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Economy-wide impacts of socio-politically driven net-zero energy systems in europe☆,☆☆

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ABSTRACT

Net-zero energy system configurations can be met in numerous ways, implying diverse economic effects. However, what is usually ignored in techno-economic and economy-wide analysis are the distinct social-political drivers and barriers, which might constrain certain elements of future energy systems. We thus apply a model ensemble that defines social-political storylines which constrain feasible net-zero configurations of the European energy system. Using these configurations in a macroeconomic general equilibrium model allows us to explore economy-wide effects and ultimately the cost-effectiveness of different systems. We find that social-political storylines provide valuable boundary conditions for feasible net-zero designs of the energy system and that the costliest energy sector configuration in fact leads to the highest European-wide welfare levels. This result originates in indirect effects, particularly positive employment effects, covered by the macroeconomic model. However, adverse public budget effects on the transition to net-zero energy may limit the willingness of policymakers who focus on shorter time-horizons to foster such a development. Our results highlight the relevance of considering the interaction of energy system-changes with labor, emission allowance and capital markets, as well as considering long-term perspectives.

1. Introduction

Historically, the energy system has been a key driver of social development and economic progress. However, due to the related emissions of greenhouse gases (GHG) and climate-related risks [1] a transition towards net-zero emissions is highly needed. To remain within the limits as set in the Paris Agreement it is indisputable that the decarbonization of the energy system is key. The silver lining is an observable strong cost reduction in renewable energy technologies [2,3] and a plethora of studies show that the technologies and economics behind low-carbon or climate-neutral systems are within reasonable and cost-effective ranges [4] [5–7]. Indeed, eliminating fossil fuels with currently available technologies can be achieved across the European energy system in hundreds of cost-effective ways [8].

Yet, while the feasibility and techno-economics of net-zero energy becomes increasingly clear, the underlying social-political drivers and barriers as well as the embedding in a larger economy-wide system remain underrepresented in modelling. These gaps are critical though, as the potential omission of relevant socio-political factors as well as economy-wide feedback effects might lead to undesirable outcomes when using rather narrow modelling results from single sectoral-analyses as a basis for policy making [9,10]. Addressing this issue requires a broad set of methods and – most importantly – their integration. Typical methods for analyzing climate mitigation measures in general and energy transformation in particular include top-down (macro-) economic integrated assessment modelling (IAM, see e.g. Ref. [11], techno-economic bottom-up engineering modelling (see e.g. Ref. [12] and various other quantitative and qualitative methods of social sciences. IAMs focus on the whole economy, often using multiple regions, economic sectors, and households. Engineering models take a technology-rich, but narrow, sectoral perspective, considering the full energy cascade from primary supply to end-use. Methods of social

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sciences substantiate research findings using text-based analysis, surveys and other qualitative approaches to understand softer factors such as social-political preferences, drivers and barriers.

There are several limitations regarding these methods, though, particularly when using them in isolation [13]. The idea of optimally trading-off costs of climate change impacts with costs of mitigation in order to find an optimal warming level – rooted in the seminal work of [14] – involves substantial limitations, highlighted for example by Refs. [15–17]. As summarized by Ref. [18]; the estimated optimal warming levels of cost-benefit IAMs will always remain highly disputed due to, among other things, fat-tailed and discontinuous damage functions, and social discounting. Instead, Pezzey (2019), and also others such as [19]; suggest an alternative approach, which focuses on process-based and soft-linked IAMs [20] for low-carbon pathway evaluation [21]. review such pathway evaluations, focusing on computable general equilibrium (CGE) models which are soft-linked with sectoral models of energy and agricultural systems. Their review emphasizes the merits of model linking but criticizes that the advancement of linked against unlinked modelling often remains disregarded or nontransparent.

Studies that use the suggested alternative approach are often confronted with another limitation, namely the type of comparison they are doing for isolating effects. Typically, such studies compare results to a hypothetical baseline scenario, which neither accounts for climate policy nor for climate change impacts. Such a framework is problematic as it focuses on the costs of mitigation measures and neglects the avoided climate change impacts and other co-benefits, as well as the eventual rectifying of existing imperfections in the socio-economic system [22]. Carefully incorporating these neglected elements tends to increase economic activity and welfare, eventually deriving net gains of mitigation. On top of the sample of articles discussed in Ref. [21]; we investigate further contributions to this strand of the literature. The study by Ref. [23] is of global scope with a focus on regional effects and finds that energy demand reductions combined with power sector decarbonization achieves substantial emission cuts with relatively small GDP losses. Similar conclusions are drawn by Refs. [24,25]; focusing on Europe [26]. also comes to a similar conclusion when comparing a future German system with increased renewables against the status quo (i.e., historical base year). Equity implications, a key potential barrier, are addressed for example in Ref. [27]; finding that a redistribution of carbon tax revenue can increase equity.

Another key limitation we see in the current energy-economy modelling literature is the lack of including socio-political drivers and barriers in the socio-economic system. Social and political factors are in fact important drivers and constraints of the energy transition (see e.g. Refs. [28–30], for recent examples), however, this research often remains qualitatively whereas quantitative energy modelling focuses mainly on techno-economic aspects and less on non-technical aspects [9].

In this paper, we contribute to resolving the mentioned limitations. One of the main contributions of this paper is the combination of the useful features from various interdisciplinary perspectives and methods on climate change mitigation and energy transformation. Specifically, the scenario framework in the present analysis follows the suggestion of [22]; p. 1041) "*to compare welfare and development outcomes of climate trajectories that are similar but stem from different policy packages.*" More precisely, in this article we present a novel soft-linking approach of a social-political method, an energy system model and an economic impact model. The applied sequence starts with the QTDIAN toolbox [31], which quantifies social-political barriers and drivers of net-zero energy in Europe. In a storyline manner, the output of QTDIAN informs the design of net-zero energy systems across Europe explored by the Euro-Calliope model [8] which is finally passed on to the macroeconomic model WEGDYN [32] to investigate economy-wide feedback effects. This one-way soft-link overcomes the mentioned limitations and combines the strengths of standalone models. The model setup covers the reduction of all domestic combustion-based and industrial process emissions of CO_2 and thus allows us to reflect on regional effects in terms of changes in the system-wide unit-cost of electricity as well as derived employment, welfare and public budget implications, all of which can be traced back to the social-political storylines.

The described combination of models is useful in three ways. First, QTDIAN provides social-political drivers and barriers to which Euro-Calliope and WEGDYN are otherwise agnostic. Second, Euro-Calliope captures the fluctuating operating and capital expenditures for intra-annual and of spatially explicit firm supply of energy that the coarsely resolved WEGDYN model cannot. Third, WEGDYN extends the analysis of Euro-Calliope to the economy-wide level. In addition, we emphasize to increase transparency in modelling, by providing detailed information on the models themselves as well as the coupling (particularly between Euro-Calliope and WEGDYN).

To summarize, our analysis contributes to the strand of macroeconomic impact analysis of climate change mitigation that highlights the relevance of social-political drivers and barriers, and the limits of conventional standalone applications of top-down models. We focus on the interaction between net-zero configurations of the energy system and labor, emission allowance and capital markets, amending the bottom-up energy sector modelling. The main research question asks "*what are the economy-wide impacts of net-zero energy systems in Europe if social-political drivers and barriers have certain characteristics?*"

The remainder of the paper is structured as follows. We describe our methodology and data in section 2, present results in section 3, discuss main findings in section 4, and conclude in section 5. The interested reader will find further results in the Appendix and a more detailed description of the method in the online supplementary material (OSM).

2. Methodology

2.1. Overview

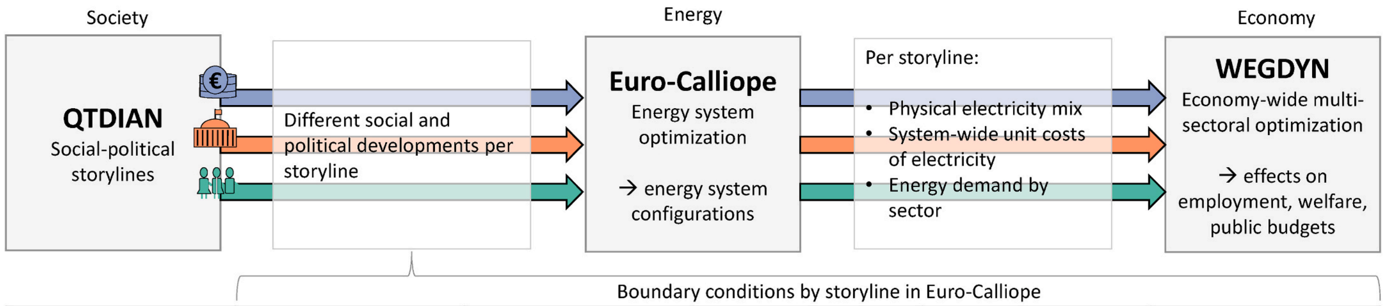
We set up a framework that links the QTDIAN modelling toolbox, the Euro-Calliope energy model and the WEGDYN macroeconomic model and apply it in a sequential unidirectional manner (see Fig. 1 for an overview). In a nutshell the linking is as follows: QTDIAN is a toolbox for the Quantification of Technological DIffusion and sociAl constraints. It creates storylines that build on governance logics, allowing for the exploration of different, possible social-political developments. These storylines imply different boundary conditions for Euro-Calliope which calculates optimal energy system configurations under the given storyline-specific boundary conditions. Finally, we include the configurations of Euro-Calliope into WEGDYN via a soft-link, allowing for an economy-wide assessment including effects on employment, welfare or public budgets.[1] Note that there is no direct link between QTDIAN and WEGDYN; it is the energy system model that bridges this gap by providing energy-related supply and demand changes to WEGDYN. In the following we describe each model in its standalone version, followed by details on the model linking.

