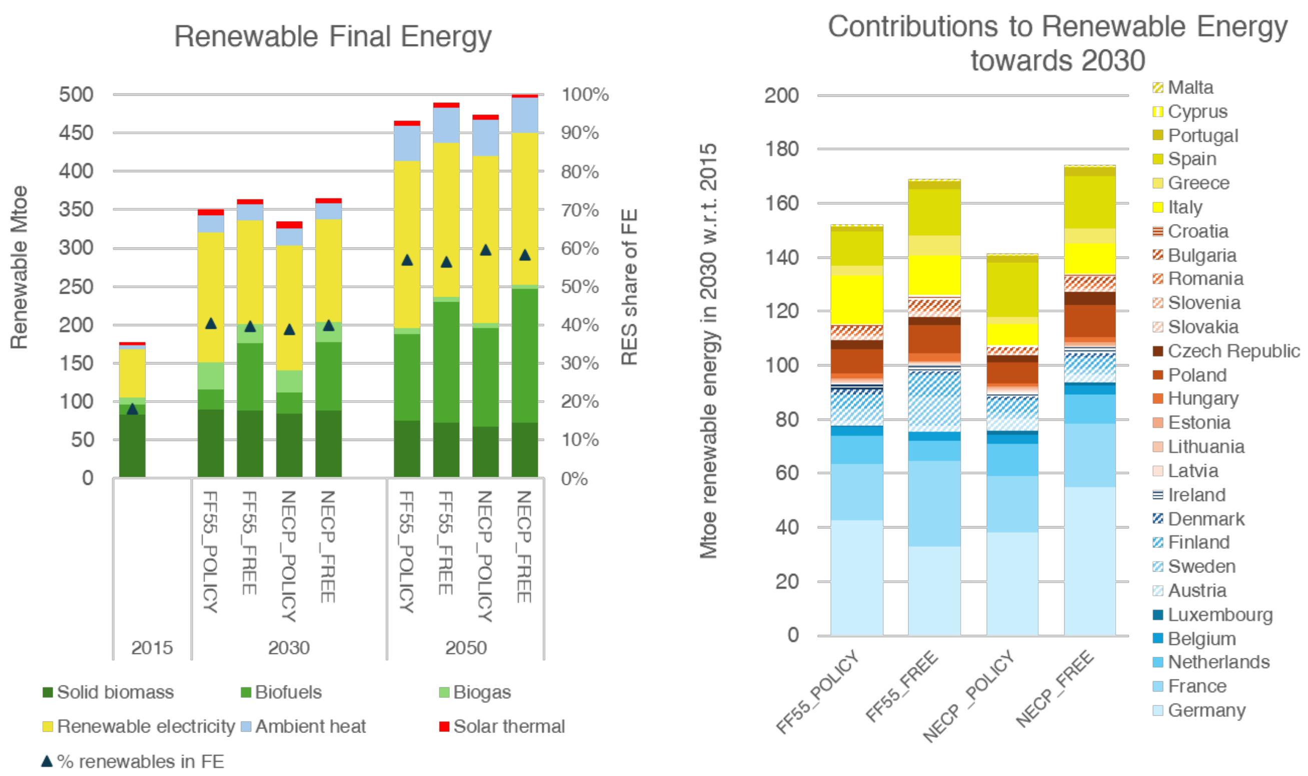

Figure 5-5: Renewable energy use in Mtoe and as a share of final energy in 2015, 2030, and 2050 at the EU level (left) and renewable energy use in 2030 with regards to 2015 in all Member States (right) for all scenarios

New power system capacities

The spatial distribution and technological composition of newly installed electricity generation, storage, and transmission capacities across Europe in 2035, compared to 2018 levels, under different climate policy scenarios is shown in Figure 5-7. Across all panels, wind power (onshore and offshore) and solar PV (both rooftop and open-field) dominate the expansion, reflecting their key role in the decarbonisation of the European power system. Notably, large additions are concentrated in regions with abundant renewable potential, such as offshore wind power in the North Sea, solar in southern Europe, and onshore wind across central and eastern Europe. The maps also highlight the deployment of battery storage and hydrogen production technologies, particularly in western and northern Member States. New transmission infrastructure concentrated on the Italy, France, Germany, and UK axis, connects high-renewable areas with demand centers, signaling the need for grid reinforcement to enable flexibility and integration of intermittent sources. These results underscore the scale and geographical specificity of investment needs in a decarbonised system, while also illustrating that reaching EU climate targets will require coordinated infrastructure planning alongside renewable deployment.

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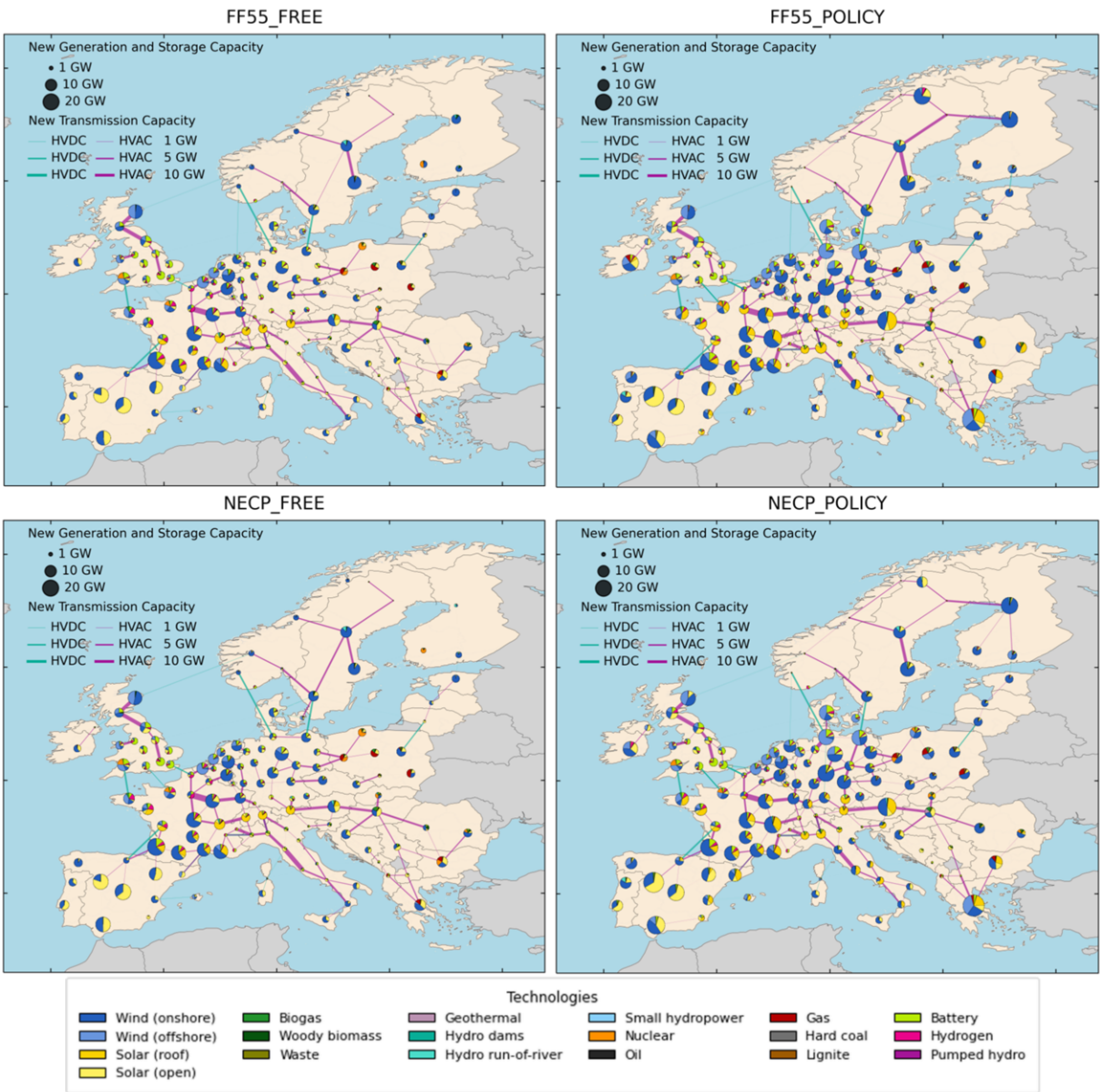

