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Towards a green recovery in the EU: Aligning further emissions reductions with short- and long-term energy-sector employment gains

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A R T I C L E I N F O

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A B S T R A C T

To tackle the negative socioeconomic implications of the COVID-19 pandemic, the European Union (EU) introduced the Recovery and Resilience Facility, a financial instrument to help Member States recover, on the basis that minimum 37% of the recovery funds flow towards the green transition. This study contributes to the emerging modelling literature on assessing COVID-19 vis-à-vis decarbonisation efforts, with a particular focus on employment, by optimally allocating the green part of the EU recovery stimulus in selected low-carbon technologies and quantifying the trade-offs between resulting emissions reductions and employment gains in the energy sector. We couple an integrated assessment model with a multi-objective linear-programming model and an uncertainty analysis framework aiming to identify robust portfolio mixes. We find that it is possible to allocate recovery packages to align mitigation goals with both short- and long-term energy-sector employment, although over-emphasising the longer-term sustainability of new energy-sector jobs may be costlier and more vulnerable to uncertainties compared to prioritising environmental and near-term employment gains. Robust portfolios with balanced performance across objectives consistently feature small shares of offshore wind and nuclear investments, while the largest chunks are dominated by onshore wind and biofuels, two technologies with opposite impacts on near- and long-term employment gains.

1. Introduction

Since its outbreak at the end of 2019, the COVID-19 pandemic has posed significant challenges to public health, as well as to medical and research communities in their efforts to battle and study the impacts of the global health crisis (Fauci et al., 2020). With many nations facing diverse restrictions—including lockdowns—to mitigate the transmission of the virus in the different stages of the pandemic, economic activities came to a halt, with various direct and indirect socioeconomic implications (Nicola et al., 2020). In addition, the pandemic came amidst a major, ever-unfolding climate emergency. Pandemics and the climate crisis share common roots, notably the human exploitation of natural resources, with implications on biodiversity losses and the destruction of natural habitats (Tollefson, 2020). But they also share common socio-economic challenges, including the lack of awareness and acceptance of policy response, social inequalities, and employment implications (Manzanedo and Manning, 2020). This establishes a triple front of crises that humankind must face in the coming years: health, economic and environmental. These crises should be addressed co-dependently (Nikas et al., 2021b), especially as the temporary positive environmental impacts of the pandemic (e.g., reduced greenhouse gas emissions and air pollutants) are diminishing (Saadat et al., 2020; Le Quéré et al., 2020).

In this direction, the EU has mobilised financial resources to assist Member States' economic recovery as part of the NextGenerationEU programme, and specifically the Recovery and Resilience Facility (RRF). Through these instruments, the EU aims to provide additional financial support to Member States and fund recovery-oriented investments in the near term (European Commission, 2020a). To jointly address the socio-economic impacts of the health and climate crises, Member States' national recovery and resilience plans should allocate at least 37% in support of a green transition and include investments towards tackling climate change. Among the overarching objectives of the recovery and

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resilience plans is to support the sectoral integration of 40% of the 500 GW of renewable energy that is aimed to be installed by 2030, as part of the EU's path to net-zero (European Commission, 2020b), which will help the EU realise its updated pledges as part of the EU Green Deal.

The aim of the fiscal package as a whole is the recovery of a flourishing and healthy economic system from a broad perspective, with the goal to improve performance on economy-wide indicators such as GDP, imports, and exports. However, considering that the COVID-19 pandemic had a major negative impact on labour markets around the world, a key goal of this recovery package lies in job creation. The labour market in the European Union (EU) has taken a considerable blow. From a low point of 6.4% in March 2020, harmonised (seasonally adjusted) unemployment saw a rise to 7.8% in August 2020 (Eurostat, 2022), which corresponds to an equivalent of 2.5 million jobs lost within a period of five months. Although employment rates appear to return to pre-pandemic levels as of late 2021, the labour market is far from a full recovery, which is expected to lag behind any 'return to normal' (IMF, 2021). First, this sharp increase in unemployment disrupted a seven-year period of an almost steady decrease, a trend that might have continued in the absence of COVID-19. Second, the nature of employment itself has changed as a result of the pandemic, including remote/hybrid working, reduced working hours, and employment income losses of around 5% in 2020 (Eurostat, 2020). Third, permanent job losses from COVID-19, such as those in the energy sector due to project cancellations and/or supply chain-related delays (IRENA, 2020), will further accelerate the shift of workforce and capital among sectors and the reallocation of EU jobs, with the latter expected to be around 1.2% by 2050 before the pandemic (Claeys et al., 2019; Fragkos and Paroussos, 2018). This leads to the establishment of new norms in the labour market, and especially in the energy sector, where such changes come on top of the expected shifts from decarbonisation efforts such as, for example, the potential loss of 160,000 jobs in the coal sector (Alves Dias et al., 2018), unless attention is paid to reskilling. As such, it is evident that even the part of the recovery package that is focused on the green transition and the financing of renewable energy projects should expand its focus on environmental targets and incorporate additional dimensions such as employment implications, especially on the largely affected power generation and fuel sectors, to be in line with the broader

Table 1
Recent literature on climate economy modelling exercises related to COVID-19 and/or employment.

Study	Model	Region	Inclusion of COVID-19	Inclusion of employment	Method for including employment
Pai et al., (2021)	WITCH	Global	N/A	Energy-sector employment	Employment factors
Malik et al., (2021)	REMIND	Global	N/A	Energy-sector employment	Employment factors
(Malik and Bertram, 2022)	REMIND	India	N/A	Energy-sector employment	Employment factors
Shan et al., (2021)	Adaptive regional input–output (ARIO)	Global	Impacts of COVID-19 and fiscal stimuli on global emissions	N/A	N/A
Lahcen et al., (2020)	CGE	Belgium	Macroeconomic impact of the COVID-19 crisis	N/A	N/A
Kikstra et al., (2021)	MESSAGE-GLOBIOM	Global	Impact of post-pandemic recovery to the medium- and long-term energy transition	N/A	N/A
Keramidas et al., (2021)	PIRAMID framework	Global	Pathways considering the immediate effects of the pandemic	Only as input	IMF and ILO projections (assuming no long-term impact from COVID)
Rochedo et al., (2021)	COFFEE-TEA, PROMETHEUS	Global	Gap between pledged recovery packages and actual investment needs of the Paris Agreement	N/A	N/A
Dafnomilis et al., (2020)	E3ME, GEM-E3-FIT, IMAGE	Global	Scenarios exploring the long-term impact of the COVID-19 crisis	Aggregated global employment	Macro-economic model projections
Pollitt et al., (2021)	E3ME	Global	Macroeconomic impacts of COVID-19	Aggregated global employment	Macro-econometric model projections
Ju et al., (2022)	AIM/Enduse, TIMES-Japan, Input-Output model	Japan	N/A	Domestic electricity-related employment (disaggregated only per activity)	Introducing coefficients from the I/O to the partial equilibrium models
Fragkos et al., (2021)	GEM-E3-FIT	EU	N/A	Involuntary unemployment and income by skill	Internal model calculations based on the GTAP database
Fragkos and Fragkiadakis, (2022)	GEM-E3-FIT	Global	Short-term impacts of COVID-19 on GDP	Global disaggregation based on activity and skills	Internal model calculations based on the GTAP database
Joshi and Mukhopadhyay, (2022)	E3-India	India	N/A	Regional employment and aggregated per sector	Internal model calculations
Spijker et al., (2020)	E3ME	Netherlands	N/A	Economy-wide employment	Internal model calculations
Fujimori et al., (2020)	AIM (combined with multiple components)	Asia	N/A	Unemployment rate	Internal calculations of the AIM/Hub component (demographic trend-driven)
D'Alessandro et al., (2020)	EUROGREEN	France	N/A	Economy-wide employment	Internal model calculations
Tamba et al., (2022)	PRIMES-TRIMOVE, JRC-GEM-E3	EU	Only the assumption that COVID-19 will not affect EV sales	Sectoral (transport) employment	Based on JRC-GEM-E3 calculations
Zhang et al., (2022)	SWITCH-China, Job Impact Model for China Power System (JIMC)	China	Reference scenario based on the coal-based COVID response	Energy-sector employment	Employment factors based on the JIMC model
(den Elzen et al., 2022)	IMAGE, GLOBIOM, GEM-E3-FIT	Global	Economic projections based on the implications of the COVID-19 pandemic	Aggregated global employment	Based on GEM-E3-FIT calculations
van de Ven et al., (2022)	GCAM, TIAM, GEMINI	Global (USA, EU, China, India, Japan, Canada)	COVID-19 recovery packages	Energy-sector employment	Employment factors

goals of the recovery.

