




Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2 °C climate stabilization

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Abstract

The European Union has recently established the “Clean Energy for all Europeans” climate policy framework, aiming at the achievement of the European Nationally Determined Contribution (NDC) submitted to the Paris Agreement. The EU28 NDC includes a commitment for emission reductions in 2030 but also refers to an economy-wide effort towards 2050 so as to contribute effectively to the long-term mitigation of climate change. We discuss the respective EU28 emission pathways in the context of a well below 2 °C global climate stabilization target and estimate the macroeconomic impacts for the EU28 economy by considering alternative levels of climate action for major non-EU emitters. We employ two models, the technology-rich energy system model PRIMES, and the global large-scale hybrid computable general equilibrium model GEM-E3. The two models are soft linked so as to ensure a consistent and robust framework of analysis. We find that emission reductions in the energy supply sector are dominant up to 2030 while transport takes the lead in 2050. Transport and non-CO₂ emissions are the main remaining emitting sources in 2050. We present the key decarbonization pillars and confirm that the impacts on the EU28 economy largely depend on the level of mitigation action adopted by the rest of the world and by the relative carbon intensity across regions. Due to asymmetric ambition of climate policies, a global implementation of NDCs results in economic losses for the EU28 when compared with a “pre-Paris” policy reference scenario, despite positive effects on energy-intensive and clean technology exports. On the contrary, we find that the region registers economic gains in the case of coordinated 2 °C global climate action.

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1 Introduction

Climate change mitigation has been acknowledged by the international community as one of the most important challenges that our society has to tackle. Scientists, local and national governments, international organizations, civil society and industries are increasingly being involved in climate action with different levels of participation and ambition. To that end, the European Union (EU28) has established a long-term domestic climate policy framework and thus plays a key role in the formulation of an effective international framework via the UNFCCC proceedings. Already in 2007, the EU28 established the “2020 Climate and Energy Package.”¹ This policy package formulates a complete framework of climate policies by setting targets with a horizon to the year 2020 for an overall reduction of greenhouse gas emissions, for renewable energy penetration, and for improvements in energy efficiency. Building on this framework, EU leaders adopted in 2014 the “2030 Climate and Energy Framework”² that sets target levels for the year 2030, in line with the long-term objective of reducing greenhouse gas (GHG) emissions by 80% below 1990 levels by 2050, as described in the “Energy Roadmap 2050”³ and the “Roadmap for moving to a competitive low carbon economy in 2050.”⁴ In 2015, Europe was among the first parties to submit its (Intended) Nationally Determined Contribution ((I)NDC) in the front-run to COP21 in Paris (European Union 2015) in line with the EU level agreement on the “2030 Climate and Energy Framework.” While most NDCs refer to the short-term emission abatement efforts up to 2030, the EU28 NDC submission also refers to the long-term EU28 objective for 2050.

COP21, and the subsequent Paris Agreement, has formed a milestone in international climate policy by introducing a bottom-up approach for the establishment of regional emission reduction targets (the INDCs or NDCs after the formal ratification of the Paris Agreement by each respective Party) and by formally setting a long-term climate stabilization target in line with holding global warming at well below 2 °C while pursuing efforts to limit it below 1.5 °C. A large volume of literature provides quantified assessments of the impacts of climate policies on energy and overall economic systems (indicative examples include Kriegler et al. 2013; Riahi et al. 2015; Labat et al. 2015), robustly showing that strong mitigation policies require an overall system transition, not only for the energy sector but also for all economic agents and sectors. In particular, after the Paris Agreement, several global studies have assessed the effectiveness of the NDCs towards the achievement of the long-term 2 °C and 1.5 °C targets (e.g., UNEP 2017; Rogelj et al. 2016; Vandyck et al. 2016; Luderer et al. 2018; Vrontisi et al. 2018) and conclude with the need for immediate ratcheting-up of efforts. A smaller number of studies takes the analysis to a regional level, providing insights on energy system transformation, burden sharing, and equity as well as on mitigation costs (Van Soest et al. 2017; Hof et al. 2017; Höhne et al. 2017; Pan et al. 2017; Fragkos et al. 2018). On the EU28 level, peer-reviewed assessments are more limited. Prior to the Paris Agreement, Capros et al. (2012, 2014a, b) present in detail the model results that are included in the “Roadmap for moving to a competitive low carbon economy in 2050.” Knopf et al. (2013) present the results of the early EMF28 multi-model analysis, exploring low-carbon transition pathways with reference to the modeling conducted in the 2050 EU Roadmap while Solano Rodriguez et al. (2017) describe

¹ https://ec.europa.eu/clima/policies/strategies/2020_en

² https://ec.europa.eu/clima/policies/strategies/2030_en

³ <https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy>

⁴ https://ec.europa.eu/clima/policies/strategies/2050_en

an energy system transition towards the 2050 targets described in the latter EU policy paper. Following the Paris Agreement, Fragkos et al. (2017) provide a quantitative assessment of energy system and macroeconomic impacts of the EU NDC and decarbonization targets.