Figure 5-6: New installed capacities in 2035 as a difference from 2018 (results from EXPANSE)

Power system investments

FF55_POLICY shows the highest investment need because it imposes an ambitious EU-wide carbon price and renewable electricity targets, enabling optimal allocation of resources across borders but also requiring significant system transformation, particularly in generation and grid reinforcement (Figure 5-8). NECP_POLICY is slightly less costly but still more expensive than the FREE scenarios, as it layers national-level RES targets and carbon pricing, which can be more restrictive and less cost-effective system-wide.

In contrast, the FREE scenarios only replicate the emissions outcomes of their POLICY counterparts but allow the model to meet them in a cost-optimal way without imposing efficiency or renewable constraints. This leads to lower investments, especially in transmission and storage, as the model avoids rigid national RES obligations and can concentrate generation where it is cheapest. Thus, in EXPANSE, higher investments in FF55_POLICY and NECP_POLICY signal the financial and infrastructural cost of aligning electricity system transformation with both decarbonisation goals and detailed policy constraints, including equity and sovereignty considerations embedded in Member State-specific targets.

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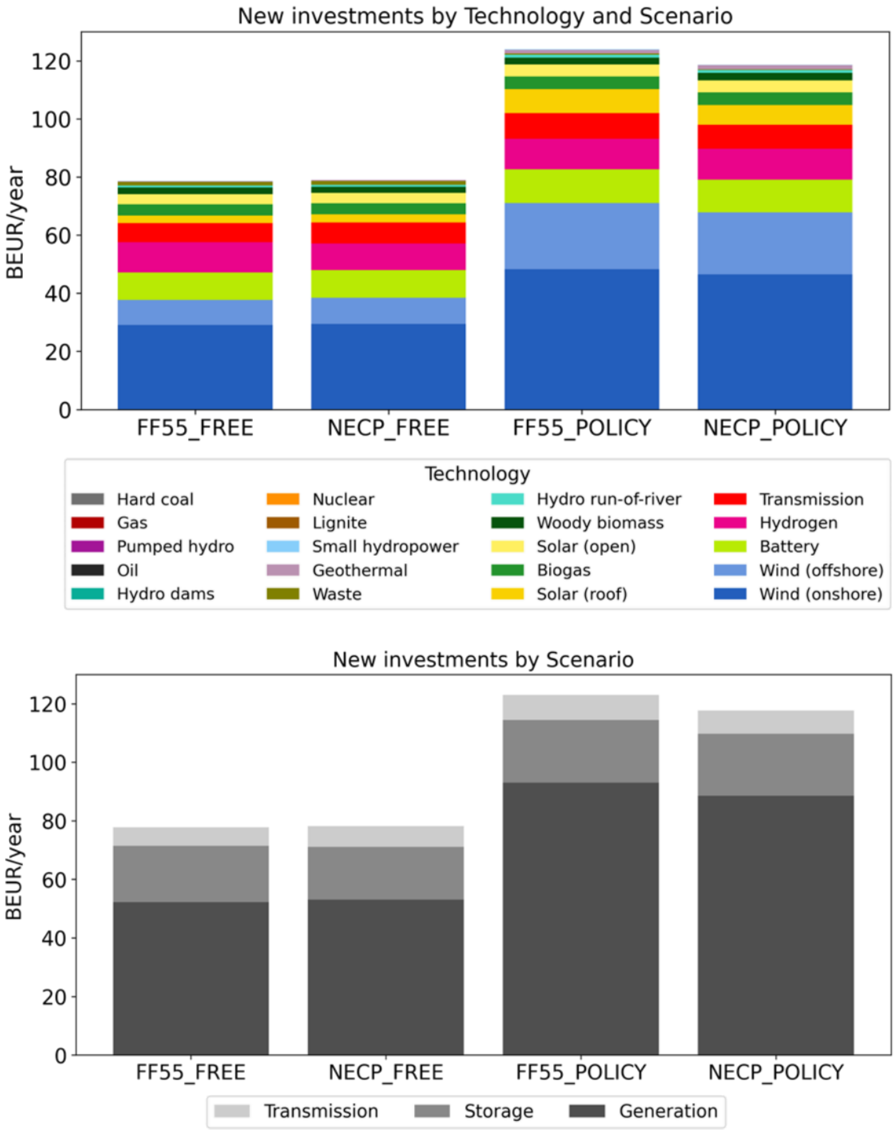

Figure 5-7: New investments in 2035 by technology (top) and by generation, transmission or storage (bottom) in all scenarios (results from EXPANSE)

The higher investment levels observed in the FF55_POLICY scenario, followed by NECP_POLICY, reflect the compounded effect of policy stringency and system-wide constraints imposed in these scenarios. Under the POLICY variants, country-specific electricity demand is lower due to efficiency measures from GCAM-Europe, but these gains are offset by additional constraints, namely, minimum RES shares in electricity and explicit carbon pricing, both of which drive up capital-intensive deployment of low-carbon technologies, storage, and transmission infrastructure.

Electricity dispatch

EXPANSE optimises electricity dispatch as part of the system cost minimisation over a full year, 2035, at six-hour timesteps. Six-hour timesteps are selected to ensure the computational tractability of the optimisation problem, while accounting for the temporal variability of renewable electricity generation and storage requirements, as shown by a previous sensitivity analysis (Schyska et al., 2021). EXPANSE determines which generation technologies are used in each hour to meet electricity demand, while also accounting for the operation of storage systems (batteries, hydrogen, pumped hydro), and transmission grid constraints. This high-resolution modelling captures the temporal variability of renewable energy, demand patterns, and the role of flexibility technologies in maintaining system balance.