This is especially the case as, not unlike climate change itself, COVID-19 can be viewed as a disruptive force (Kivimaa et al., 2021) in the broader landscape of the energy system, tending to destabilise organisational structures. However, opportunities for change also emerge from these crises, providing the choice for different pathways to be followed as the energy system evolves in the light of these disruptions (Geels and Schot, 2007). However, the sustainability of these pathways is not ensured. In the absence of committed sustainable policy reaction, windows of opportunity can trigger lock-ins and carbon-dependent trajectories, which are more difficult to destabilise in the long run (Nikas et al., 2022). Therefore, guiding policymaking throughout the three intertwined crises (health, economic, and climate) towards a sustainable pathway emerges as a major, complex challenge. To provide policymakers with useful insights, climate- and energy-economic models—including integrated assessment models (IAMs)—have been typically employed to address topics around the pandemic and employment. Table 1 summarises key recent research on these topics. However, it is evident that only a handful of studies consider these two dimensions simultaneously and, of those, most lack the regional disaggregation (i.e., they are global studies), and/or a decomposition of employment (i.e., they offer aggregated employment results), and/or typically only calculate the impact of specific policies on employment, instead of optimising for employment on top of climate goals. This leaves a gap in the literature of studies aiming to inform EU policymakers on the optimal impact that the green part of the recovery package can have on emissions and other energy system outcomes, while considering employment implications.

To address this gap, the main goal and novelty of this research is to identify and inform EU policymakers on the optimal allocation of the green part of the RRF towards subsidies for low-carbon technologies to maximise the emissions reductions achieved by broader energy system changes, while also maximising the impact these changes can have on energy-sector employment. Acknowledging the EU-level policy challenges in terms of tackling the socioeconomic consequences of the pandemic, and in response to the region's climate mitigation efforts (inter alia reflected in the European Green Deal), this study aims to answer two principal research questions:

1. Towards which low-carbon technologies should EU green recovery package funds be allocated to robustly maximise emissions cuts and employment gains?
2. What are the dynamics and trade-offs among the potentials for emissions reductions as well as near- and long-term employment opportunities in the EU, driven by RRF spending in clean energy technology subsidies?

To answer these questions, we employ the Global Change Analysis Model (GCAM) (Calvin et al., 2019), coupled with the AUGMECON-R multi-objective portfolio optimisation model (Nikas et al., 2020) and a Monte-Carlo-based stochastic uncertainty analysis framework (Forouli et al., 2020). Doing so allows us to investigate different technology subsidisation portfolios while accounting for the underlying uncertainty that is associated with the employment and emissions performance of the subsidisation of each technology. We draw and adapt from a global model inter-comparison study (van de Ven et al., 2022) to enhance the resolution of the recovery scenario space as well as highlight the trade-offs among the optimisation goals and the robustness of optimal investment mixes against parametric uncertainties, allowing to perform a deep-dive into the EU with targeted policy implications.

2. Methods and tools

To address the two research questions, we use a multi-level integrated modelling framework. First, considering that Member States have the flexibility to define the structure of their national recovery and resilience plans, we assess what part of the RRF package can realistically be channelled into clean energy projects in the EU as a whole. GCAM is then used to calculate the energy-system impacts of different subsidy levels for each of the considered clean energy technologies. We translate these energy-system impacts into implications for emissions as well as jobs across the entire energy sector, using established employment factor databases. Next, we use AUGMECON-R to carry out a portfolio analysis of the technological subsidies considering multiple employment and emissions criteria. We, finally, run a Monte Carlo simulation, assuming the implicit uncertainty of the calculated emissions and employment impacts to evaluate the optimal investment portfolios based on their robustness to the employed uncertainty perturbations. The overall process is presented in Fig. 1, while the details of the methodology are elaborated in the next sub-sections.

2.1. EU green recovery package: budget and technology selection

The NextGenerationEU is a financial instrument aiming to raise €750 billion from the capital market to establish the RRF temporary recovery instrument (€672.5 billion), a centrepiece mechanism to tackle the negative socioeconomic impact of the pandemic (European Commission, 2020a). Among the eligibility criteria, the European Commission (EC) expect national plans to allocate at least 37% and 20% of the requested funding towards green and digital investments and reforms, respectively, with emphasis on contributing to the flagship initiatives identified by the 2021 Annual Sustainable Growth (European Commission, 2021). Specifically for the green transition, these initiatives should be aligned with the updated target of the European Green Deal of 55% emissions reduction by 2030 (Jäger-Waldau et al., 2020). This entails that the green investments of the RRF should be used to develop 40% of the additional 500 GW of renewables required by 2030, install 6 GW of electrolyser capacity, produce and transport 1 million tonnes of renewable hydrogen across the EU, double the renovation rate, and build one of the three million charging points and half of the 1000 hydrogen stations needed by 2030.

Based on these priorities and guidelines, about €250 billion can be expected to be used in support of investments in renewables and broader clean energy projects, energy efficiency in the built environment, and sustainable transportation. Estimates based on expected and/or announced projects indicate that around €75 billion will flow towards eight clean energy technologies, including utility-scale photovoltaics (PV), concentrated solar power (CSP), onshore and offshore wind, nuclear, geothermal, biomass, and biofuels, excluding related infrastructure investments (Ernst & Young, 2020). This indications hint that the respective share of the funds is subject to competition among these eight technologies, contrary to other pillars of the RRF, in which the allocation is more straightforward (i.e., grid infrastructure). This raises the challenge of identifying how to best allocate the available budget with a view to maximising the environmental and socioeconomic benefits. GCAM lacks a separate, disaggregated representation of the United Kingdom (UK), as most integrated assessment models typically used to support key international scientific assessments and high-level national and international climate policymaking; we therefore also account for approximately €5 billion from the UK fiscal plan towards similar investments (HM Government, 2020), bringing the total of our selected budget to €80 billion for the eight low-carbon technologies.

2.2. Baseline and recovery scenarios

Climate-economy models and IAMs have largely been used to address topics regarding COVID-19 (e.g., Shan et al., 2021; Kikstra et al., 2021; Lahcen et al., 2020; Pollitt et al., 2021), as presented in Table 1. Here, we use GCAM, a "recursive dynamic" cost-optimisation integrated assessment model, to assess the impact of the subsidies to these eight technologies on the energy system. To assess the contribution of the recovery scenarios, a pre-pandemic baseline was configured based on