We contribute to this literature by presenting an assessment of EU decarbonization pathways towards a well below 2 °C climate stabilization. Moving beyond existing literature, we estimate the macroeconomic impacts for the EU economy by considering also the climate action of other major emitters, both under the case of fragmented action, in line with the Paris NDCs, and under the case of a global mitigation action for a well below 2 °C climate stabilization. The analysis is relevant to current policy-making challenges as our scenarios feature policies of the “Clean Energy for all Europeans” or “Winter package” (European Commission, 2016a, b, c, d), linked to the “2030 Climate and Energy Framework” and the EU NDC. Furthermore, this paper provides insights on key decarbonization sectors and of overarching policies, indicating potential gaps towards a well below 2 °C target. It further describes the macroeconomic implications of the global implementation of the Paris Agreement on the EU economy and can thus be considered as of wider policy significance for the UNFCCC processes.

2 Methods

2.1 Modeling framework

Our analysis is based on a combined, complementary utilization of two models; the detailed energy system model, PRIMES, and the economy-wide computable general equilibrium (CGE) model, GEM-E3. Both models have been widely used in Impact Assessment studies of the European Commission (recent examples include the European Commission, 2016a, b, c) and in a number of peer-reviewed papers (for example, see Saveyn et al. 2011; Vrontisi et al. 2016; Capros et al. 2012, 2014a, b; Siskos et al. 2018; Paroussos et al. 2015). This section briefly describes the two models of our modeling toolbox while more details can be found in the relevant publications provided in the text or in the Supplemental Material (e.g., Table S.1 and S.2). The last paragraph of the section describes the integrated model framework developed for this analysis.

PRIMES (Capros et al. 2012 and E3MLab 2016) is a large partial equilibrium energy system model for the European Union with a member state detail. The model provides comprehensive projections of energy demand, supply, market prices, and system costs and investment, covering the entire energy system and the related emissions with a time horizon to 2050. PRIMES simulates multiple market equilibria and consumer responses in a forward-looking framework. It is a hybrid model that uniquely combines technological and engineering detail together with micro- and macroeconomic interactions. The PRIMES framework captures the dynamics of top-down behavioral modeling along with engineering bottom-up modeling aspects, handling dynamics under different anticipation assumptions and keeping track of technology vintages in all sectors. The detailed assumptions on technology costs are provided in Capros et al. (2016) and in De Vita et al. (2018). The PRIMES model comprises several sub-modules (e.g., for biomass demand and transport demand and supply, see Siskos et al. (2018) and Tasios et al. (2013)). The sub-models link with each other through a model integration algorithm, which determines equilibrium prices in multiple energy markets, including the emission trading market. The entire model follows the non-linear mixed complementarity approach and is able to handle multiple policy targets, such as fuel standards, emission trading,

and renewables targets. The model uses shadow values associated with each policy target in order to influence the decisions of the various actors. The shadow values (e.g., carbon, energy efficiency or renewables value) indicate the intensity of non-identified policies which are necessary to apply in addition to the explicit policy measures of a scenario, in order to meet the targets. The model covers energy and process CO₂ emissions and features a simple marginal abatement cost curve for the mitigation of aggregate non-CO₂ GHG emissions provided by GAINS (IIASA) (see Capros et al. 2014a, b, 2016).