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Figure 5-9 illustrates Europe-wide electricity dispatch across the four scenarios in 2035, showcasing how different technologies contribute to meeting demand throughout the year. The consistent orange band across all panels reflects a high and stable contribution from nuclear power, which operates as baseload due to its low marginal cost and limited flexibility. Wind (blue shades) and solar (yellow tones) dominate the variable renewable contribution, with wind providing a more constant but fluctuating supply and solar peaking during summer months.

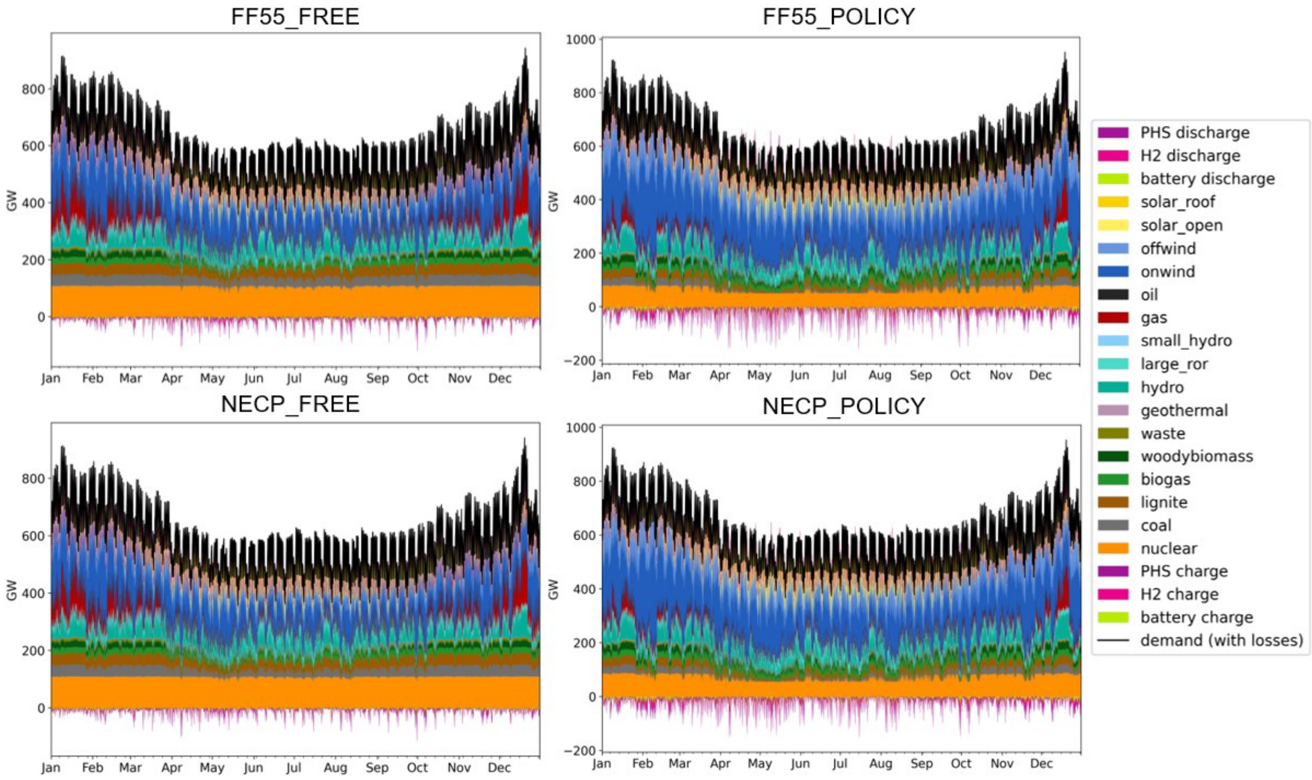

Figure 5-8: Electricity dispatch in 2035 for the entire Europe (results from EXPANSE)

The POLICY scenarios (top-right and bottom-right) show more pronounced storage activity, indicating a greater reliance on flexibility to integrate higher shares of intermittent renewables while meeting stricter emissions and renewable energy targets. To this purpose, nuclear power in the summer months is ramped down to accommodate increased solar generation. This is contrasted with the FREE scenarios (top-left and bottom-left), where the system leans more on dispatchable generation and slightly less on storage, consistent with cost-optimised, constraint-light planning. The use of fossil fuels varies significantly between the scenarios, reflecting the impact of policy constraints on generation choices. In the FREE scenarios (top-left and bottom-left), fossil fuels, particularly gas (red) and to a lesser extent lignite and coal (brown and grey), contribute more visibly throughout the year. Oil is almost not used in any of the scenarios due to the high fuel cost. These scenarios are designed to achieve the same CO_2 reductions as the POLICY scenarios but without mandates on renewable shares or energy efficiency, allowing the system to rely more on cost-effective but carbon-intensive dispatchable sources during periods of low renewable output or high demand.

Average LMP price

The yearly average wholesale locational marginal prices (LMPs) of electricity, demand-weighted, can be seen in Figure 5-10. These prices reflect the true cost of supplying the next megawatt-hour of electricity at a specific location. In the EXPANSE model, Locational Marginal Prices (LMPs) reflect the cost of delivering one additional unit of electricity to each of the 128 modelled transmission grid nodes, accounting for generation, congestion, and losses. Figure 5-10 shows the spatial distribution of average LMPs across Europe under the four scenarios for 2035. The POLICY scenarios (top-right: FF55_POLICY and bottom-right: NECP_POLICY) show elevated LMPs,

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particularly across Central, Eastern, and Southern Europe. This is driven by high CO_2 prices as they rise the marginal cost of flexible generation, which, even if it is less needed than in the FREE scenarios, still sets the locational marginal price in many hours of the year due to the merit-order effect. In contrast, the FREE scenarios (top-left and bottom-left) exhibit lower and more uniform prices, especially in Northern and Eastern Europe. The merit-order effect plays a key role in the spatial distribution of prices across Europe: where renewables dominate the mix with flexibility from firm renewables, storage, and grid interconnections, marginal costs are low, whereas marginal costs increase where CO_2-intensive resources are needed to balance the system. These results highlight the geographic disparities in electricity affordability and the value of flexibility and interconnection in mitigating high LMPs in a decarbonised power system.