2.2. Standalone model descriptions

2.2.1. The QTDIAN toolbox and its storylines

QTDIAN [33] consists of two main elements: (i) Qualitative storylines that are based on governance logics of the energy transition and build on observed social and political drivers and barriers in the European energy transition. Empirically observed patterns are adapted to generate quantifications of the storylines. (ii) Quantitative social and political data can be used together with the storylines or as separate building blocks to answer specific research questions with energy

[1] The choice of putting the macroeconomic model at the end of the modelling chain is motivated by the research question itself, asking about the economy-wide effects of the energy transition.



Storyline	Climate targets	Renewable generation	Transmission & interconnection	Storage capacity	Mobility
Market Driven (MDR)	≥55% emission reduction in line with „Fit for 55"-policy target; stronger decline in energy intensity	Only techno-economic limits	No quantitative limits	High	Electrification; no change in transport modes
Government Directed (GDI)	≥55% emission reduction in line with "Fit for 55"-policy target; stronger decline in energy intensity	Nuclear capacity at current level; coal phase-out by 2038; 1/2 centralized	Network expansion; < 15% hourly exchange of current capacity	Medium	Electrification; moderate decline in motorized individual transport
People Powered (PPO)	More ambitious CO_2 reduction than "Fit for 55"-policy target (≥65% emission reduction); lower energy intensity decline	More ambitious expansion of renewables; Nuclear and coal phase-out by 2030; 4/5 decentral	Network expansion minimized; < 5% hourly exchange of current capacity	Low	Electrification; strong decline in motorized individual transport

Fig. 1. Overview of model ensemble, specification of storylines and model linkages. Note: "centralized" refers to the deployment of offshore wind, open field PV, conventional power plants, whereas "decentral" covers onshore wind, rooftop PV, combined heat & power.

models, putting social and political trends and preferences center-stage. In this study, three socio-political storylines and quantifications are applied to update the inputs or constraints of the Euro-Calliope model.

In comparison to existing storylines, which typically focus on technological and economic aspects, QTDIAN *social-political* storylines are based on governance logics and have the needs, preferences and capacities of citizens and their role within the energy transition at its core. QTDIAN presents three ideal-typical developments, each driven by different sets of technological and institutional changes, and each triggering different engineering and social challenges: a *people-powered (PPO)*, a *government-directed (GDI)*, and a *market-driven* (MDR) storyline. In reality a mix of the storylines may occur, they could exist in parallel depending on the contexts, or we could even experience switches from one storyline to another. Fig. 2 presents the social-political storylines and their key features/variables. A more detailed description of the storylines can be found in Ref. [33]. For each storyline, we assume different developments for policy targets, energy mixes and grid expansions, mobility, and distance/density restrictions.

2.2.2. The euro-calliope energy system model

The sector-coupled Euro-Calliope model [34] is based on Calliope, which is a framework to build energy system models, designed to analyze systems with selectively high spatial and temporal resolution, permitting analyses ranging from single urban districts to countries and continents [35]. Moreover, Calliope facilitates the specification of user-defined objective functions. Under its default configuration, the objective function is oriented towards cost minimization of annualized total system costs. Calliope presents an inbuilt feature to model the generation of alternatives, which practically contributes to find near cost-optimal, technological diverse and spatially explicit energy system configurations [36].

In this study, the sector-coupled Euro-Calliope model is based on version 0.6.8 of the Calliope framework, and it incorporates electricity, heat and transport sectors. The model encompasses 13 carriers: electricity, hydrogen, CO_2, liquid and gaseous hydrocarbons (kerosene, methanol, diesel, and methane), solids (residual biofuel and municipal waste), low-temperature heat (combined space heat and hot water, and cooking heat), and vehicle distance (heavy- and light-duty road vehicles). Since future international energy commodity prices are highly uncertain, (mostly fossil) energy imports from outside our model region are assumed to fade out by 2050. For this analysis the model is working on a national spatial scale considering 35 countries. It solves at hourly resolution for a full year and deploys technologies overnight to fulfil hourly demand in each modelled region. The optimization process addresses two future years, namely 2030 and 2050. Energy carrier demand uses projected service demand from the models DESSTINEE [37] and HEB [38]. A flow chart of the technology-rich resolution can be found in the OSM.

2.2.3. The WEGDYN macroeconomic model

WEGDYN is a global computable general equilibrium (CGE) model. In general, CGE models solve on an annual basis to find optimal states is which demand equals supply simultaneously on all markets in an economy. Economic sectors maximize profit from their production and households maximize their utility from consuming goods and services, both according to sector and household-specific production and consumption functions.[2] Economic sectors combine intermediate inputs and primary factors in order to supply goods and services to markets, which are demanded by other sectors or private and public households. Private households earn income by supplying the primary factors (in WEGDYN labor, capital and land) to production sectors and receive public transfers. The public households represent the regional governments and spend their tax income on public consumption, subsidies and transfers to private households.

[2] Specifically, we use nested constant elasticity of substitution (CES) functions, which specify how goods are combined to generate output (either a good or utility) subject to expenditure shares from the benchmark year and empirically estimated parameters that measure how strong certain inputs into this function are being substituted by another good when relative prices are changing (i.e. elasticities of substitution).

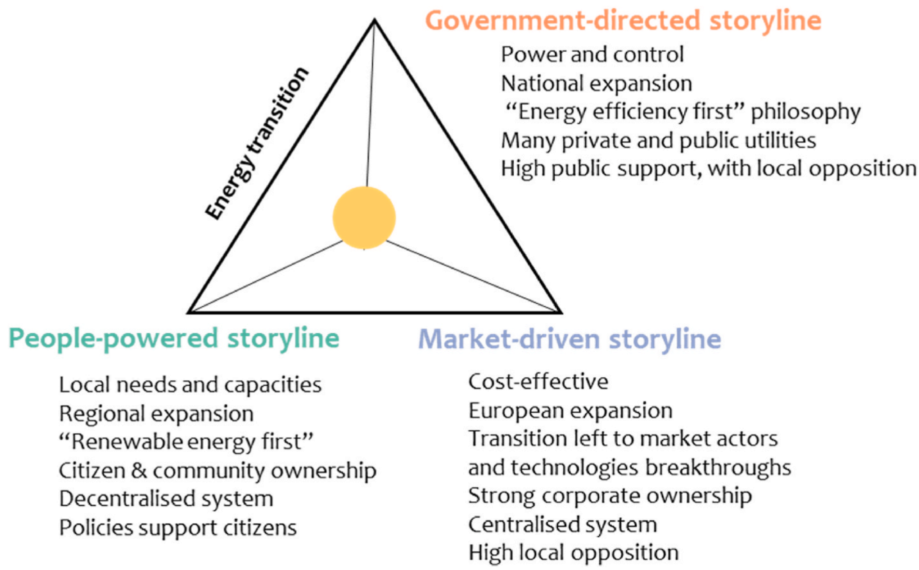


Fig. 2. The energy transition logics and their use for the QTDIAN social-political storylines; adapted from Foxon (2013).

WEGDYN is based on [39] with the advancement to a recursive dynamic version solving in 5-year steps as laid out in Ref. [32]. The database is GTAPv9 with benchmark year 2011 [40]. For this study, the electricity sector distinguishes the following subsectors (based on [41]: five fossil fuel-based and five renewable generation technologies, one nuclear generation technology as well as a sub-sector that provides transmission, distribution and storage services. Combustion-based CO_2 emissions are taken from GTAPv9 and industrial process emissions from the UNFCCC emissions inventory. The regional resolution is described in Table 1, including a mapping to Euro-Calliope's regions. Further, we model a regional wage rate that is tied to the respective consumer price index (i.e. a real minimum wage) that allows for constant purchasing power below which people would voluntarily decide not to supply their labor to the market. This allows the assessment of changes in unemployment. Regarding factor mobility we follow the typical assumption of perfect mobility across sectors and immobility across regions.