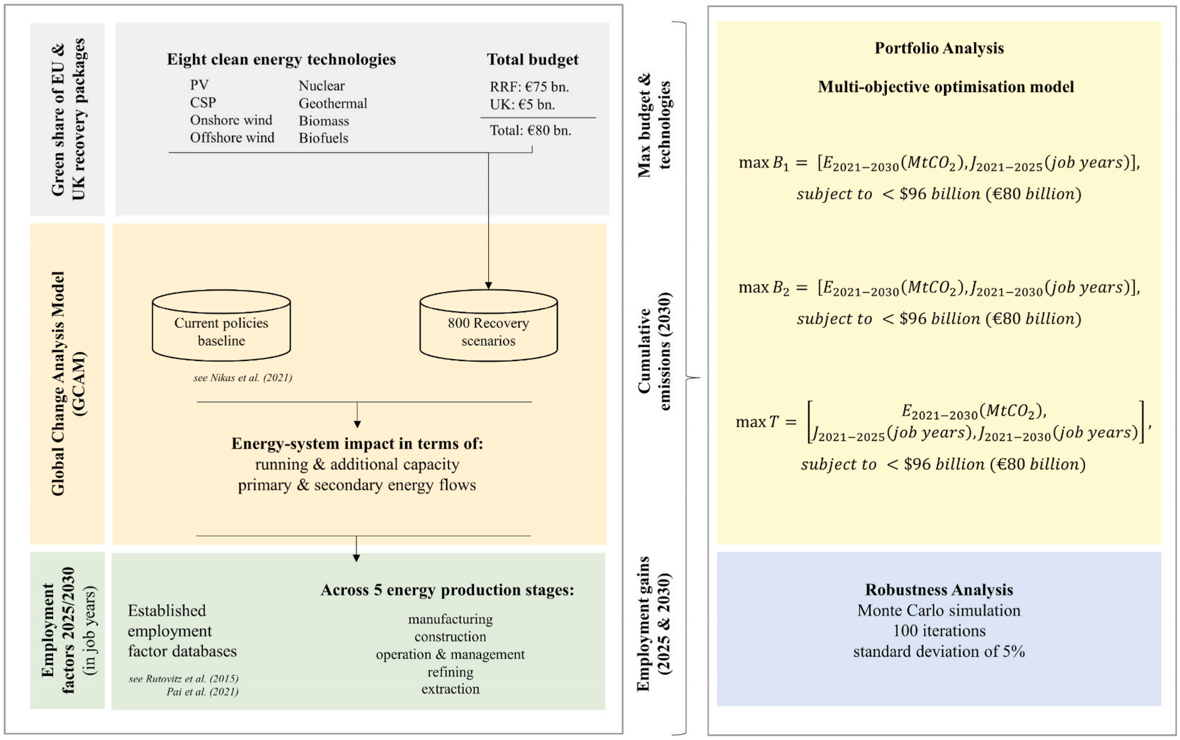


Fig. 1. Methodological approach.

the "where is the EU headed" scenario logic (Nikas et al., 2021a), which quantified the impact of current policies in the EU until 2030. These policies include the pre-pandemic targets (i.e., 43% emissions reductions in EU ETS sectors, 32% renewables in the energy sectors, 3.5% advanced biofuels in the fuel mix by 2030, -32.5% energy consumption by 2030; details on how these policies are modelled in the current policies can be found in Nikas et al. (2021a) and Sognnaes et al. (2021)) before the increased ambition of the European Green Deal and the "Fit for 55" package update. The recovery package should additively contribute to the implementation of these newly established goals.

We calculate 100 scenarios on top of this current policy baseline and for each of the eight technologies individually (800 scenarios in total), gradually increasing the subsidy with each step until reaching the highest subsidy amount possible—i.e., the lowest among maximum technology costs (depending on capital and non-capital costs) and the available budget of €80 billion (corresponding to 96 billion USD in 2020, which is the monetary value used internally in GCAM). Apart from emissions, the impact of each subsidy on running capacity, additional capacity, and primary and secondary energy for 12 technology/fuels (biofuels, biomass, coal, CSP, natural gas, geothermal, nuclear, onshore and offshore wind, oil, PV, and rooftop-mounted photovoltaics) was extracted from GCAM for each scenario, enabling the calculation of employment implications (see Section 2.3).

The results for the recovery scenarios were reported as a net difference from the baseline. This approach is found preferable when analysing job variation, as it enables understanding employment shifts compared to the baseline across all technologies instead of gross employment. The approach also accounts for the replacement of jobs from conventional sources (García-García et al., 2020), which is a grave concern for many communities that heavily rely on the fossil fuel industry (Baran et al., 2020).

2.3. Employment factors

Modelling the labour market is usually a daunting process since, in a full-employment job market, jobs added in one area just slash jobs in other areas and/or raise wages. As presented in Table 1, there are usually two approaches in including employment implications in climate-economy models: (a) models with internal representation of labour markets, which however tend to provide aggregated employment results, and (b) employment factors, which usually do not capture broader trends in the markets and labour shifts and mobility. Contrary to models based on input-output tables (Distelkamp and Meyer, 2019; D'Alessandro et al., 2020), computable general equilibrium (CGE) models (Fujimori et al., 2020; Fragkos et al., 2018) or macroeconometric models (Spijker et al., 2020), GCAM does not represent the labour market internally; therefore, to address this gap, the use of external databases of employment factors is required (Fragkos and Paroussos, 2018; Malik et al., 2021). Since the main goal of this study is to calculate optimal packages of specific low-carbon technology subsidies based on their energy-system impacts, and on top of that include employment implications to consider socioeconomic goals of the recovery, the route of GCAM with employment factors is selected for two reasons. First, as a technology-rich model with detailed energy and climate-system representation, GCAM is ideal for simulating the substitution of high-for low-carbon technologies, in response to their relative costs and changes thereof driven by subsidies, before calculating the associated emissions cuts and other energy-system implications. Second, albeit imperfect (that is despite their wide use in the literature to project job market outcomes of low-carbon futures—see, e.g., Table 1), the use of employment factors offers a more disaggregated level of employment estimates across different sectors and mainly technologies of key interest for our study.

Since recovery scenarios are calculated on top of current policies and the subsidies are applied after 2021, net employment in 2020 is assumed to be zero. For 2025 (the first time-step of GCAM runs), employment for each of the 12 technologies was calculated for 5 different processes/stages of energy production: (i) extraction and/or (ii) refining (fossil fuels, biomass, and biofuels), as well as (iii) operation and management, (iv) construction, and (v) manufacturing (all but biofuels), using the factors presented in Table 2. To harmonise employment calculations across the different stages, we calculated employment gains in job-years.

Table 2
Employment factors in 2025.

Employment factors 2025							
Technology	Manufacturing	Construction	Operation & Management	Refining	Extraction	Manufacturing import factor	Extraction import factor
	Job-years per GW installed			*Job-years per PJ processed*		*Share of demand from import (2018 values) (%)*	
Biofuels	–	–	–	7.3	–	–	–
Biomass	2690	12800	1500	–	29..9	–	5.2
Coal	5400	11200	140	–	26.9	–	52.4
CSP	3627	7255	405	–	–	–	–
Gas	930	1300	140	–	8.6	–	78.7
Geothermal	3687	6429	375	–	–	–	–
Nuclear	1300	11800	600	–	7.3	–	100
Onshore Wind	4250	2894	278	–	–	0	–
Offshore Wind	12821	6575	183	–	–	0	–
Oil	930	1300	140	1.5	14.4	–	87.1
PV (utility-scale)	3775	7325	367	–	–	76.7	–
Rooftop PV	3775	13561	740	–	–	76.7	–

Employment factors for the power sector were drawn from Rutovitz et al. (2015), a well-established and widely used database in the literature (Malik et al., 2021). Exceptionally, factors for fossil fuels and biofuels were extracted from Pai et al. (2021), which was based on Rutovitz et al. (2015) but introduced a more detailed spatial representation of these fuels. Manufacturing and extraction factors were adapted based on the EU's domestic capacity to locally create the jobs required for the additional installed capacity of each technology; for example, manufacturing materials for PV panels in the EU depend on imports, implying that a share of the jobs created for each new installed capacity of solar PV should be counted elsewhere (such as China, which dominates the supply chain). These import factors were calculated based on the relative share of domestic supply in domestic demand (IEA, 2019; World Nuclear Association, 2019), assuming this share will not markedly change in the near-term, i.e., until 2025, when recovery funds are allocated.

Subsidies are assumed to be allocated within the first GCAM timestep (i.e., by 2025), closely reflecting the EC's intention for the funds to be spent the soonest possible (European Commission, 2020a). However, parts of these subsidies will in reality be spent towards the end of this period—or towards technologies that require long construction times (e.g., nuclear, offshore wind)—leading to installed capacity coming online in 2025–2030, especially for technologies with high lead times. As such, we also calculated employment gains up to 2030 using the employment factors presented in Table 1, adapted based on decreasing technology-specific CAPEX and OPEX over time (Giarola et al., 2021), as suggested by Ram et al. (2020).