The GEM-E3 model is a hybrid general equilibrium model (E3MLab 2017 and Capros et al. 2014) that provides insights on the macroeconomic and sectoral impacts of the interactions of the environment, the economy, and the energy system. The model has been calibrated to the latest statistics (GTAP 9, IEA, UN, ILO) while Eurostat statistics have been used for the EU. The GEM-E3 model simultaneously calculates the equilibrium in goods and service markets, as well as in the labor and capital markets based on an optimization of objective functions (the maximum welfare for households and the minimum cost for firms). The model is dynamic, recursive over time, and driven by the accumulation of capital with a time horizon to 2050. Different regions are linked through endogenous bilateral trade in accordance with the Armington assumption. Production functions are based on a CES structure and include labor, capital, energy, and intermediate goods. For the demand side, the model simulates consumer behavior and distinguishes between durable and disposable goods and services. A distinctive feature of GEM-E3 model is the representation of an imperfect labor market through involuntary unemployment, simulated by an empirical labor supply equation that links wages and unemployment levels through a negative correlation. The current version of the GEM-E3 model includes 19 regions with 39 categories of economic activities, including a separate representation of the sectors that produce low-carbon power supply technologies, electric cars, and advanced appliances (see Supplemental Material Table S.1). In addition to the above sectors, the model includes a detailed representation of the power generation system (10 power technologies) and a detailed transport module (private and public transport modes, see Karkatsoulis et al. 2017). GEM-E3 model features endogenous learning by doing for clean technology sectors, as described in Eq. 1 and Table S.7 of the Supplemental Material. The GEM-E3 environment module covers all GHG emissions and a wide range of abatement options, as well as a thoroughly designed carbon market structure (e.g., grandfathering, auctioning, alternative recycling mechanisms).

Our methodological framework is similar to that of Vandyck et al. (2016) and Fragkos et al. (2017); namely, it features a one-way soft linkage of two models, establishing a link from the energy system model towards the macroeconomic CGE model. In that way, the evolution of the energy system characteristics is consistent across the two models, enabling a robust macroeconomic assessment of energy and climate policies. We adjust not only the power supply system of the CGE model, as in the above-mentioned literature, but also incorporate input on the evolution of the transport sector and the fuel mix of different end users (i.e., industry, services, and households) taken from the energy system model towards GEM-E3. In particular, to achieve the soft link for the power mix, GEM-E3 features a Leontief production function for power supply, whose parameters are set equal to the shares of each technology in the power mix of the energy system model. The soft link of the detailed GEM-E3 transport module with the energy system model is conducted as described in Table 3 of Karkatsoulis et al. 2017, while the fuel mix and electrification of final energy demand of other end-use sectors, namely households and industry, are adjusted by changing (or re-calibrating) the values of share parameters that influence the expenditure on fuels in the production and

consumption functions. In addition to the energy system characteristics, we also harmonize the carbon price trajectory across the two models for the EU28. This methodological approach is applied not only for the EU28 with PRIMES model but also for the non-EU regions with input from other energy system models⁵ that feature a wider sectoral representation. The soft link for all regions is performed in all scenarios under analysis. We highlight that a prerequisite for this combined assessment is the integration of detailed energy system modules in the CGE framework, which facilitates the one-way linkage and therefore the harmonization of energy systems across the two models. We note that other similar analyses may feature a two-way linkage through an iterative processes that allows for a gradual convergence of certain variables across the two models (e.g., in Fortes et al. (2014) for a two-way linkage of TIMES_PT energy system model and GEM-E3_PT CGE model). For example, through a two-way linkage, the change in global fossil prices due to mitigation policies is fed back to the energy system model. This can be considered as a caveat of our methodological approach.

2.2 Scenarios

Our assessment is based on a common set of scenarios, namely the *Reference* and the EU28 well below 2 °C (*EU-WB2°C*) scenarios, which are implemented by both models. The latter scenario further expands to an impact evaluation of different external climate actions on the EU economy, assessed by GEM-E3 model, namely the *EU-WB2°C_NDC* and the *WB2°C_Global*. For robustness of results, both models share key macroeconomic assumptions and techno-economic characteristics for the EU28 as will be described below.