Regarding CO_2 emissions we model a cap-and-trade system reflecting an EU-wide emission trading scheme (ETS) covering all production-based CO_2 emissions in the EU27+ model region. Regions trade emission allowances on a common single market, determining the EU-wide allowance price (i.e. CO_2 price). The revenues flow into regional public budgets and are spent for generic public service provision. The modelling of the ETS has three advantages. First, it reflects the current plans of the EU of emission allowance trading also in the transport and buildings sectors already before 2030. Second, the model ensemble is able to reveal the interaction between changes in the energy system and emission markets. Third, the alignment of emission caps for all storylines allows for a consistent and comparable cost-effectiveness analysis until 2050, exploring the economic impacts in Europe for a given CO_2 emission reduction target. Please see the OSM for details.

Table 1
Regional resolution for Europe and mapping to Euro-Calliope.

European regions	Acronym	Comprising GTAP regions	Mapping to Euro-Calliope
Germany	DEU	Germany	DEU
Austria	AUT	Austria	AUT
Italy	ITA	Italy	ITA
UK	UKD	UK	GBR
France	FRA	France	FRA
Greece	GRC	Greece	GRC
Iberian Peninsula	IBE	Spain, Portugal	ESP, PRT
Belgium, Netherlands, Luxemburg and Switzerland	BNL	Belgium, Netherlands, Luxemburg, Switzerland	BEL, NLD, LUX, CHE
Northern Europe	NEU	Sweden, Ireland, Denmark, Finland, Norway, Estonia, Latvia, Lithuania, Rest of EFTA (Liechtenstein, Iceland), Rest of the world (Antarctica, French Southern Territories, Bouvet Island, British Indian Ocean Territory)	SWE, IRL, NOR, DNK, ISL, FIN, EST, LTU, LVA
Central-Eastern Europe	CEU	Czech Republic, Hungary, Poland, Slovenia, Slovakia	SVN, HUN, POL, CZE, SVK
South-Eastern Europe	SEE	Cyprus, Malta, Bulgaria, Croatia, Romania, Albania, Rest of Europe (Bosnia and Herzegovina, Macedonia, Serbia and Montenegro, Faroe Islands, Gibraltar, Monaco, San Marino)	ROU, SRB, BGR, HRV, BIH, ALB, CYP, MKD, MNE

2.3. *Specification of model links*

2.3.1. *Using QTDIAN storylines in euro-calliope*

Following the logic of each storyline, we assume different developments for policy targets, energy mixes and grid expansions, mobility, and infrastructure density restrictions. The three storylines have been translated into a set of storyline features/variables used in Euro-Calliope assumptions (see Fig. 1 and the OSM for details). The specific storyline implementation in Euro-Calliope model concerns the components of electricity and heat generation as well as the conversion (e.g. synthetic fuels and hydrogen), storage (e.g. batteries) and transmission of energy. The market-driven (MDR) system prioritizes least-costs applying no limit on hourly production transmitted to or from neighboring countries, no limit on new transmission and nuclear capacity (but limited to countries currently using nuclear), a high-capacity maximum for batteries and a full availability for renewables on technically feasible land. The government-directed (GDI) system aims to balance central versus decentral electricity generation, while limiting hourly transmission increases to neighboring countries by no more than 15 % of current production and new transmission lines. Official public schedules currently available limit the share of nuclear in the energy mix, the maximum battery capacity is mediocre and onshore wind power and PV is prohibited on protected land and forest. In the people-powered (PPO) system, small-scale, citizen-owned technologies are given adoption-priority with a transmission limit of less than 5 % of produced energy and only current transmission capacities. People demand faster climate action, resulting in faster decrease of emission levels. Nuclear power is excluded from the energy mix due to a lack of social acceptance and the maximum of battery capacities is low. Offshore wind power and open-field PV are subject to limited land availability. As a result of the different constraints, the different storylines also lead to different system-wide costs of electricity. The storyline-specific energy system configurations of energy supply depend on specific assumptions on energy demands of industry, transport and heating which are detailed in Ref. [34]. More detailed information on the linking between QTDIAN and Euro-Calliope can be found in [42].

2.3.2. Soft-linking euro-calliope and WEGDYN

WEGDYN processes the outputs from Calliope as inputs along the three storylines. There are two entry points in WEGDYN: (i) the supply of energy and (ii) the demand for different energy carriers by economic sector (see OSM for details on the matching process of sectors and regions between the two models).

We first describe the supply side translation. For that we use annual energy cost-quantity pairs of electricity generation, conversion and storage (power-to-X), as well as electricity transmission for 2030 and 2050. For electricity generation, we use both the shares of physical input quantities (in TWh) and system-wide unit-cost of electricity from Euro-Calliope's storyline-specific outputs. This enters WEGDYN via a multiplicative electricity-mix-shifter *EMS* in the production function of the electricity aggregate (i.e. mix). *EMS* is specified for each storyline *stl*, region *reg* and technology *tec*. Equation (1) shows how *EMS* is calculated. Note, that for readability we drop the *stl* and *reg* indices.

$$EMS_{tec} = \sum_{tec} \overline{Y}_{tec} * \frac{Q_{tec}}{\sum_{tec} Q_{tec}} * \frac{SUCE_{tec}}{\overline{\varnothing SUCE}} * \frac{1}{\overline{Y}_{tec}} \tag{1}$$

with $\overline{Y}$ being the contribution of an electricity technology's generation to the mix in monetary terms in the benchmark year[3] as given in WEGDYN, Q the new physical quantities by technology, *SUCE* the technology-specific system-wide unit-cost of electricity both coming from Euro-Calliope and $\overline{\varnothing SUCE}$ the average system-wide unit-cost in the benchmark year.

Hence, when multiplying *EMS* to the individual electricity generation technology's contributions $\overline{Y}_{tec}$ in WEGDYN's production function of the electricity mix, this changes the composition of the electricity mix in monetary terms:

$$EMS_{tec} * \overline{Y}_{tec} = \sum_{tec} \overline{Y}_{tec} * \frac{Q_{tec}}{\sum_{tec} Q_{tec}} * \frac{SUCE_{tec}}{\overline{\varnothing SUCE}} \tag{2}$$

The right-hand-side of Equation (2) can be interpreted as follows. The first expression is the total of electricity in the mix in monetary terms in the benchmark year, which is multiplied by the technology-specific physical target share of the future (second expression) as well as a cost-markup that accounts for relative cost (dis)advantages of the individual technologies as compared to the initial situation (third expression). Equation (2) thus gives the target share of a generation technology's input to the electricity mix in monetary terms in a future year, which is met by applying the *EMS*. The *EMS* parameter thus captures not only the physical target mix, but also accounts for relative cost differences across technologies.[4] Keeping everything else equal, a higher/lower SUCE would thus increase/decrease the required expenditures for the same amount of physical electricity, leading to lower/higher economic productivity.

For energy conversion and storage (battery, syngas and biofuels), we add respective integration costs as additional fixed-share input in the cost function of affected WEGDYN sectors. Importers and exporters equally split additional costs of transmission lines, which is modelled as an expenditure-neutral shift in the structure of the import basket of the importing region.

Now we describe the link on the demand side. This is done in two steps. First, for each time step physical demand flows per storyline *stl*, region *reg*, economic sector *ecs* and energy carrier *nrg* are converted to monetary flows (expenditures) *D* as shown in Equation (3). Again, we drop the *stl* and *reg* indices.

$$D_{ecs,nrg} = \frac{Q_{ecs,nrg}}{\overline{Q}_{ecs,nrg}} * \overline{D}_{ecs,nrg} \tag{3}$$

with $\overline{D}$ being benchmark year energy expenses as given in the WEGDYN database and $\overline{Q}$ being physical quantities in the WEGDYN's benchmark year given by Ref. [43].

Second, and based on monetized energy demands *D*, we update the share of energy demands in monetary terms relative to the benchmark via an energy demand multiplier *EDM*, as shown in Equation (4).

$$EDM_{ecs,nrg} = \frac{D_{ecs,nrg}}{\sum_{nrg} D_{ecs,nrg}} * \frac{\sum_{nrg} \overline{D}_{ecs,nrg}}{\overline{D}_{ecs,nrg}} \tag{4}$$

By multiplying EDM with $\overline{D}$ (see Equation (5)) we obtain the new expenditure requirements for different energy carriers (i.e. inputs) in respective production and consumption functions of WEGDYN. Thus, this adjustment updates all energy-using production functions in the WEGDYN model.

$$EDM_{ecs,nrg} * \overline{D}_{ecs,nrg} = \frac{D_{ecs,nrg}}{\sum_{nrg} D_{ecs,nrg}} * \sum_{nrg} \overline{D}_{ecs,nrg} \tag{5}$$

Further, next to supply and demand side linkages, we also adjust emission factors in WEGDYN to capture that by 2050 refinery products and gases are produced synthetically, and industrial processes (steel, chemicals) are based on a range of power-to-X options.