and cumulative jobs created from 2021 to 2025 ($J_{2021-2025}$); this is deemed of political priority and therefore relevant to policymakers as they expect immediate returns on their spendings with a few to achieving swift economic recovery from the pandemic's impacts (Equation (1)). Then, a slightly modified problem was formulated (B_2), comprising again cumulative emissions cuts by 2030 and cumulative jobs created from 2021 to 2030 ($J_{2021-2030}$) to account for the total impact of the subsidies and understand longer-term trends (Equation (2)), while also exploring to what extent employment gains can be sustained in the longer run. Acknowledging the need to both create near-term jobs and sustain employment gains in the longer run, a third, tri-objective mathematical problem was formulated and solved (T), this time with all three objectives (Equation (3)). The three problems were solved independently. This process was critical to identify trends between the different directions triggered by short-term and longer-term employment planning as well as trade-offs and/or synergies among all three priorities. The optimisation problems are defined as follows:

$$\max B_1 = [E_{2021-2030}(MtCO_2), J_{2021-2025}(job\ years)],\ subject\ to\ < \$96\ billion\ (€80\ billion) \tag{1}$$

$$\max B_2 = [E_{2021-2030}(MtCO_2), J_{2021-2030}(job\ years)],\ subject\ to\ < \$96\ billion\ (€80\ billion) \tag{2}$$

$$\max T = [E_{2021-2030}(MtCO_2), J_{2021-2025}(job\ years), J_{2021-2030}(job\ years)]\ ,subject\ to\ < \$96\ billion\ (€80\ billion) \tag{3}$$

2.4. Portfolio analysis

The emissions and jobs implications of the 800 recovery scenarios were then used as inputs in AUGMECON-R, a multi-objective optimisation model, to establish dominant portfolio mixes based on combinations of subsidies to the different technologies towards optimising the environmental and employment performance of the green recovery package. Different problems were formulated, to respond to the research questions while enhancing the policy insights depending on the political priorities in terms of the timing and sustainability of returns on the recovery budget spending. Initially, a bi-objective mathematical programming model was formulated (B_1), in which portfolios were optimised by cumulative emissions cuts from 2021 to 2030 ($E_{2021-2030}$), considering that 2030 is a milestone year to achieve the NDC targets,

2.5. Robustness analysis

To increase policymakers' confidence in the provided portfolio mixes, a robustness analysis framework was employed (Forouli et al., 2020), based on a Monte Carlo simulation, to quantify the uncertainty of the energy system changes, as typically represented by integrated assessment models (Pfenninger et al., 2017; Ellenbeck and Lilliestam, 2019).

In particular, following a normal distribution with a mean value fixed on the GCAM outputs (and the subsequent employment conversions) and a standard deviation of 5% (Forouli et al., 2019), 100 iterations of the portfolio analysis (in Section 2.4) were performed to calculate the vulnerability of the optimal investment portfolios to uncertainties associated with the performance of a single investment in terms of new jobs created and additional emissions cuts achieved. From iteration to iteration, different portfolio mixes typically emerge as dominant, while others are crowded out of the solution space (Pareto front), based on the fluctuating impact of subsidies on emissions and employment. For this reason, here we introduced a robustness metric reflecting the number of iterations each portfolio made it among the dominant solutions (Pareto front) in the total of 100 iterations. The physical interpretation of robustness in this case is that, if a portfolio consistently makes it into the solution space in x iterations, it means that it is more robust than a portfolio appearing in $y < x$ iterations, against the assumed parametric uncertainty in the modelling results.

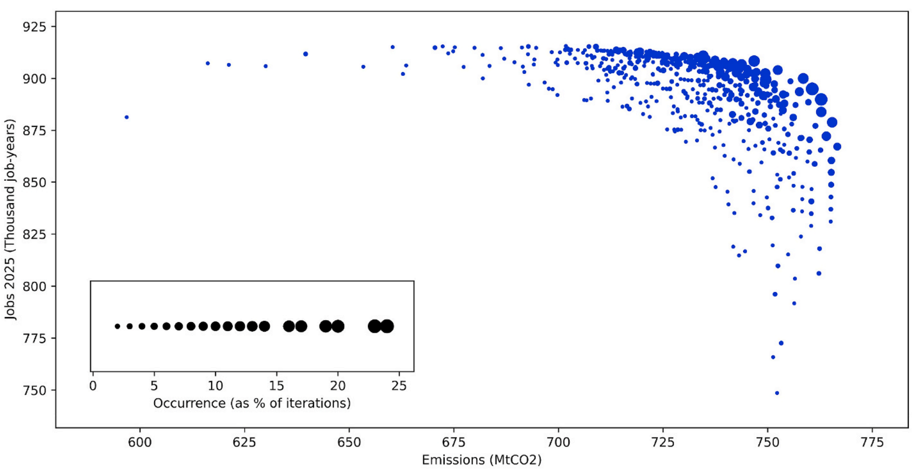
3. Results and discussion

Following the multi-stage methodology presented in Section 2, we sought to determine how to optimally spend the green part of the European recovery funding towards further mitigating CO_2 emissions on top of the current policy framework, while maximising energy-sector employment gains, first in the near-term (by 2025) and then in the longer run (by 2030).

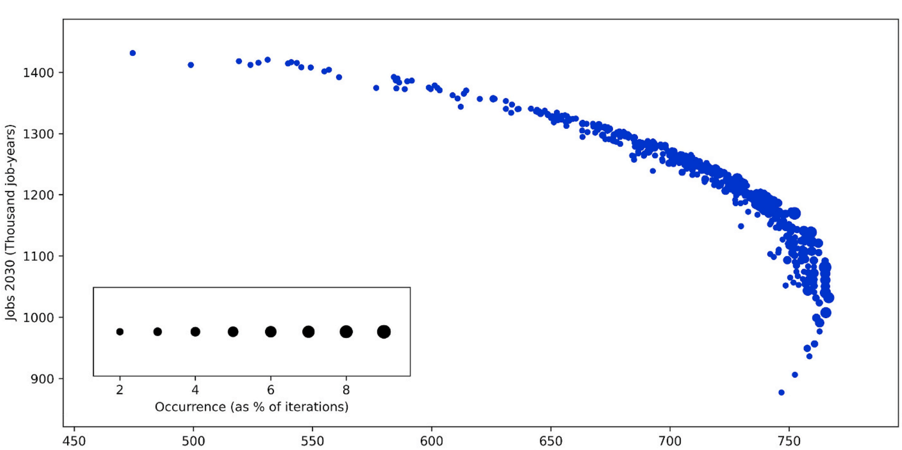
In both cases, we observed a clear trade-off between emissions reductions and employment gains, meaning that portfolios performing well in relation to net-positive employment gains were found suboptimal in terms of emissions cuts, and vice versa. In particular, when looking at near-term employment opportunities, we calculated a potential for 766–915 thousand new job-years created in the energy sector by 2025 as well as a capacity for cumulative emissions cuts of 596–748 $MtCO_2$ up to 2030, both compared with the current policy baseline (Fig. 2a). Considering this trade-off between emissions and employment gains, the maximum (minimum) potential for new energy-sector jobs by 2025 is 915 (766) thousand job-years, achieved by a green recovery portfolio that can lead to a drop in cumulative CO_2 emissions of 596 (748) $MtCO_2$ by 2030. When maximising employment gains by the end of the decade, instead, we calculated a potential for 877-1431 thousand job-years created by 2030. Here, opting for longer-term sustainability of new energy employment opportunities did not significantly hamper the range of emissions reductions, which however is now slightly larger (474–766 $MtCO_2$ up to 2030, Fig. 2b).

A second insight directly emerging from Fig. 2 is that for both time horizons (2025 and 2030), optimal portfolios achieving moderate gains along both objectives (emissions and employment gains) are less prone to uncertainty perturbations compared to portfolios predominantly focusing on either of the two objectives. Similarly, we can observe that in the second case—i.e., when maximising full-decade emissions and employment gains—portfolios appear to be considerably less robust against uncertainties, with all portfolios appearing in less than 10% of iterations (i.e., robustness <10%).