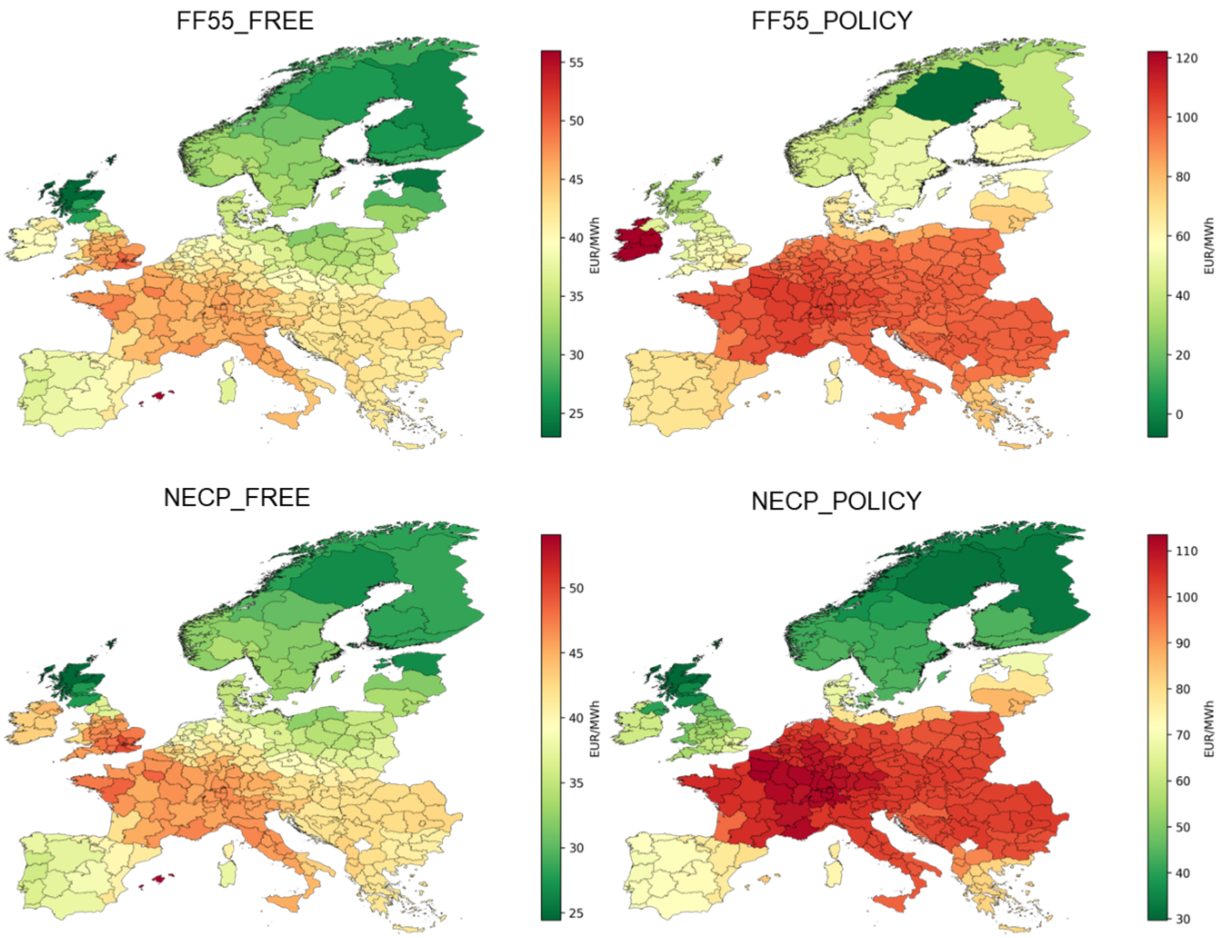

Figure 5-9: Average wholesale locational marginal price (LMP) (results from EXPANSE)

5.5 Conclusions

This study demonstrates that both EU-wide and Member State-level climate policy targets, as defined in the Fit-for-55 package and the updated NECPs, can lead to deep reductions in CO_2 emissions across the EU power sector by 2030—closely aligning with cost-optimal decarbonisation pathways. Emissions outcomes under both NECP_POLICY and FF55_POLICY scenarios converge with their cost-optimal counterparts (NECP_FREE and FF55_FREE), confirming that current policies are largely in line with efficient mitigation trajectories. This is particularly evident in countries like Germany, France, and Italy, where emissions reductions under NECPs are also consistent with WAM projections, validating the credibility of the modelling framework. Moreover, the scenarios show that the EU's 2030 targets for renewable energy and emissions reduction are broadly achievable across Member States, though a gap remains in reaching the final energy efficiency objective. Large Member

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States drive most of the energy efficiency and renewable deployment gains, underscoring their importance in EU-level target delivery. However, achieving such targets will require ongoing implementation of structured and enforceable policy instruments, especially in countries where the ambition gap is still evident.

By coupling GCAM-Europe with the spatially and temporally detailed EXPANSE model, this study reveals the power system-level implications of reaching these targets. Investment needs are highest in the FF55_POLICY scenario due to more stringent EU-wide constraints on emissions and renewables, followed by the more nationally fragmented NECP_POLICY, while both FREE scenarios show lower investment costs due to their flexibility in technology deployment. The required investments are driven not only by renewable generation but also by the associated infrastructure, i.e., grid expansion, storage, and hydrogen capacity, needed to integrate variable resources and ensure system reliability. Wind and solar dominate new generation capacity, with large regional variation depending on resource potential. These findings underscore the need for coordinated infrastructure planning to enable a cost-effective and geographically balanced transition, as well as the added cost and complexity of meeting policy-driven targets when compared to purely cost-optimal pathways, an important consideration for EU institutions aiming to balance ambition, equity, and feasibility in their long-term climate strategies.

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Annex A1: Regional electricity sector employment and skills under different European policy scenarios

EXPANSE model

Unless otherwise stated, the assumptions of this model are the same as those listed in the Supplementary Information of (Sasse and Trutnevyte, 2023). The assumptions for the minimum load values of thermal electricity generators in EXPANSE are listed along with sources in the Supplementary Material of (Rubino et al., 2025).

Employment factors

Table A1. Regional and fuel employment factors for each technology

Technology	Regional Employment Factor (construction, operation & maintenance, decommissioning) (Job/MW) (Ram et al., 2020; Sasse and Trutnevyte, 2023)	Fuel Employment Factors (Job/MWh of fuel use) (Ram et al., 2020; Sasse and Trutnevyte, 2023)
Wind – onshore	0.53	
Wind – offshore	1.07	
Solar PV – open-field	1.25	
Solar PV - rooftop	1.27	
Hydropower - large dams	0.36	
Hydropower - run of river	0.42	
Hydropower – small	0.36	
Nuclear	1.75	
Gas	0.19	0.09
Hard Coal	0.46	0.34
Lignite	0.46	0.38
Geothermal	0.63	
Biogas	2.22	0.26
Woody Biomass	2.07	0.29
Waste	2.07	0.30
Oil	0.18	0.16
Pumped hydro storage	1.15	
Battery	0.35	
Hydrogen Storage	0.63	
Transmission	180 (Jobs/TWkm)	

Biomass calculations

Woody biomass extraction employment is assumed to be in the same NUTS 2 region as the woody biomass electricity generation due to short transport distances in the sector (Schnorf et al., 2021). The UK, Denmark and Italy are exceptions to this method since a large fraction of the wood pellet consumption in these countries are from imports (Sikkema et al., 2021). Trade data from these countries (UK (Piller, 2024), Italy (Bettini, 2017), Denmark (Tony Hansen, 2023)) reveal the countries from which wood pellets are imported and the corresponding quantities. The extraction jobs are allocated to the source countries proportional to the import quantities, while

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the jobs are allocated evenly across the regions in which woody biomass electricity is generated in these countries.

Peat calculations

Peat regions are accounted for in the model under lignite and are assumed to have the highest risk rating value (Alves Dias et al., 2018). The data for the peat regions are obtained from a European Commission report (Alves Dias et al., 2021).