Finally, as imposing specific energy system configurations to the macroeconomic models triggers indirect effects, which lead to indirect changes in energy demand (and supply in turn) and thus changes in CO_2 emissions, this "loose end" needs to be closed. This is done via the mentioned emissions cap-and-trade system in WEGDYN. This cap guarantees that all storylines share the same total CO_2 emission caps while the different structures of the energy system model (and eventual different *energy* related CO_2 emissions) are still included. Importantly, only this common emission level makes the results comparable across storylines.

The soft-link applied here raises the question of how robust it is. In the OSM we provide a section comparing energy cost effects derived by Euro-Calliope and the resulting energy price effects in WEGDYN, indicating robustness. We also include the full dataset that is delivered from Euro-Calliope to WEGDYN and information on how it was mapped to the resolution of WEGDYN.

3. Results

3.1. Changes in the energy system and emissions

Fig. 3 shows how the different storyline-specific constraints from QTDIAN turn into different results of Euro-Calliope. For the EU27+ we show the electricity mix (top), the components of SUCE (middle) as well as the assumed structure of electricity demand (bottom). Note that these results are already shown in the sectoral resolution of WEGDYN.

[3] Note that this corresponds to a technology's monetary output value in general equilibrium.

[4] Note that by applying EMS we rescale the monetary relative shares of generation – the upscaling to higher absolute levels happens endogenously via the overall demand for electricity.

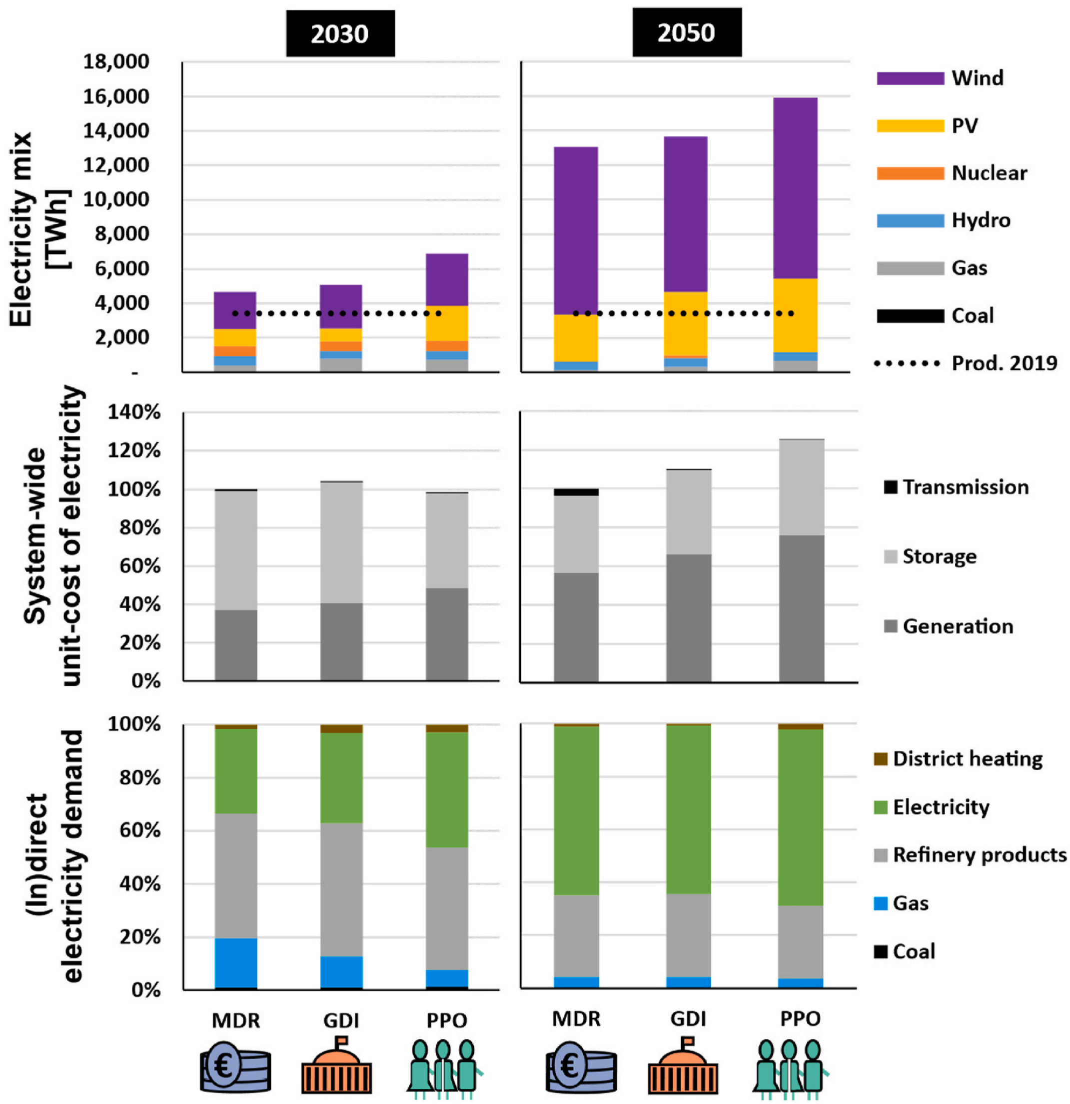


Fig. 3. EU27+ electricity mix, system-wide unit-cost of electricity and (in)direct electricity demand across storylines for 2030 (left) and 2050 (right). System-wide unit-costs of electricity are indexed to the MDR storyline in both time steps 2030 and 2050. Note that refinery products and gas are partly still fossil-based by 2030 and fully power-to-X based by 2050.

We observe the following developments. First, electricity generation in general – but particularly of renewables-based technologies – strongly increases due to overall electrification. MDR shows the slowest pace in electrification, PPO the fastest (this is given by definition of the storylines), which becomes visible in the different electricity generation levels in 2030. The respective shares of renewables (PV, wind, hydro) in the electricity mix of 2030 are 84 % (MDR), 85 % (GDI) and 89 % (PPO), with parts of gas supply already being based on renewables by then. By 2050 there is a full penetration of renewables in the electricity mix because of various power-to-X ancillary technologies. Second, when looking at the composition of SUCE in the MDR storyline we see that costs are driven less strongly by generation costs, due to a higher share of storage and transmission, while the opposite applies for PPO, which is characterized by a strongly decentralized structure. The GDI storyline requires larger expenditures for storage and conversion due to a relatively centralized supply structure balancing hourly and seasonal demand patterns. Third, in 2030 the GDI system is around 4 % costlier compared to the MDR system, while PPO is slightly cheaper by around −1%. The picture changes by 2050, though because hard-to-abate sectors (steel, cement, chemicals) also reach net-zero GHG emissions, requiring additional relatively costly generation, storage and conversion. As in GDI and PPO there are limits for transmission and storage, this leads to higher costs of around 10 % (GDI) and 26 % (PPO) compared to MDR. Finally, the EU27+ assumed energy demand structure is mirrored, underlining the strong electrification of the economy (either by using electricity directly e.g. in production processes or mobility, or indirectly e.g. for the generation of green hydrogen).

In terms of CO_2 emission reductions within Euro-Calliope, and taking supply and demand adjustments together, MDR and GDI storylines reach a 55 % system-wide reduction by 2030 (consistent with EU policy targets, with energy-related emissions being cut by 63 % and industrial process emissions by 20 %). Due to the underlying governance logic with larger public support and urge for faster climate actions, the PPO storyline leads to a faster diffusion of mitigation measures and over-achieves emission reduction targets by 2030, reaching 65 % by then (with 74 % for energy-related and 34 % for industrial process emissions). The raw data output by Euro-Calliope is available in the OSM.

3.2. *Regional economic impacts of socio-politically driven net-zero energy*

We now look into storyline-specific economy-wide effects. For doing so we use the MDR storyline as reference and compare the other two storylines to it. We first look at the relationship between SUCE and economy-wide unemployment rates across regions, which are shown in Fig. 4. SUCE is the processed output from Euro-Calliope (compare also Figure A. 1 in the Appendix) and unemployment effects are coming from WEGDYN (compare also Figure A. 2). For both, the GDI and PPO storyline and both future years of analysis, there is a trend of higher (relative) SUCE translating into higher (relative) unemployment rates for most regions due to lower energy system – and thus economy-wide – productivity. For the GDI storyline unemployment at the aggregate EU27+ level is by 1.5%-points higher in 2030 and by 3.2%-points higher in 2050. However, the PPO storyline is connected to slightly lower unemployment rates, with −0.4%-points by 2030 and -0.6%-points by 2050, even though SUCE is highest in 2050 across all three storylines. This counterintuitive result originates from indirect effects which work through the following intertwined channels.