Third, of the eight considered technologies, most portfolios heavily included investments in onshore wind and, to a smaller degree, in biofuels; these two were occasionally (i.e., across the Pareto front and the



(a)



(b)

Fig. 2. Optimal green RRF subsidy portfolios in terms of further emissions cuts (x-axis) and new employment opportunities in the energy sector (y-axis) with (a) short-term planning, emphasising employment gains by 2025; and (b) long-term planning, emphasising sustainable new energy jobs by end of 2030. Bubble size indicates robustness against uncertainty perturbations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

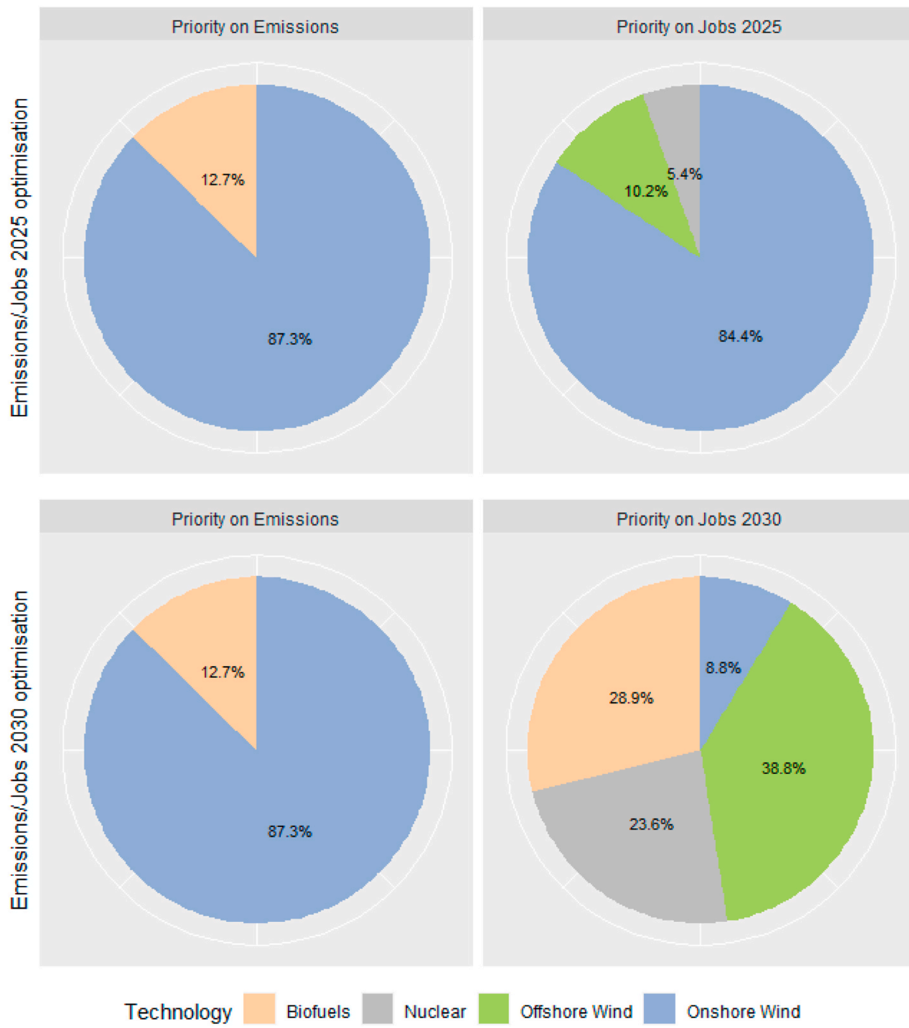


Fig. 3. Allocation of the available budget depending on the priority goal (columns) in the two bi-objective optimisation problems (rows).

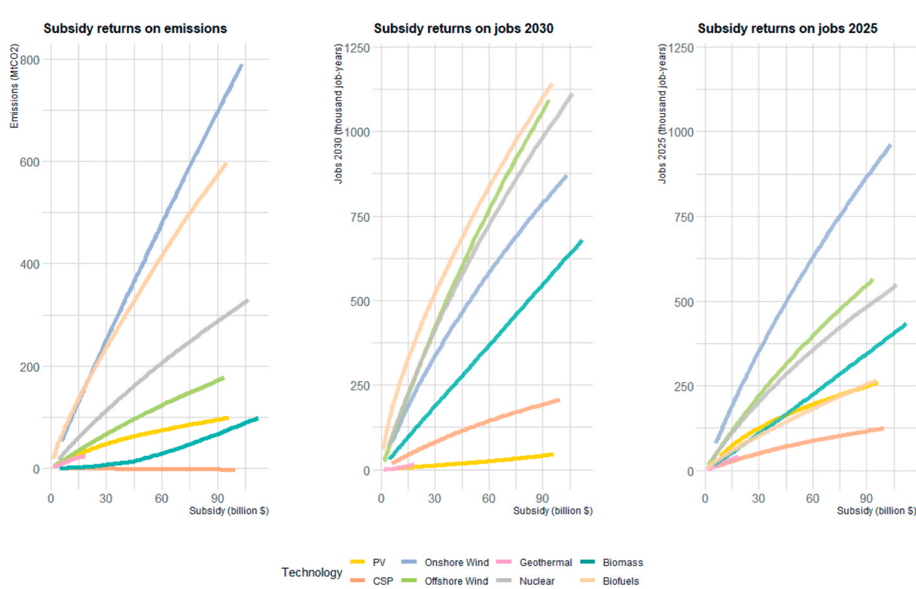


Fig. 4. Return on investment/subsidisation level across the eight technologies, in terms of emissions cuts (left), employment by 2030 (centre), and employment by 2025 (right).

assumed uncertainty range) supplemented by small shares of offshore wind and nuclear subsidies. The exact investment mix largely depended on the priorities of the optimisation (Fig. 3). In particular, the portfolio achieving most emissions cuts was the same for both time horizons of employment optimisation and relied primarily on onshore wind ($83.8 billion) and less on biofuels ($12 billion). When shifting our focus towards maximising employment, however, the selected portfolios differed among the two bi-objective problems: in the portfolio maximising near-term employment gains, onshore wind retained its $81-billion share but the remainder was now made up by investments in offshore wind ($9.8 billion) and nuclear power ($5.1 billion); on the other hand, optimising longer-term employment gains yielded a portfolio with increased diversification but without straying from the four technologies: offshore wind ($37.2 billion), biofuels ($27.7 billion), nuclear ($22.6 billion) and onshore wind ($8.4 billion).

To better understand these trends, we delve into the returns on the independent subsidisation levels for each technology along the three objectives, in the GCAM-generated recovery scenarios (Fig. 4). Onshore wind development dominates the impact on emissions and employment up to 2025 and, although it falls back in terms of employment gains by 2030, it keeps up with the rest of the technologies. Similarly, subsidies in biofuels keep up with onshore wind investments in terms of emissions cuts and have the highest employment returns by 2030. This explains the consistent inclusion of both technologies in optimal portfolios. Offshore wind and nuclear are almost equally as efficient as biofuels, in terms of creating new jobs by the end of the decade; therefore, maximising employment gains by 2030 pinpoints a portfolio comprising a split among the three technologies (bottom-right panel, Fig. 3). Given the high competition among technologies, the overall robustness of subsidy portfolios optimising the creation of new jobs by 2030 is relatively low, as no specific investment mix emerges as dominant (Fig. 2b). GCAM results show that RRF subsidies in the remaining four technologies (PV, CSP, geothermal, and biomass) fail to have a considerable positive impact across any of the three objectives, thereby ending mostly absent from optimal portfolios. Especially for PV, this contradicts insights from other integrated assessment models and/or for other major economies with announced green recovery packages (van de Ven et al., 2022; Malik and Bertram, 2022). In our case, however, a possible explanation for the poor performance of PV subsidisation can be found in the relative saturation of solar power in the current policy trajectory (Nikas et al., 2021), as well as in the reduced EU-domestic capacity to create jobs in the manufacturing sector, which predominantly takes place in China. These two factors render PV subsidies sub-optimal, in both emissions cuts and employment gains. This insight does not undermine the added value of PV growth in the context of mitigation efforts by 2030; it rather refers to their cost-optimality compared to other options as part of RRF-powered clean energy technology subsidisation.