Additional results

Figure A1. Maps with net changes in extraction and non-extraction jobs from generation and storage technologies in the case of 'Fit for 55' scenario.

Figure A2. Maps with net changes in extraction jobs and non-extraction jobs from generation and storage technologies in the case of the EU-wide coal phaseout scenario.

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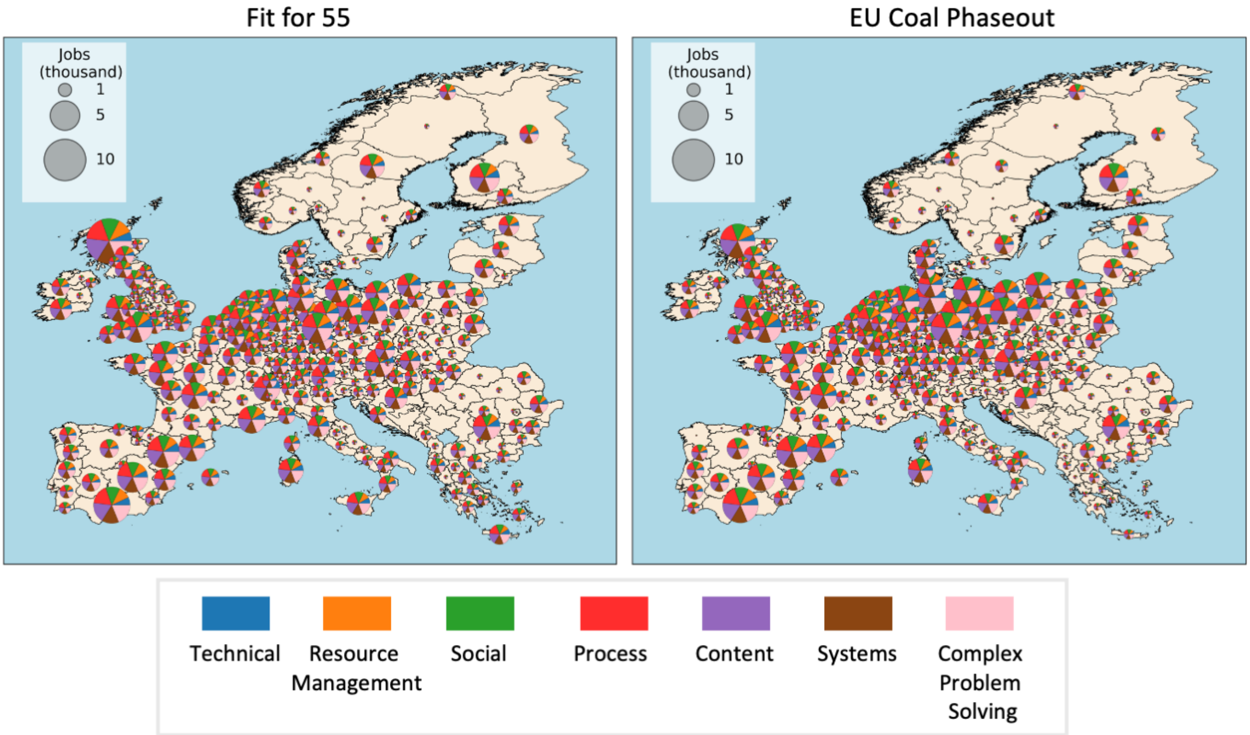

Figure A3. Regional skill needs of employment gains under both policy scenarios.

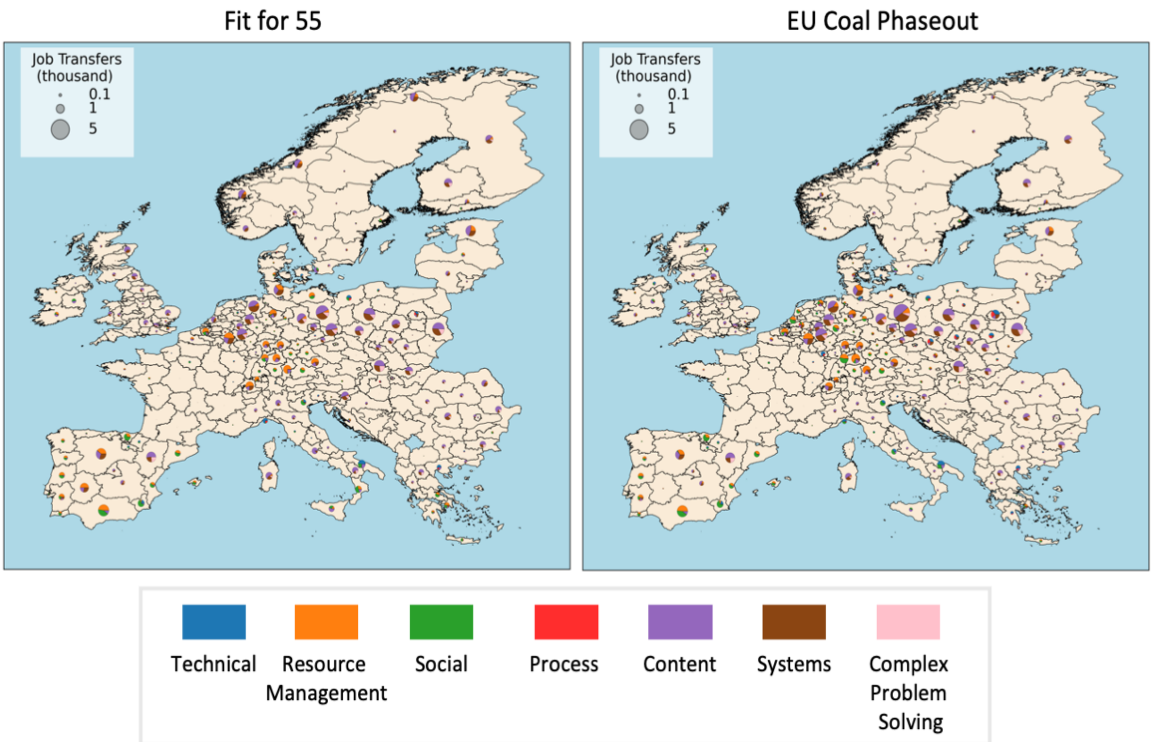

Figure A4. Regional re-skilling needs of potential employment transfers under both policy scenarios.

Skills Data

Table A2. Skills and their corresponding skill groups (O*NET and U.S. Department of Labor, Employment and Training Administration, 2024).