The emission allowance market fixes the supply of and confronts it with demand for allowances connected to the storyline-specific configuration of the energy system. For the same aggregate EU27+ emission reductions, the GDI storyline shows a 10 % higher allowance price in 2030 relative to MDR (cf. Figure A. 3) due to a larger share of remaining fossil-based energy supply (cf. Fig. 3). Contrary, the PPO storyline shows a −20 % lower allowance price relative to MDR in 2030 due to stronger renewables penetration driven by the underlying storyline logic by then. The smaller PPO carbon allowance price has a rectifying overall effect on the economy, with lower consumer prices which in turn increases real wages and thus labor supply (employment) relative to the MDR storyline. The lower unemployment in 2030 leads to higher economy-wide income, which allows for higher investments inducing stronger overall capital accumulation until 2050. This dynamic effect is particularly beneficial for a storyline like the PPO, in which a much higher capital-intensive operation of decentralized generation units is in place. However, and also visible in Fig. 4, the range of regional unemployment effects for the GDI and PPO storylines is considerable and is getting larger between 2030 and 2050. Note that in the climate-neutral state of 2050, and valid for all storylines, the remaining emission allowance demand is below the available allowances (cap) and, hence, the respective CO_2 price is zero (cf. Figure A. 3 and Figure A. 5, where also GDP effects are visible across storylines).

The WEGDYN model allows us to derive welfare effects, which are emerging from the combination of change in income and consumer price effects. We show welfare effects in Fig. 5, together with changes in SUCE and unemployment. Welfare quantifies consumption possibilities, or more precisely the willingness to pay for marketed goods and services at hypothetically unchanged relative prices, which would restore the same level of welfare for private households. In general, we expect negative welfare effects if consumer prices were rising (mainly driven by higher SUCE), and also due to higher unemployment (i.e. lower income). In most regions we clearly observe this pattern of lower/higher SUCE translating in lower/higher unemployment, which in turn results in higher/lower welfare.[5] In the GDI storyline with both the negative income effects and higher consumer prices at the EU27+ level storyline, welfare is also lower in 2030 and 2050 (relative to MDR), as shown in the top row panels of Fig. 6. For PPO (bottom row panels), and at the EU27+ level, the slightly higher income and lower consumer prices in 2030 have slightly welfare-enhancing effects, while in 2050 the higher economy-wide income dominates the slightly higher consumer prices leading to a small welfare benefit.

The economic value of electricity transmission in the MDR storyline is evident due to limited new transmission capacity in the GDI and PPO storylines, resulting in higher average SUCEs across the EU27+. The MDR storyline's initial energy system configuration influences SUCE variations in other storylines. In the GDI storyline, countries like IBE, NEU, and UKD, previously exporters in MDR, face penalties due to constraints balancing centralized and decentralized capacity. SUCE variations in 2030 and 2050 depend on each country's ability to balance centralized and decentralized production based on local resources. For instance, in 2050, GRC and ITA shift to onshore wind to offset high production from centralized open-field PV plants incurring higher costs. In the PPO storyline, regional differences in 2030 are within a lower range. IBE, ITA, and UKD experience adverse SUCE changes as they transition from open-field PV, hydro, and onshore wind to rooftop solar panels. By 2050, open-field PV will be replaced by onshore and rooftop PV, favouring decentralized technologies and generally leading to higher SUCEs for most countries.

An explicit feature of WEGDYN, and a relevant influencing factor of decision-making, is the public budget effects of the different storylines. On the aggregate EU27+ level, the GDI storyline implies larger public budgets by 2030 driven by larger revenues from CO_2 pricing and lower budgets by 2050 due to lower revenues from labor and commodity taxation (Fig. 6). On the contrary, the PPO storyline implies smaller public budgets by 2030 due to lower carbon prices and higher budgets by 2050 due to positive employment effects inducing larger labor tax revenues.

3.3. Sensitivity analysis

The central model results highlight the relevance of emissions trading and the labor market. In terms of results sensitivity, we provide Figure A. 6 in the Appendix comparing EU27+ welfare effects between our central model runs with a run that neutralizes emission allowance trading and deactivates the assumption of a slack labor market. For isolating the first channel, we fix the carbon price as it develops in the MDR storyline. Hence, additional distortionary or rectifying effects can only come indirectly from changes in the level of CO_2 emissions (and consequently emission targets are not achieved necessarily). We find that allowance trading is beneficial for the PPO but not for the GDI storyline, which confirms the conclusion from the central runs because the sign of effects remains the same but magnitude sizes change. The second channel investigates the relevance of boom phases, where changes in nominal-wage-driven demand for labor do not affect labor supply. In such a situation, welfare effects are less negative for GDI and less positive for PPO in 2030 and even turn negative in 2050, which points to the eventual relevance of labor market frictions during the energy transition.

Further, we briefly demonstrate the usefulness of the applied integration of bottom-up and top-down models (see OSM for details and results). For doing so we take the coupled MDR storyline-setup as an illustrative case for a coupled model run and compare it to a "top down-only" (TDO) model setup without such a coupling. In the TDO setup without a link to an energy model, any structural change is solely driven by profit and utility maximization using production and consumption functions that are calibrated to statistically estimated elasticities of substitution based on historical data. In contrast, in the coupled setup we integrate bottom-up information from Euro-Calliope as describe earlier, which allows for more radical changes as compared to what was overserved in the past. When looking into CO_2 price effects as an illustrative indicator we find that in 2050 CO_2 prices are differing strongly between the two setups. Under TDO, allowance prices are soaring due to structural frictions in WEGDYN. By contrast, the imposed structural changes of the coupled setup overcomes such frictions, requiring much lower CO_2 prices for staying below the given emission limits and putting much less burden on the economy.

4. Discussion

A stand-alone application of a state-of the art macroeconomic model is helpful but has its limits. Here, we have explored substantial structural

[5] For all storylines and both time steps we find a very strong correlation between unemployment and welfare ($R2 > 0.93$ for all four cases with an OLS estimation, see Figure A. 4).

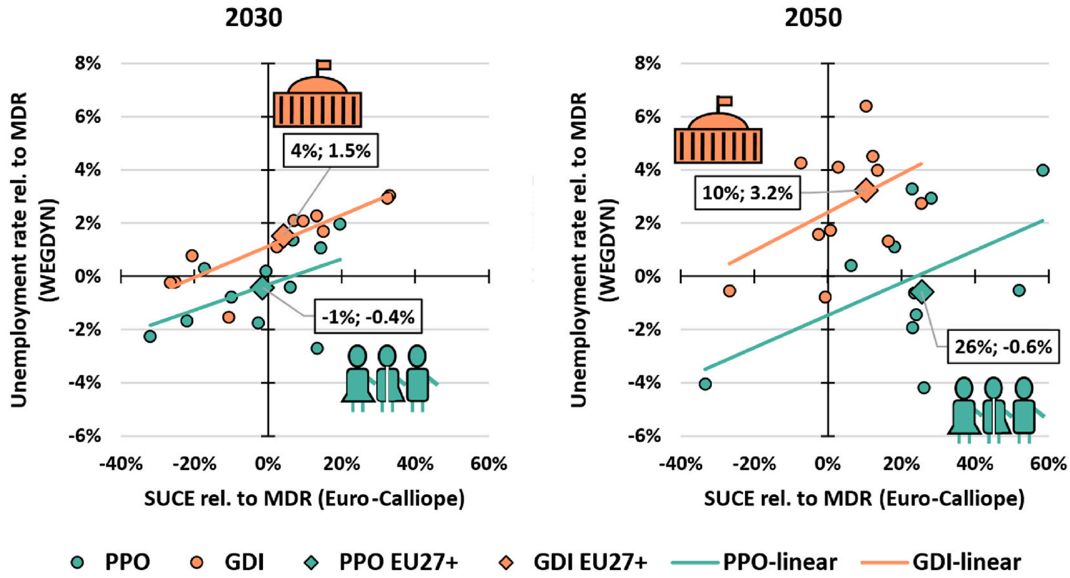


Fig. 4. System-wide unit-cost of electricity (SUCE) (x-axis, Euro-Calliope output = WEGDYN input) and unemployment rate (y-axis, WEGDYN output) for GDI and PPO relative to MDR; single dots represent individual WEGDYN EU27+ regions; diamonds are for the aggregate effect at the EU27+ level.

breaks from a top-down perspective by sourcing information from more fine-grained models, tailor-made for the issue under consideration. This allows us to take advantage of the merits of both bottom-up and top-down approaches. In this study, social and political aspects are core drivers to generate future alternatives of net-zero energy systems (QTDIAN). Fed into an energy system model, the approach considers temporally, spatially and technologically resolved service demands to optimize the net-zero energy supply to cover them. Hence, the resulting net-zero allocation is physically possible and shown to be of low-cost (Euro-Calliope). Additionally, we use a comprehensive economic approach that accounts for economy-wide effects exploring the indirect effects of such an allocation (WEGDYN).