Considering the significant differences of the technology mix maximising full-decade employment gains from those optimising the other two goals, we find that the conflict between longer-term and near-term employment gains (as well as between longer-term employment gains and emissions cuts) is higher than the conflict between achieving large cumulative emissions cuts by 2030 and creating new energy-sector jobs by 2025—with onshore wind dominating both cases. This trade-off between near- and longer-term employment gains also shows in the synthesis of optimal portfolios emerging in each of the two problems, tracing back to how investment choices fare against current policies. When focusing on longer-term planning, it was found preferable to subsidise less competitive technologies that would not have been subsidised absent the recovery package; as such, maximum employment gains are mostly observed beyond 2025. In contrast, should policymakers opt for a shorter-term planning with immediate employment

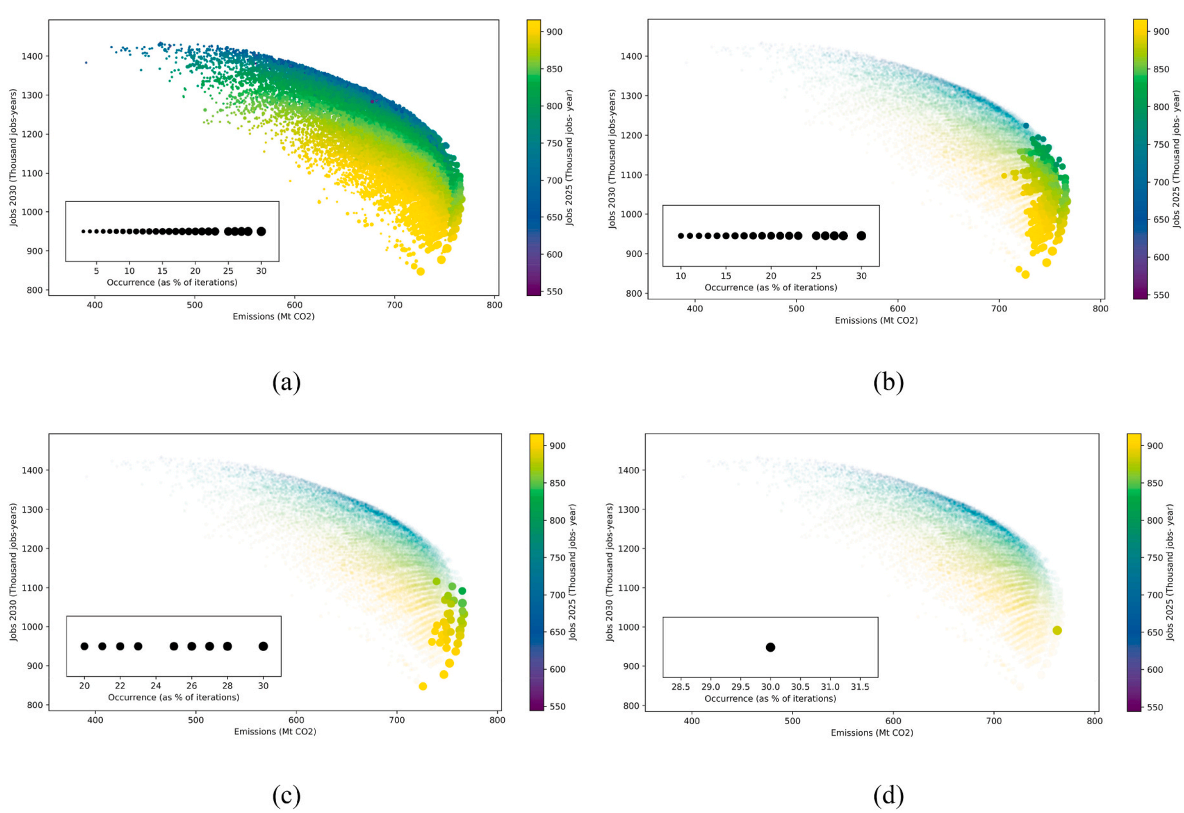


Fig. 5. Optimal green RRF subsidy portfolios in terms of further emissions cuts (horizontal axis) as well as long-term (vertical axis) and near-term (colour axis) employment gains in the EU, highlighting only the portfolios occurring in (a) over 1%, (b) over 10%, (c) over 20%, and (d) 30% of iterations. Bubble size indicates robustness against uncertainty perturbations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

returns on recovery funds spending, investments should heavily focus on onshore wind. This technology, however, is already mature and highly competitive in the current policy context, and any investments in it would essentially accelerate the achievement of the current policy targets. Such a strategy would be effective at creating short-term jobs but would quickly lose momentum post-2025, undermining long-term employment gains. Due to relative scarcity for resource-rich onshore wind sites as well as limits to integration of intermittent wind power in the European power mix, a large part of these quickly created jobs would have been created towards the end of the decade regardless of the RRF investments.

Given these dynamics, we further explored if the technological mix of green recovery spending can be diversified towards a better balance between near- and longer-term employment gains, by optimising emissions cuts, employment by 2025, and employment by 2030 simultaneously. After solving the tri-objective problem, we found a similar potential across the three objectives as in the bi-objective problems. This potential ranges between 391 and 766 $MtCO_2$ emissions reductions by 2030, 843-1433 thousand cumulative job-years by 2030, and 544–915 thousand cumulative job-years by 2025. Fig. 5 displays the solution front of the tri-objective problem, highlighting solutions of any robustness (excluding portfolios occurring only once; Fig. 5a), occurring >10% (Fig. 5b), >20% (Fig. 5c), and 30% (Fig. 5d) among the 100 Monte Carlo runs. Despite yielding comparable results, here the trade-off between full-decade employment gains and the other objectives is further highlighted, as the upper end of the range (1.4 million job-years by 2030) cannot be achieved without giving up on the potential for emissions reductions and without losing out on possible employment gains by 2025 (as evident by the outer blue perimeter in the solution front in Fig. 5a). Also, shifting to portfolios maximising employment gains by 2030 significantly reduces robustness (Fig. 5b–d), as observed in the respective bi-objective problem. Contrary to the latter, however, we now identify portfolios appearing in more than 10% of the iterations (Fig. 5b), which can potentially reach up to 1.2 million job-years by 2030 without undermining near-term job gains nor additional emissions reductions.

Among portfolios with high robustness (occurrence >20%, see Fig. 5c–d), subsidy portfolios again comprise mostly onshore wind (above $75 billion), biofuels (up to $16 billion), and to a smaller extent nuclear (up to 10$ billion) and offshore wind (up to $3.3 billion). We can, therefore, gain robust insights into which technologies the green part of the RRF spending should flow towards. However, the exact investment mix largely depends on policy priorities in terms of targets, as we have identified a set of 30 portfolios of >20% robustness (Fig. 6) that could all be efficiently implemented but with largely different impacts each. In these portfolios, there are strong indications of a positive correlation between subsidies for onshore wind and job gains by 2025 and equally strong indications of a negative correlation between subsidies for onshore wind and job gains by 2030. In fact, every additional $1 billion of investments in onshore wind can increase employment in 2025 by more than 3000 job-years, but at the same time reduce employment in 2030 by approximately 12,500 job-years. In contrast, biofuels feature opposite trends, with every additional $1 billion having the capacity to increase employment in 2030 by more than 16,000 job-years, while limiting the potential for new employment in 2025 by 5000 job-years and for further emissions reductions by 4 $MtCO_2$ (whereas there was no indication of a correlation on emissions for onshore wind). The small investment shares on nuclear and offshore wind do not allow extracting meaningful correlations, although there are indications of a positive correlation between nuclear investments and employment gains by 2030.

Only one portfolio was found with a robustness level of 30%, which was made up by investments explicitly in onshore wind ($87.5 billion) and biofuels ($8.2 billion), closely resembling the emissions-focused optimal portfolio of the bi-objective models (Fig. 3). This does not necessarily imply that it should be the single best choice for policymakers, as robustness is yet another decision criterion and the final decision may depend on other policy priorities. This portfolio has the potential to achieve 763 $MtCO_2$ emissions reductions on top of the current policy mitigation efforts, as well as 883 and 991 thousand job-years created in the energy sector by 2025 and 2030, respectively. Evidently, when optimising all three objectives and strongly