Skill Group	Individual Skills
Content	Reading Comprehension, Active Listening, Writing, Speaking, Mathematics, Science
Process	Critical Thinking, Active Learning, Learning Strategies, Monitoring
Social	Social Perceptiveness, Coordination, Persuasion, Negotiation, Instructing, Service Orientation
Technical	Operations Analysis, Technology Design, Equipment Selection, Installation, Programming, Operations Monitoring, Operations and Control, Equipment Maintenance, Troubleshooting, Repairing, Quality Control Analysis
Systems	Judgement and Decision Making, Systems Analysis, Systems Evaluation
Resource Management	Time Management, Management of Financial Resources, Management of Material Resources, Management of Personnel Resources
Complex Problem Solving	Complex Problem Solving

Table A3. A list of assumed jobs per technology that was used to create the skill data per technology. The job titles are obtained from O*NET (O*NET and U.S. Department of Labor, Employment and Training Administration, 2024). Each job is associated with a set of skills from Table A2. The skills have an importance and level value which are combined to create a score (Greenspon and Raimi, 2024; Lim et al., 2023; Soydan et al., 2024).

Technology	Construction	Operation and Maintenance	Decommissioning	Extraction
Coal and Lignite	Construction Laborers; Helpers--Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Civil Engineers	Power Plant Operators; Helpers--Installation, Maintenance, and Repair Workers; Electrical Engineers; Civil Engineers	Brownfield Redevelopment Specialists and Site Managers; Riggers; Construction Laborers	Continuous Mining Machine Operators; Roof Bolters, Mining; Loading and Moving Machine Operators, Underground Mining; Helpers--Extraction Workers; Laborers and Freight, Stock, and Material Movers, Hand; Underground Mining Machine Operators, All Other; First-Line Supervisors of Construction

				Trades and Extraction Workers
Oil and Gas	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Chemical Engineers; Civil Engineers	Power Plant Operators; Gas Plant Operators; Helpers--Installation, Maintenance, and Repair Workers; Electrical Engineers; Chemical Engineers; Civil Engineers	Brownfield Redevelopment Specialists and Site Managers; Riggers; Construction Laborers; Riggers	Petroleum Engineers; Wellhead Pumpers; Helpers--Extraction Workers; Rotary Drill Operators, Oil and Gas; First-Line Supervisors of Construction Trades and Extraction Workers; Derrick Operators, Oil and Gas
Geothermal	Construction Laborers; Helpers--Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Power Plant Operators; Geothermal Technicians; Geothermal Production Managers; Helpers--Installation, Maintenance, and Repair Workers; Electrical Engineers; Civil Engineers	Riggers; Construction Laborers	
Hydropower	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Power Plant Operators; Hydroelectric Plant Technicians; Helpers--Installation, Maintenance, and Repair Workers; Electrical Engineers; Civil Engineers; Hydroelectric Production Managers	Riggers; Construction Laborers	

Large Run of River	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Power Plant Operators; Hydroelectric Plant Technicians; Helpers--Installation, Maintenance, and Repair Workers; Electrical Engineers; Civil Engineers; Hydroelectric Production Managers	Riggers; Construction Laborers	
HVDC	Construction Laborers; Helpers--Installation, Maintenance, and Repair Workers; Electrical Power-Line Installers and Repairers; Construction and Building Inspectors; Electrical Engineers; Electrical and Electronic Equipment Assemblers	Electrical Power-Line Installers and Repairers; Power Distributors and Dispatchers; Electrical Engineers; Electrical and Electronic Engineering Technologists and Technicians	Telecommunications Line Installers and Repairers; Construction Laborers; Riggers	
HVAC	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Electrical Power-Line Installers and Repairers; Construction and Building Inspectors; Electrical Engineers; Electrical and Electronic	Electrical Power-Line Installers and Repairers; Power Distributors and Dispatchers; Electrical Engineers; Electrical and Electronic Engineering Technologists and Technicians	Telecommunications Line Installers and Repairers; Construction Laborers; Riggers	

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	Equipment Assemblers			
Nuclear	Construction Laborers; Helpers--Installation, Maintenance, and Repair Workers; Nuclear Engineers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Power Plant Operators; Nuclear Power Reactor Operators; Nuclear Technicians; Nuclear Monitoring Technicians; Nuclear Engineers	Hazardous Materials Removal Workers; Construction Laborers; Riggers	
Onshore Wind	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers; Wind Energy Development Managers	Wind Energy Operations Managers; Wind Turbine Service Technicians; Electrical Engineers; Civil Engineers; Wind Energy Engineers; Wind Energy Development Managers	Construction Laborers; Riggers	
Offshore Wind	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers; Wind Energy Development Managers	Wind Energy Operations Managers; Wind Turbine Service Technicians; Electrical Engineers; Civil Engineers; Wind Energy Engineers; Wind Energy Development Managers	Construction Laborers; Riggers	

Small Hydropower	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Power Plant Operators; Hydroelectric Plant Technicians; Helpers--Installation, Maintenance, and Repair Workers; Electrical Engineers; Civil Engineers; Hydroelectric Production Managers	Construction Laborers; Riggers	
Solar PV – open-field	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Solar Photovoltaic Installers; Solar Energy Installation Managers; Solar Thermal Installers and Technicians; Electrical and Electronics Installers and Repairers, Transportation Equipment; Electrical and Electronic Equipment Assemblers; Civil Engineers	Power Plant Operators; Helpers--Installation, Maintenance, and Repair Workers; Electrical Engineers; Solar Energy Systems Engineers; Electrical and Electronic Engineering Technologists and Technicians; Civil Engineers	Construction Laborers; Riggers	
Solar PV – Rooftop	Construction Laborers; Helpers--Installation, Maintenance, and Repair Workers;	Power Plant Operators; Helpers--Installation, Maintenance, and	Construction Laborers	

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	Construction and Building Inspectors; Electrical Engineers; Solar Photovoltaic Installers; Solar Energy Installation Managers; Solar Thermal Installers and Technicians; Electrical and Electronics Installers and Repairers, Transportation Equipment; Electrical and Electronic Equipment Assemblers	Repair Workers; Electrical Engineers; Solar Energy Systems Engineers; Electrical and Electronic Engineering Technologists and Technicians		
Waste	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Biomass Power Plant Managers; Power Plant Operators; Electrical Engineers	Hazardous Materials Removal Workers; Construction Laborers; Riggers	Construction Laborers; Laborers and Freight, Stock, and Material Movers, Hand; First-Line Supervisors of Construction Trades and Extraction Workers
Woody Biomass	Construction Laborers; Helpers--Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Biomass Power Plant Managers; Power Plant Operators; Electrical Engineers	Brownfield Redevelopment Specialists and Site Managers; Construction Laborers; Riggers	Helpers--Extraction Workers; Laborers and Freight, Stock, and Material Movers, Hand; Log Graders and Scalers; First-Line Supervisors of Construction Trades and Extraction Workers

Hydrogen	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Chemical Engineers; Civil Engineers	Power Plant Operators; Gas Plant Operators; Chemical Equipment Operators and Tenders; Electrical Engineers; Chemical Engineers	Brownfield Redevelopment Specialists and Site Managers; Construction Laborers; Riggers	
PHS	Construction Laborers; Helpers--Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Civil Engineers	Power Plant Operators; Helpers--Installation, Maintenance, and Repair Workers; Hydroelectric Plant Technicians; Electrical Engineers; Civil Engineers	Construction Laborers; Riggers	
Battery	Construction Laborers; Electrical and Electronic Equipment Assemblers; Helpers--Installation, Maintenance, and Repair Workers; Construction and Building Inspectors; Electrical Engineers; Electrical and Electronic Equipment Assemblers; Civil Engineers	Electrical Engineers; Electrical and Electronic Engineering Technologists and Technicians; Electrical and Electronics Installers and Repairers, Transportation Equipment	Electrical and Electronics Installers and Repairers, Transportation Equipment; Construction Laborers; Riggers	