We find that social-political storylines provide valuable boundary conditions for the design of feasible net-zero energy systems and that the people-powered (PPO) storyline with the highest system-wide unit-cost of electricity has the potential to have a more beneficial European-wide welfare effect compared to market-driven (MDR) and government-directed (GDI) storylines. This result originates in dominating indirect effects covered by the macroeconomic model, particularly positive employment effects which leads to higher income and stronger capital accumulation over time. This highlights the relevance of interactions between different markets and the need for economy-wide dynamic analysis. Also, in terms of regional differences, we see that a simple causation between changed direct costs for energy and welfare effects is not always possible. A prime driver is the interaction with the emissions trading scheme, because the speed and emissions coverage of CO_2 pricing in the energy system strongly affect economic distortions or rectifications. There is evidence at the sector [44] and installation level [45] for the EU ETS to have contributed to effective emission reductions in the past. If this dynamic incentive claim holds, the higher allowance price in GDI may change and drive the energy system configuration to come closer to the PPO storyline. To explore this hypothesis, a feedback link from WEGDYN to Euro-Calliope would be required. Such a feedback loop would also enable us to use energy demand changes derived from WEGDYN in Euro-Calliope.

The economy-wide analysis reveals different effects on public tax revenues implying that there are different medium and long-term capabilities for European governments to provide fiscal impulses to support and co-design different energy system configurations. Policymakers with a short-term view would see an incentive to foster the GDI storyline because of higher budgets in the near future, while in the longer term, policymakers would prefer the PPO storyline. Public budgets could also be useful for mitigating adverse regional effects by granting climate dividends to vulnerable regions/households financed by the revenues of carbon pricing. However, instead of shifting tax revenues between regions based on political processes, the MDR storyline happens in a framework with stronger net-zero electricity transmission between borders to places where it is most useful and, hence, represents an efficient transfer mechanism based on market processes. However, energy networks are of a monopolistic character [46] and thus together with the internal energy market development, require common priority setting at and regulation from various policy levels.

One possible springboard for further transdisciplinary research is the soft-link between Euro-Calliope and WEGDYN, which could be used for clustering the economic effects of the already explored large option space of more than 400 configurations of net-zero energy in Europe [8]. This agnostic approach of modelling to generate alternatives would not only raise the scholarly but also social value of model results. Second, the underlying analysis focuses on the difference between various energy supply side options to serve the similar levels and structures of decarbonized energy demand. A deeper investigation of a range of options on the energy demand side seems promising. The latter is also relevant for the discussion of changing risk profiles in Europe's value chains because a strong reduction of European fossil energy imports may come with an increased material supply risk. Such changes in material demands are unquantified in the underlying analysis but could be explored by linking the storylines to social metabolism models such as ENBIOS [47]. On the one hand, international trade of Europe with the rest of the world also raises questions of waterbed effects and carbon leakage if unilateral climate mitigation measures are put forward. On the other hand, there are also high-cost reduction potentials of transmission between Europe and other world regions [48], which is neglected here with fully autarkic energy systems. However, the analysis shows how a prosperous net-zero development in energy and economic terms can look, to raise the attractiveness of following such a path or to convince non-European partners to potentially join a climate club.

We acknowledge several limitations regarding the macroeconomic model. First, we assume that there is no mobility of capital and labor across the larger economic regions of WEGDYN, which is a standard, but strong, assumption in CGE modelling. When allowing for a stronger inter-regional integration we would expect results to converge, meaning that regional disparities would be weaker. For example, higher capital

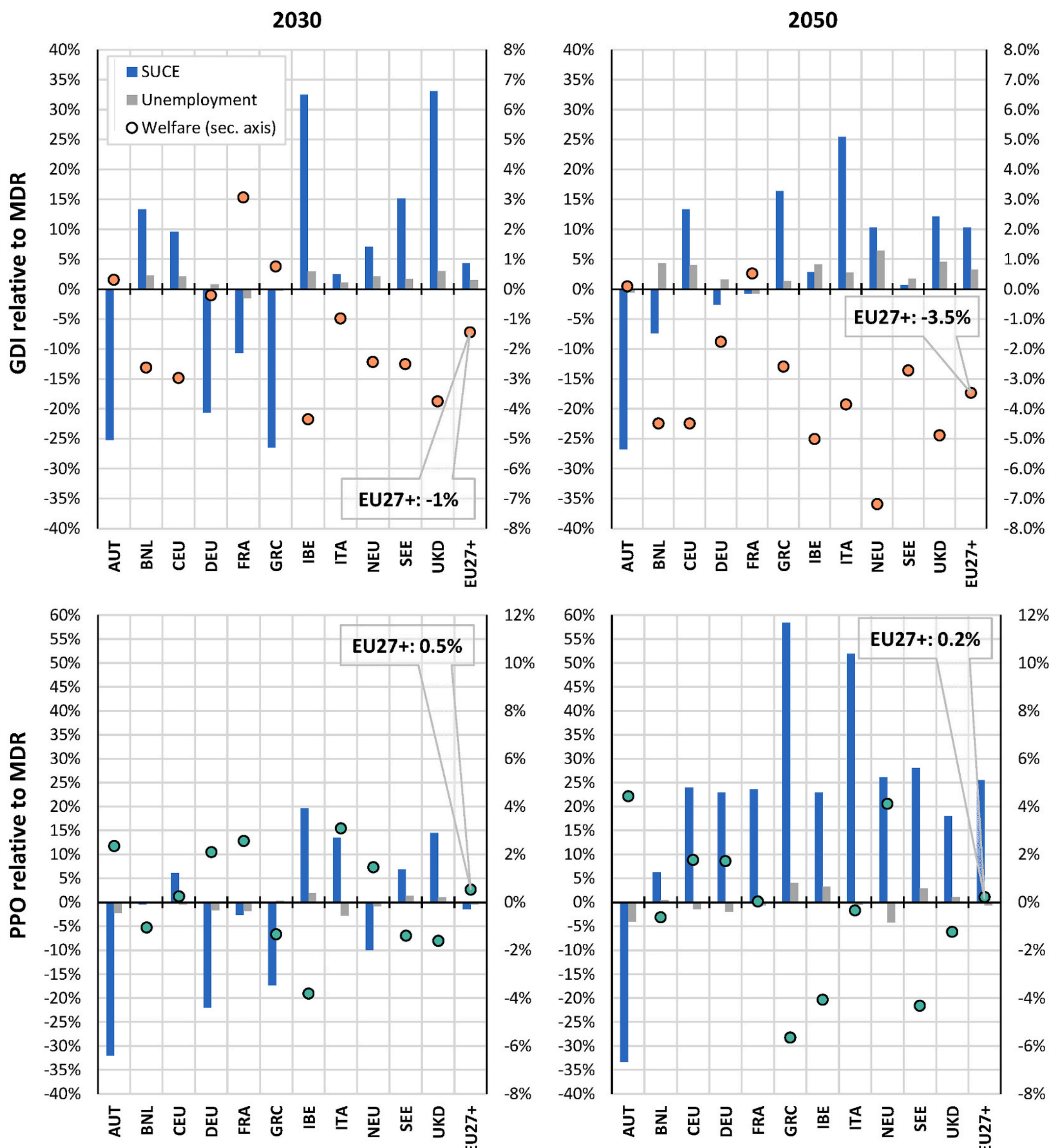


Fig. 5. System-wide unit-cost of electricity (SUCE), unemployment and welfare effects (on secondary axis) across EU27+ regions for GDI (top) and PPO (bottom) relative to the MDR storyline.

rents might attract investments in a region, buffering the pressure on capital markets and the resulting pressures in consumer prices. Further, the use of conventional metrics such as welfare and GDP as key performance indicators can be challenged in favor of more growth-agnostic metrics. Other criteria may be more relevant real-world drivers and barriers such as the health co-benefits of increased air quality, international security considerations or strengthened institutions to limit excessive use of market power.

5. Conclusion

On top of system-wide unit-cost of electricity across European regions, we focus on macroeconomic effects for employment, welfare and public budgets and capture the economy-wide dimension and social-political driving forces along the transition to net-zero energy. We show that the most expensive system from an energy sector perspective can be the one with highest continental welfare due to interacting and indirect effects with non-energy markets but at the expense of dispersed regional effects. A closer look at the different regional frequency distribution of per capita welfare effects highlights that only a very strong inequality aversion of society would create substantial differences between social-political storylines. Public budgets effects point to different short to long-run fiscal capacities for supporting the transition. The soft-linking method, using a semi-quantitative toolbox for generating social-political storylines, a technology-rich and temporally-spatially highly resolved energy system design model, and a macroeconomic model offers a valuable starting point for an even broader assessment of trans-disciplinary research questions with respect to net-zero energy in Europe.

Code availability

Euro-Calliope: https://github.com/calliope-project/sector-coupled-euro-calliope.