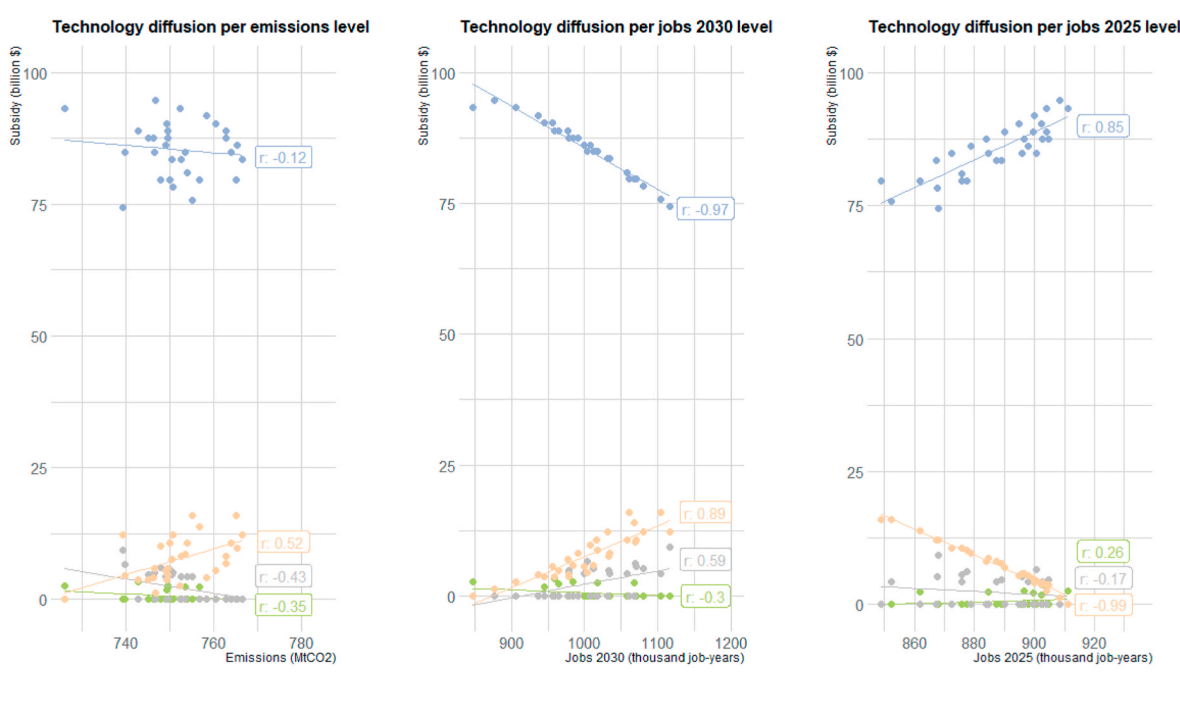


Fig. 6. Participation of each technology in the most robust (>20%) portfolios (subsidy) depending on the impact on emissions (left), employment by 2030 (centre), and employment by 2025 (right).

emphasising robustness, giving up on near-term employment gains or emissions cuts is found costlier than losing longer-term sustainability of new energy-sector jobs, which is also found relatively uncertain. Still, cumulative employment gains by 2030 can be far from the lower end of the potential range (Fig. 2b) and remain above the near-term energy-sector job creation potential, highlighting the potential of continuous (albeit slower) growth of the intended immediate returns on recovery spending. In their pre-pandemic study, Malik et al. (2021) had showed that climate policy efforts could drive an increase in employment in the energy sector by 2025, which however would be followed by a reverse trend post-2025 and beyond, depending on the stringency of climate action (Malik and Bertram, 2022). Here we show that, with a nuanced approach to allocating the COVID-19 recovery packages in the EU with a view to coupling mitigation goals with both near- and longer-term employment planning, this energy-sector unemployment rebound can be mitigated, at least by the end of this decade.

In terms of how these additional jobs are distributed across sectors and technologies/fuels in the most robust portfolio (Fig. 7), we find that most employment gains until 2025 are expectedly observed in the manufacturing and construction sectors as well as in onshore wind, which is heavily subsidised. Post-2025, the increase in these sectors could halt, with manufacturing jobs even rebounding; however, the positive net impact is maintained as jobs in the later stages of project pipelines (i.e., O&M) start to increase. As such, continuous policy support (including reskilling) is required beyond the duration of the RRF instrument to ensure these shifts do not lead to job losses post-2025. Interestingly, we also observe a significant increase in PV-related employment within the region, despite the absence of any subsidies. On the other hand, losses in rooftop PVs indicate internal shifts in the solar market as a spillover effect from investments in onshore wind: huge increases in subsidised wind in electricity significantly reduce the electricity price, increasing overall demand for grid electricity and disincentivising distributed generation. Nevertheless, a net positive employment impact for the entire solar sector is maintained. Considering the link between rooftop PV installations and demand-side transformations, including their role in energy democracy and energy poverty alleviation (Rodríguez et al., 2018), careful consideration should be placed on such shifts in the supply sector to control the interplay with other parts of the RRF focusing on the demand side (e.g., energy efficiency in the built environment), as well as broader demand-side shifts—especially in response to Russia's invasion of Ukraine and subsequent energy-planning decisions, such as the introduction of the REPowerEU program, which are expected to significantly affect energy demand.

Finally, despite investments being channelled explicitly towards onshore wind and biofuels in the most robust portfolio, the subsidies can have broader implications for the entire energy sector, as evident in the employment boost in solar PVs, including capacity additions in renewables: we calculate that this portfolio could achieve the integration of 108 GW of additional installed capacity from renewables by 2030, on top of the current policies reference trajectory. This, however, would fall short of the 200 GW target envisaged in the RRF. This inadequacy is further validated when feeding five other indicative portfolios (the three portfolios of Fig. 3 and the robustness-weighted average of the portfolios of Fig. 5a and c) back into GCAM, which would yield an additional renewable energy capacity of 49–118 GW by 2030, depending on the technology mix of each portfolio. This additional capacity Recovery plans designed by the Member States should, therefore, account for this shortcoming and pursue domestic investments that could also raise additional funds (i.e., from the private sector) that would help close the gap.

4. Conclusions and policy implications

The RRF is a major financial instrument in the EU intended to mitigate and/or alleviate the socioeconomic impacts of the COVID-19 pandemic within the region, while pushing forward the envisaged green transition. At least 37% of the total funds made available to Member States should constitute a green stimulus package, expected to flow towards climate mitigation-compatible investments and clean energy projects. With employment hit especially hard by the pandemic, and notably in the energy sector as the crisis came on top of shifts triggered by climate efforts, key questions arise over the trade-offs between socioeconomic and mitigation potentials of the EU green recovery

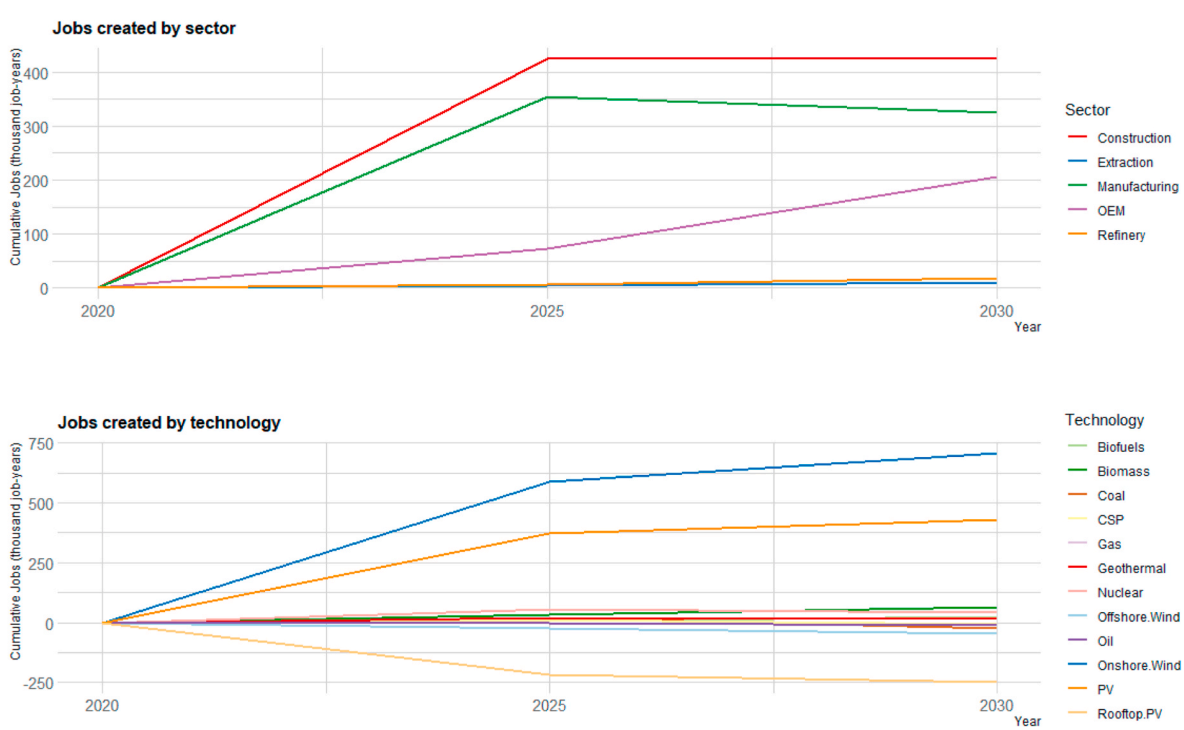


Fig. 7. Breakdown of cumulative employment created by sector (top) and by technology/fuel (bottom) in the most robust portfolio (robustness of 30%).