Biogas	Construction Laborers; Helpers-Installation, Maintenance, and Repair Workers; Riggers; Construction and Building Inspectors; Electrical Engineers; Chemical Engineers; Civil Engineers	Power Plant Operators; Gas Plant Operators; Chemical Equipment Operators and Tenders; Electrical Engineers; Chemical Engineers	Hazardous Materials Removal Workers; Brownfield Redevelopment Specialists and Site Managers; Construction Laborers; Riggers	Water and Wastewater Treatment Plant and System Operators; Chemical Engineers; Chemical Technicians

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Annex A2: Comparing cost-optimal to policy-driven scenarios for a decarbonised European energy system

EXPANSE

This section is a summary of the Supplementary Information of (Sasse & Trutnevyte, 2023a) that is relevant to this study.

Input data and assumptions

We compile data on existing electricity infrastructure across Europe, encompassing generation technologies (Felice & Kavvadias, 2020; IEA, 2019; Open Power System Data, 2020a; Open Power System Data, 2020b), storage systems (Felice & Kavvadias, 2020) , and transmission lines (Hörsch et al., 2018). The spatial representation of existing power generation infrastructure for biomass (including biogas, woody biomass, and waste), solar photovoltaics (both open-field and rooftop), and wind power (onshore and offshore) is refined using datasets at the global ((Dunnett et al., 2020), continental (Gotzens et al., 2019), and national (Department of Energy and Climate Change, 2020; Elia Group, 2021; Ministry for Ecological Transition, 2021; Ministry of Ecological Transition, 2019; Österreichischer Biomasse-Verband, 2019; Swiss Federal Office of Energy, 2020, 2021; Terna, 2021) levels.

Potential generation capacities for biomass, geothermal, hydropower, solar PV, and wind are sourced from existing modelling studies (European Commission, 2019; Limberger & others, 2014; Ruiz & others, 2019; Tröndle et al., 2019) . These potentials are constrained to areas suitable for renewable energy deployment, taking into account factors such as land cover and use, settlement locations, terrain slope, protected areas, and water depth, alongside the spatial requirements of different technologies. To reflect realistic deployment levels by 2035, we impose upper bounds on solar PV and wind generation capacities, based on country-specific limits defined by European Transmission System Operators (ENTSO-E, 2020). Additionally, woody biomass capacity is capped at 20% of its technical potential (Ruiz & others, 2019). Geothermal potential, drawn from a European modelling study (Limberger & others, 2014), is limited to regions where the levelised cost of electricity (LCOE) is below €150/MWh, with an assumption that no more than 1% of this economic potential will be utilised by 2035. These constraints align with maximum capacity estimates reported by European TSOs (ENTSO-E, 2020).

EXPANSE uses capacity factor time series to determine the maximum electricity output per unit of installed capacity in each time step. These time series for solar PV, wind, and hydropower are derived from recent modeling work (Tröndle et al., 2020). For solar and wind, bias-corrected data from Renewables Ninja (Pfenninger & Staffell, 2016) is used. Hydropower capacity factors are estimated in two stages: first, using ERA5 runoff data (Dee et al., 2011) and hydrological basin boundaries (Lehner & Grill, 2013) to calculate water inflows; and second, applying bias-correction factors based on national generation statistics from IRENA (IRENA, 2018).

We assume that no new fossil fuel (hard coal, lignite, gas, oil) or nuclear power plants are built, except for those currently under development as documented in EU National Energy and Climate Plans (European Commission, 2025b). Nuclear plants in Belgium and Germany are assumed to be decommissioned by 2035.

Storage capacity from large hydropower and pumped hydro systems (Felice & Kavvadias, 2020; Geth et al., 2015) is assumed to remain unchanged through 2035. For battery and hydrogen storage, a greenfield approach is used, with no initial capacity assumed. EXPANSE can invest in these technologies where necessary. Hydrogen is modeled as stationary storage (like batteries) and is assumed non-transportable between or within countries.

Transmission line capacities are sourced from the PyPSA-Eur dataset (Hörsch et al., 2018), which includes both existing infrastructure and lines currently in at least the permitting phase. EXPANSE allows for the expansion—but not reduction—of existing line capacities, up to twice their current levels. To account for system stability, hourly power flow on each line is limited to 50% of its nominal capacity. If flows reach this threshold, EXPANSE invests in additional transmission capacity.

To project electricity demand at the grid-node level for 2035, we begin with country-level hourly demand profiles for 2030, derived from TSO projections (ENTSO-E, 2020). These profiles capture expected changes in electricity use across residential, tertiary, and industrial sectors, including electrification of transport and heating. We then spatially disaggregate these national demand estimates to the 128-grid-node system using spatial weights based on population and GDP distribution from the PyPSA model (Hörsch et al., 2018).

Mathematical formulation of the EXPANSE model

Nomenclature

f_{cost}	total system costs (in EUR year^{-1});
C	annualised investment costs (in EUR MW^{-1} year^{-1});
O	marginal costs (in EUR MWh^{-1});
G	electricity generation capacity (in MW);
g	electricity generation operation (in MWh);
H	storage capacity (in MW);
d	maximum hours per discharge (in hours);
$\eta^{\text{discharge}}$	efficiency of discharging storage units;
F	transmission capacity (in MW);
f	transmission flow (in MWh);
r	NUTS-2 region label;
n	transmission grid node label;
l	transmission line label;
c	technology type label;
t	time step label;
w	constant weight (equal to six when modeling six-hour time steps);

Objective function of cost minimisation mode

The basic version of the EXPANSE model is a cost optimisation model, which minimises total system costs f_{cost} across all NUTS regions r, transmission grid nodes n, transmission lines l, technology types c, and time steps t.

$$f_{cost} = \sum_{r,c} C_{r,c}\, G_{r,c} + \sum_{n,c} C_{n,c}\, H_{n,c} + \sum_{l} C_l F_l + \sum_{t} w_t \left[\sum_{r,c} O_{r,c,t}\, g_{r,c,t} + \sum_{n,c} O_{n,c,t}\, h_{n,c,t}^{discharge} + \sum_{l} O_{l,t} \left| f_{l,t} \right| \right] \quad [1]$$

Total system costs in EXPANSE comprise both annualised investment costs C (in EUR MW^{-1} year^{-1}) and marginal costs O (in EUR MWh^{-1}) across electricity generation, storage, and transmission infrastructure. Annualised investment costs include both annualised capital expenditures (CAPEX) and fixed operation and maintenance costs (FOM). Marginal costs encompass variable operation and maintenance costs (VOM) as well as fuel costs.