WEGDYN: The current code of the WEGDYN CGE model is developed over more than two decades at University of Graz and is not available in a publicly shareable version. The code will continue to be developed and hosted by University of Graz, Wegener Center for Climate and Global Change (https://wegcenter.uni-graz.at/en/). Requests for code should be addressed to Gabriel Bachner (gabriel.bachner@uni-g

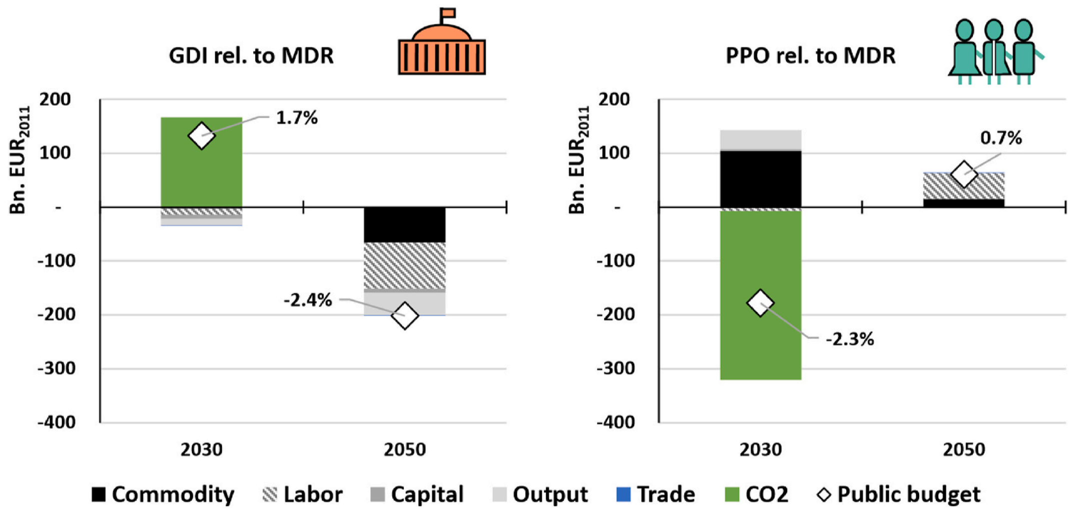


Fig. 6. EU27+ public budget decomposition for GDI (left) and PPO (right) relative to the MDR storyline.

raz.at).

CRediT authorship contribution statement

Jakob Mayer: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Diana Süsser:** Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Bryn Pickering:** Conceptualization, Methodology, Validation, Writing – review & editing. **Gabriel Bachner:** Conceptualization, Validation, Writing – review & editing. **Francesco Davide Sanvito:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jakob Mayer reports financial support was provided by European Commission.

Data availability

Links to Zenodo and Github repositories included.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.130425.

Appendix

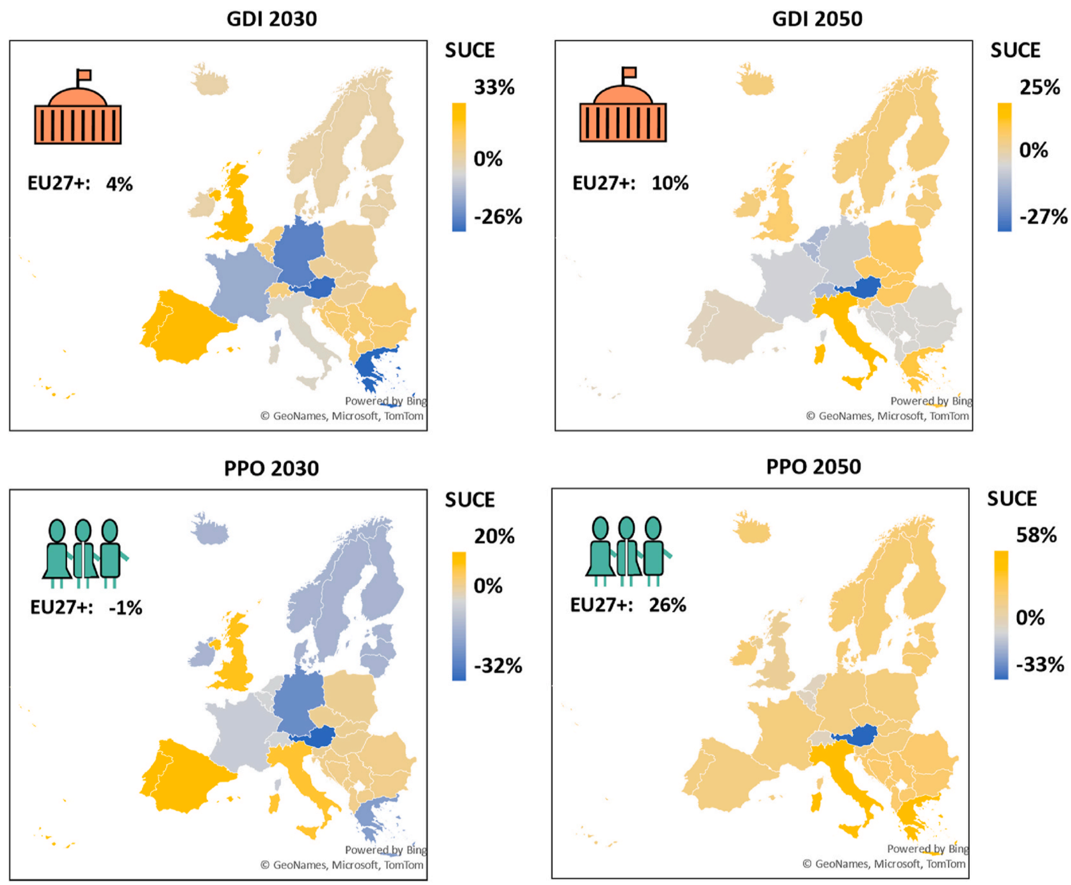

Fig. A. 1. System-wide unit-cost of electricity (SUCE) effects across EU27+ regions for GDI (top) and PPO (bottom) relative to the MDR storyline.

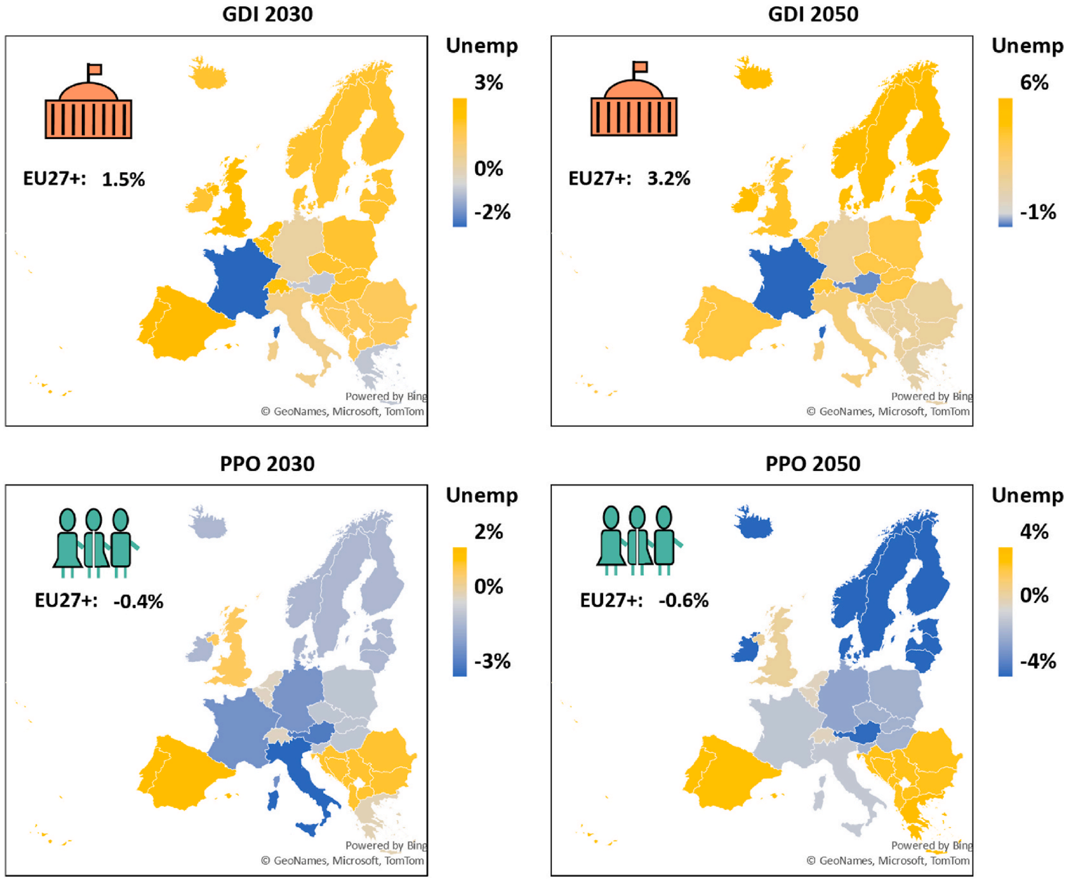

Fig. A. 2. Change in unemployment rate (%-point difference) across EU27+ regions for GDI (top) and PPO (bottom) relative to the MDR storyline.