package, in terms of employment gains in the energy sector and emissions cuts, as well as over the optimal allocation of these funds to maximise both goals. To answer these questions and support policymakers in the EU in designing and implementing their respective recovery and resilience plans, this study employed a multi-stage integrated modelling framework. Delving into the EU (plus the UK's) recovery package, an €80 billion budget was identified as relevant for projects of eight energy technologies, with high competition among them to absorb these funds. The GCAM integrated assessment model was used to calculate 800 recovery scenarios of technology subsidies (100 subsidy levels for each of the eight technologies) that were applied on top of a current policies baseline. After translating the energy system outputs of these scenarios to employment impacts using well-documented employment factor databases in the literature, the AUGMECON-R portfolio analysis model was used to solve three optimisation problems for maximising full-decade additional emissions cuts as well as near- (2025) and longer-term (2030) employment gains in the energy sector. The portfolio analysis was further coupled with a Monte Carlo simulation to identify robust technological mixes among the optimal investment portfolios.

First, we determined a clear trade-off among all three objectives, hinting the conflicting nature of different clean energy projects as well as the challenge in reaching the maximum potential in terms of employment and CO_2 emissions cuts. This trade-off is evident in the overall potential of the green RRF part (achieving approximately 400–770 $MtCO_2$ emissions reduction by 2030, and 550–915 and 850-1450 thousand energy-sector job-years created by 2025 and 2030 respectively, additionally to what the current policy framework is expected to achieve). Second, the most challenging objective was maintaining employment gains by the end of the decade, as this was found to considerably undermine creating new jobs by 2025 and nearing the EU's NDC target. Indicatively, in the most robust portfolios, achieving about two-thirds of the maximum employment potential by 2030 (1.45 million job-years) enables hitting the upper bound of the other two objectives; aiming for the maximum potential of new energy-sector job-years in the energy sector was found at odds with climate objectives and the main goal of immediate socioeconomic returns on the RRF investments. Third, we found that recovery policy plans could benefit from investments in specific technologies, with a large chunk of optimal portfolios heading towards onshore wind, and then biofuels, nuclear power, and offshore wind.

The exact investment mix should largely depend on the policy priorities: larger investments in onshore wind appear to yield positive impacts on emissions cuts and near-term employment gains, while shifting towards the other three technologies (biofuels, nuclear, and offshore wind) can benefit larger energy-sector employment gains by the end of the decade. In general, investment portfolios favouring already cost-competitive technologies (such as onshore wind) may create the most jobs by 2025 but could quickly lose momentum, leading to negligible jobs gains onwards. This is because certain investments would only pull forward employment opportunities that could have been created anyway within the decade, driven by the policies currently in place. On the other hand, prioritising currently less cost-competitive technologies (such as offshore wind or advanced biofuels) could leverage the opportunity arising from the recovery package and benefit the maturity of these technologies, altering the current policy energy-system trajectory and boosting diversification of technological capacity with an ongoing running positive effect in the future and longer-lasting job opportunities. These trade-offs with the current policies should be an important consideration in interpreting the results of the study. For example, PVs appeared to be a less favourable investment, tracing back to their strong presence in the current policies baseline; however, this does not imply that solar deployment should not be reinforced throughout the decade, but rather that policy efforts should be aligned with the targets set (which includes large PV capacity additions) and complemented with the optimal investment mix identified.

Finally, although an additional 200 GW capacity from renewables by 2030 lies among the EU's intentions behind the green RRF package, we estimated that only half of this potential can be achieved based on the available budget, if energy-sector employment should also be prioritised. To close this gap, different criteria should be considered and/or additional funds be raised, as there may be limited capacity to further increase the RRF's share towards clean energy production, considering that it is a multi-purpose mechanism.

This study has undergone significant effort to realistically represent employment impacts of the recovery package in the EU, if centrally coordinated. However, we acknowledge that most socioeconomic impacts from the pandemic are present at the national level, while calculated employment gains may not be equally distributed across Member States (especially considering the earlier stages of project pipelines, as well as domestic renewable energy potentials for the later stage of relevant projects). This is even more so for the UK, the green recovery package of which has been included in the study to align our analysis with the employed model's regional disaggregation, despite it not being a Member State. We also acknowledge that this optimal allocation of the RRF spending requires a level of EU-wide/supranational coordination that may not be reflected in national recovery and resilience plans, which are left flexibly up to Member States. Still, broader insights into a general EU-level direction may be drawn, while future research based on the proposed approach can delve into the national-level spending of the available funds as the implementation of the recovery and resilience plans starts taking shape.

A strong caveat of an approach based on employment factors, such as the one used here, lies in the challenging task of addressing the heterogeneity of unemployment: some people cannot find a job, while some jobs cannot be filled; this further stresses the need to go beyond first-order effects examined here and account for labour mobility and the required reskilling of the workforce, as well as the impact on wage levels in different sectors and regions. Even more so for COVID-19 recovery spending, since initiatives aimed at stimulating the EU economy do not focus solely on the energy sector, but rather aim to create value-added across multiple sectors, including inter alia the transportation, residential, food, and agricultural sectors. As such, future research could draw from the optimal portfolios calculated here, introduce them to models with more advanced representation of the entire economic system and the underlying labour markets (including, e.g., production functions, prices and substitution elasticities, input and output markets, trade flows, etc.) to elaborate on broader impacts of both the subsidies as well as the entire recovery package.

Apart from the use of one integrated assessment model, in which capacity factors for power technologies are fixed (while additional renewables in power could potentially push more fossil technologies out of the market through dispatch, see van de Ven et al., 2022), another important caveat of this study lies in the assumption that markets will be the same as today. For instance, the assumption of a fixed market for manufacturing materials in 2030 may be one of the reasons behind PVs being found sub-optimal. Further development of the PV manufacturing supply chain within the EU, for example, may yield different results, considering the employment impact in the early stages of the solar power project pipeline. In this sense, our study provides a baseline scenario of the implications of RFF spending, assuming business-as-usual in terms of interactions and spillover effects between markets, both within and beyond Europe. While the exact investment mix may be subject to these interactions as well as to other uncertainties (such as repercussions from the Ukraine conflict to the European economy), our study shows that the (near-) optimal use of the green part of the RFF can lead to both emissions reductions and short- and long-term jobs in the energy sector, while providing indications of which technologies can be impactful. Future studies could further investigate scenarios of market evolution and employ tools such as agent-based models to examine said interactions between markets and relevant actors in more detail.

Finally, it is also noteworthy that not all relevant technologies have been considered for subsidisation; although the inclusion of some technologies would not have changed the outcome (e.g., hydro, given the limited potential for additional hydropower in the EU), future work should focus on representing options such as hydrogen or infrastructure projects, which may be central in the EU's recovery plans and/or pathway to net-zero. Apart from additional technologies, future research can shed light on spillover effects that the subsidies in specific technologies, such as the ones calculated here, could have–for example, the use of biofuels on land use changes, solar and wind expansion on mineral extraction, and the challenge of end-of-life disposal of wind turbines and PV panels.

CRediT authorship contribution statement

Konstantinos Koasidis: Conceptualization, Software, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alexandros Nikas:** Conceptualization, Software, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing, Supervision. **Dirk-Jan Van de Ven:** Conceptualization, Software, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Georgios Xexakis:** Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Aikaterini Forouli:** Formal analysis, Software, Validation, Visualization, Writing – original draft. **Shivika Mittal:** Software, Methodology, Investigation, Validation, Writing – original draft. **Ajay Gambhir:** Conceptualization, Methodology, Investigation, Validation, Writing – review & editing. **Themistoklis Koutsellis:** Software, Validation, Visualization, Writing – original draft. **Haris Doukas:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Georgios Xexakis reports article publishing charges was provided by Horizon 2020.

Data availability

Data will be made available on request.

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