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Generation capacities *G* (in MW) and their corresponding operation levels *g* (in MWh) are spatially defined for each of the 296 NUTS regions rrr. Storage capacities *H* (in MW), along with charging and discharging operations *h* (in MWh), are defined at each of the 128 transmission grid nodes *n*. Transmission infrastructure is represented by line capacities *F* (in MW) and electricity flows *f* (in MWh) for each transmission link *l* connecting the nodes.

Equation (1) uses constant weights www to annualise marginal costs, ensuring that their sum equals 8,760 (the number of hours in a year). For example, at a six-hour temporal resolution, each weight is set to 6. The equation originally includes an absolute value term for transmission operation costs associated with the flows *f*. This absolute term ensures non-negative cost contributions even when power flows in reverse direction, but it introduces non-linearity into the objective function. To maintain a linear programming formulation, this absolute value is reformulated using transformation technique for absolute values (Berkelaar et al., 2004), resulting in the equivalent set of Equations (2) through (4).

$$f_{cost} = \sum_{r,c} C_{r,c}\, G_{r,c} + \sum_{n,c} C_{n,c}\, H_{n,c} + \sum_{l} C_l F_l + \sum_{t} w_t \left[\sum_{r,c} O_{r,c,t} g_{r,c,t} + \sum_{n,c} O_{n,c,t} h_{n,c,t}^{discharge} + \sum_{l} O_{l,t}\, f_{l,t}^{+} \right] \; [2]$$

$$f_{l,t}^{+} \geq f_{l,t} \; [3]$$

$$f_{l,t}^{+} \geq -f_{l,t} \; [4]$$

NECP data

Table A 1: CO2 emissions by EU member state and EU-wide, as assumed/applied in the EU_NECP and EU_FF55 scenarios respectively

	2015	2019-2021	2025	2030
	Observed CO_2 emissions		**Target CO_2 emissions**	
Austria	66.4	66.9	56.4	46.05
Belgium	101.3	97.3	84.5	71.62
Bulgaria	48.2	42.3	35.6	28.86
Croatia	17.8	17.6	15.8	13.98
Cyprus	7.0	7.2	5.9	4.65
Czech Republic	105.8	99.5	76.1	52.67
Denmark	35.5	30.5	22.1	13.66
Estonia	15.8	11.3	11.2	11.09
Finland	44.2	40.2	36.6	32.97
France	341.3	320.0	269.7	219.54
Germany	800.8	694.3	563.3	432.30
Greece	74.9	61.6	49.9	38.27
Hungary	46.6	48.7	42.6	36.36
Ireland	38.7	37.4	32.1	26.82
Italy	361.9	339.4	333.9	328.48
Latvia	7.3	7.5	5.8	4.13

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Lithuania	13.1	13.8	10.8	7.83
Luxembourg	9.3	9.1	6.7	4.35
Malta	1.7	1.6	1.3	1.03
Netherlands	164.2	146.5	123.0	99.44
Poland	313.3	324.8	297.8	270.72
Portugal	52.4	44.1	33.6	23.15
Romania	77.8	76.9	58.4	39.90
Slovakia	34.6	34.6	32.8	31.00
Slovenia	13.6	13.5	12.3	11.00
Spain	270.7	239.8	199.8	159.76
Sweden	43.4	39.7	37.6	35.55
EU-wide	3107.7	2866.3	2455.72	2045.18

Table A 2: The share of Renewable Energy Sources (RES) in final energy use by EU member state and EU-wide, as assumed/applied in the EU_NECP and EU_FF55 scenarios respectively

	2015	2020	2025	2030
	Observed % RES in final energy		**Target % RES in final energy**	
Austria	33.5%	34.3%	43.8%	57.0%
Belgium	8.1%	11.5%	15.8%	21.7%
Bulgaria	18.3%	20.5%	26.6%	35.0%
Croatia	29.0%	29.9%	35.2%	42.5%
Cyprus	9.9%	16.4%	23.4%	33.0%
Czech Republic	15.1%	16.9%	22.4%	30.0%
Denmark	30.5%	39.4%	45.9%	55.0%
Estonia	29.0%	34.5%	47.3%	65.0%
Finland	39.2%	42.8%	50.9%	62.0%
France	14.8%	18.2%	27.9%	41.3%
Germany	14.9%	18.3%	27.8%	41.0%
Greece	15.7%	20.8%	30.1%	43.0%
Hungary	14.5%	13.4%	20.3%	30.0%
Ireland	9.1%	12.5%	25.3%	43.0%
Italy	17.5%	18.5%	21.7%	26.2%
Latvia	37.5%	41.5%	50.1%	62.0%
Lithuania	25.7%	26.8%	38.6%	55.0%

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Luxembourg	5.0%	9.4%	20.9%	37.0%
Malta	5.1%	10.4%	16.5%	25.0%
Netherlands	5.7%	11.0%	22.7%	39.0%
Poland	11.9%	15.5%	21.5%	29.8%
Portugal	30.5%	32.3%	40.1%	51.0%
Romania	24.8%	24.1%	30.0%	38.3%
Slovakia	12.9%	17.2%	20.4%	25.0%
Slovenia	22.9%	23.5%	27.5%	33.0%
Spain	16.2%	19.2%	31.3%	48.0%
Sweden	52.2%	59.2%	62.4%	67.0%
EU-wide	17.8%	21.0%	30.0%	42.5%

Table A 3: Total consumption of final energy by EU member state and EU-wide, as assumed/applied in the EU_NECP and EU_FF55 scenarios respectively, in Million Tons of Oil Equivalent (Mtoe).

	2015	**2020**	**2025**	**2030**
	Observed Mtoe final energy use		**Targeted Mtoe final energy use**	
Austria	25.9	26.6	24.7	21.6
Belgium	34.5	33.4	32.1	29.9
Bulgaria	9.5	9.9	9.5	8.8
Croatia	6.6	6.8	6.4	5.9
Cyprus	1.7	1.7	1.7	1.8
Czech Republic	23.3	24.6	23.0	20.2
Denmark	14.1	13.8	13.8	13.7
Estonia	2.8	2.8	2.8	2.9
Finland	23.7	23.8	23.4	22.8
France	145.4	134.7	124.5	106.9
Germany	207.1	200.2	183.7	155.5
Greece	16.6	14.9	15.0	15.2
Hungary	17.0	18.4	18.1	17.7
Ireland	11.3	11.3	11.0	10.5
Italy	115.3	111.4	111.3	111.0
Latvia	3.8	4.0	3.9	3.7
Lithuania	4.9	5.5	5.4	5.2

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Luxembourg	4.0	4.0	3.7	3.2
Malta	0.6	0.6	0.6	0.7
Netherlands	47.1	44.7	42.4	38.4
Poland	61.4	72.7	67.5	58.5
Portugal	16.0	15.4	15.0	14.4
Romania	21.8	24.6	23.8	22.5
Slovakia	9.6	10.1	9.5	8.5
Slovenia	4.7	4.6	4.5	4.3
Spain	80.2	77.5	75.4	71.7
Sweden	31.2	30.6	30.4	30.1
EU-wide	940.0	928.7	883.1	805.3