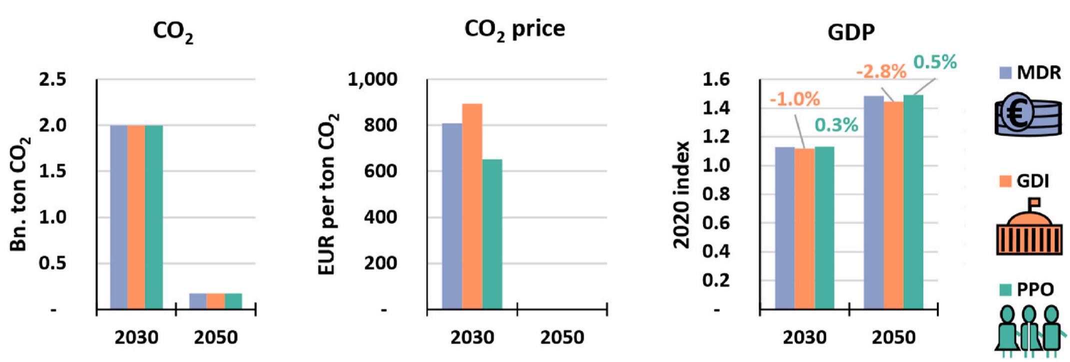

Fig. A. 3. EU27+ CO_2 emissions, allowance prices and GDP across storylines.

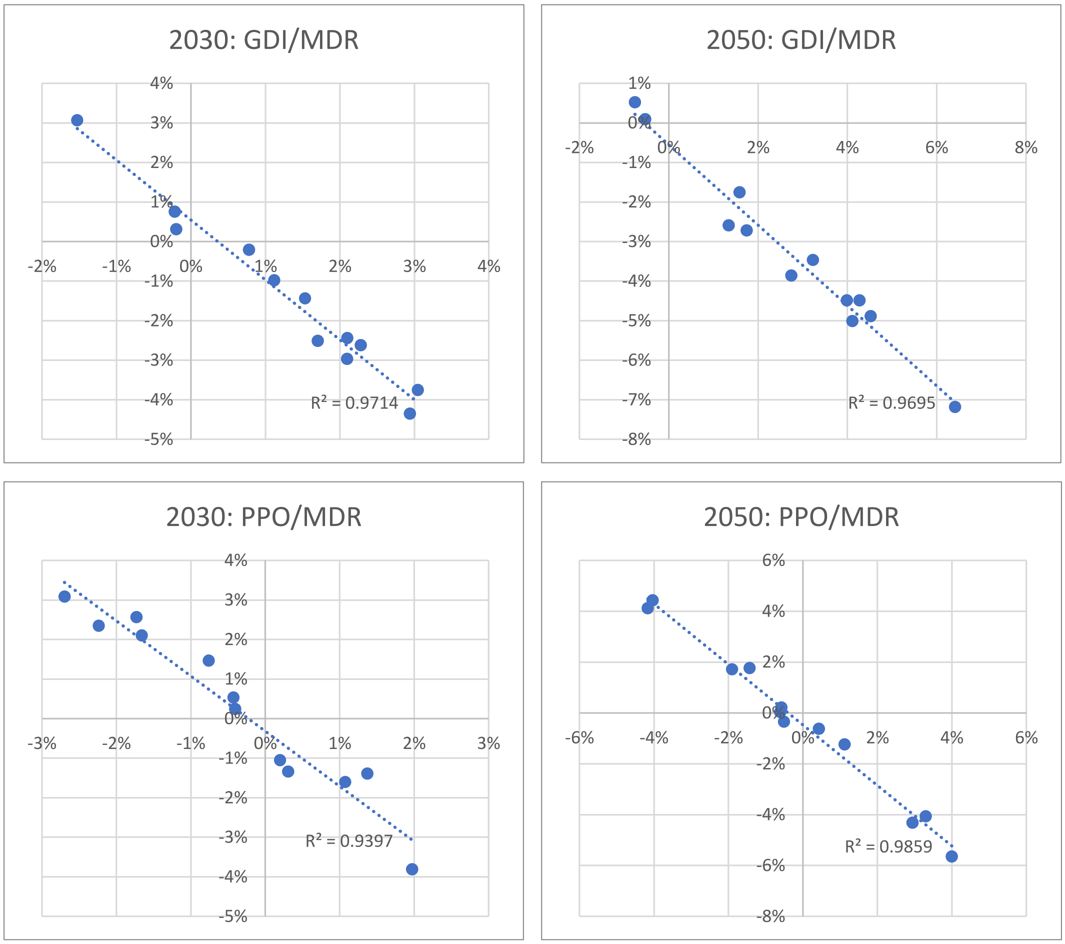

Fig. A. 4. Correlation between welfare and unemployment effects, both relative to the market driven storyline (x-axis: unemployment; y-axis: welfare).

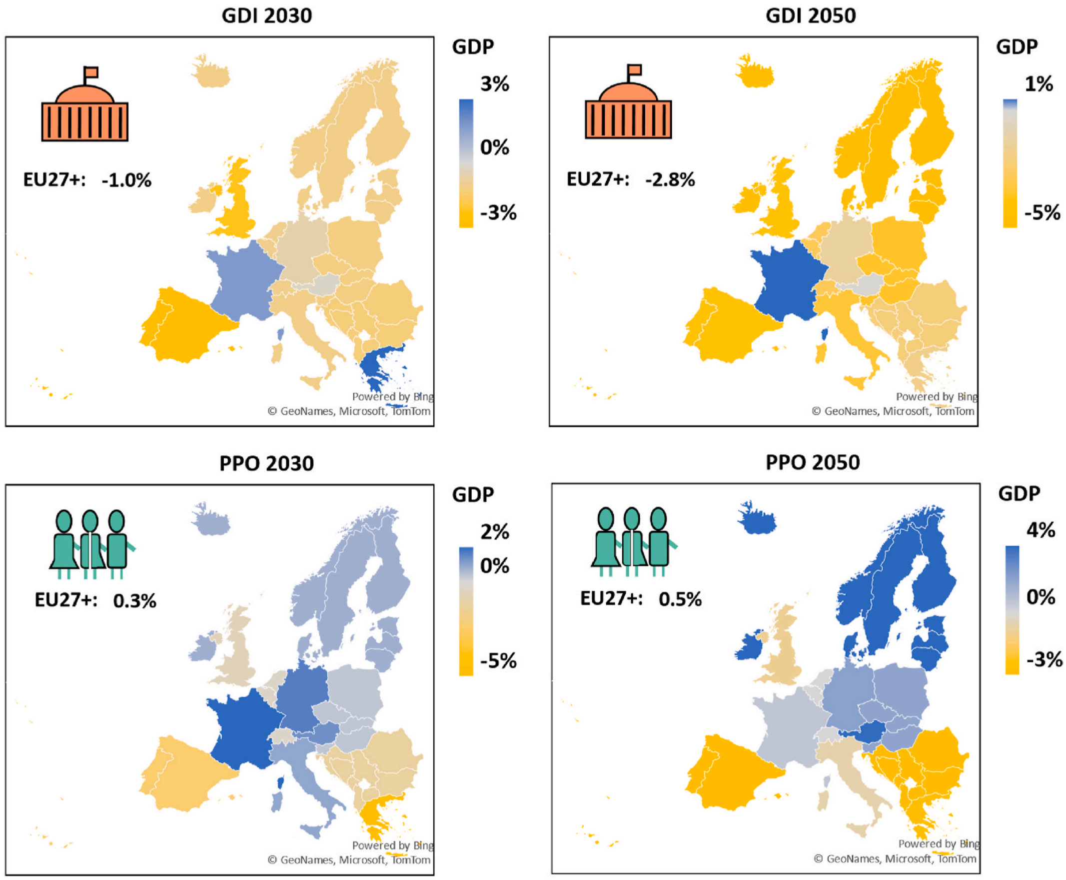

Fig. A. 5. Gross domestic product effects across EU27+ regions for GDI (top) and PPO (bottom) relative to the MDR storyline.

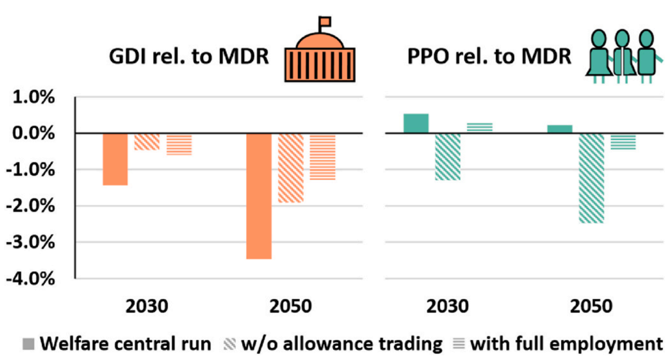

Fig. A. 6. EU27+ welfare effects for the central run, without allowance trading and with full employment assumption.

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