The first scenario is the *Reference* scenario, which serves as a basis of comparison for alternative policy scenarios. This scenario presents a trajectory of key economic, energy and environmental indicators under current economic and climate policies without incorporating the NDCs submitted in the run-up to the Paris Agreement. For the EU28, the Reference scenario uses the socioeconomic and energy system assumptions presented in the 2015 Aging Report (European Commission 2015) and the EU Reference 2016 scenario of Capros et al. (2016), which constitutes a benchmark scenario for EU energy- and climate-related policies. The implementation of the Reference scenario in PRIMES model incorporates a detailed list of climate and energy policies legislated at EU28 and member state level until the end of 2014, such as emission standards for cars and vans, eco-design directives, and energy performance of buildings (for a detailed descriptions of incorporated policies see Annex 4.1 of Capros et al. 2016). The implementation of policies in all scenarios simulated by PRIMES model has been achieved through carbon prices (for the ETS sectors) and constraints (e.g., quotas, share targets) for renewable energy penetration and energy efficiency. The latter are simulated in the model through the use of policy values (efficiency value, renewable value) that represent the shadow prices (dual values) of the constraints so as to incorporate policies that have not been explicitly linked with dedicated measures. The development of the Reference scenario for EU28 in GEM-E3 model is based on common assumptions with regard to total and sectoral economic growth, population projections, and total greenhouse gas emissions, energy, and carbon prices.

⁵ In this analysis, we have utilized the model outputs of IMAGE model, provided in the CD-LINKS scenario database. The database will be available here when it is made public: <https://db1.ene.iiasa.ac.at/CDLINKSDB/>. IMAGE model is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. It is a partial equilibrium model of the energy-land-environment system with a wide representation of detailed policies. More details can be found in https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation

Regarding the non-EU regions in the GEM-E3 model, the Reference scenario develops on exogenous assumptions of main socioeconomic drivers, such as GDP, population and autonomous energy efficiency, taking stock of recent publications and reports by international organizations (e.g., UN 2015, OECD SSP2 projections,⁶ OECD 2014). This scenario builds upon a number of assumptions with regard to the evolution of trade balance, investment, and sectoral production, all in line with the storyline of a gradual global economic convergence and a moderate transition towards more diversified and sustainable economies. Current energy and climate policies are taken from Vandyck et al. (2016) (in particular, details can be found in Supplementary data file) and do not include the NDCs, while further GHG emission trajectories are taken from Kitous et al. (2016).

In *EU-WB2°C* policy scenario, we assume for the EU28 a full implementation of the EU NDC in 2030 and more explicitly the implementation of the “2030 Climate and Energy Framework” as described in detail in the Impact Assessments accompanying the “Winter package” (European Commission, 2016a, b, c, d) and the detailed policy framework description of the respective technical report (E3MLab and IIASA 2016). The latter framework includes three main targets for the year 2030, namely (i) an EU-wide reduction of GHG emissions by 40% compared with 1990 levels, (ii) a GHG emission reduction by 43% compared with 2005 for the economic sectors that participate in the EU Emissions Trading Scheme (ETS) and a respective 30% reduction in the non-ETS sectors, (iii) a renewable target for 27% share of renewable energy in gross final energy demand, and (iv) an energy efficiency target for 27% reduction from the 2007 European Commission Reference levels. The aggregate GHG target in 2030 coincides with the submitted EU NDC. The key tools in the decarbonization process implemented by the PRIMES model are similar to the ones described under the Reference scenario (i.e., carbon prices, power mix constraints, policy values carbon value, efficiency value to achieve the overall targets) along with increased renovation rates, banning of least efficient technologies (e.g., to simulate eco-design standards), and more stringent CO₂ standards for vehicles. In the longer term to 2050, the PRIMES 2 °C scenario is in line with the EU Roadmap to 2050, achieving a reduction of GHG emissions by 80% from 1990 levels. This 2050 emission reduction falls within with the cost-optimal 2 °C (or 450 ppm CO₂eq) scenario as indicated in Van Soest et al. (2017).⁷ The 2015–2050 carbon budget (cumulative CO₂ emissions) is exogenously set, similarly to the methodology presented in Capros et al. (2014), so as to comply with a cost-efficient emission trajectory compatible with a well below 2 °C target (see also Schaeffer et al. in this issue). This budget (excluding land use, land use change, and forestry (LULUCF) emissions) is set equal to 81 Gt CO₂, while if we also exclude captured emissions through CCS technologies, the budget is equal to 86 Gt CO₂. This is well in line with the regional cost-optimal allocation for the achievement of the 2 °C target but above the fair and equitable levels, as discussed in Duscha et al. (2018), although close to estimations for per capita convergence as provided in Gignac and Matthews (2015).

In the GEM-E3 scenario simulations, the EU28 follows the policy framework described in the *EU-WB2°C* scenario, implemented via a soft link of the GEM-E3 energy system with the

⁶ <https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about>

⁷ Van Soest et al. (2017) (Table 2) present for the cost-optimal 450 ppm CO₂eq scenario the 2050 GHG emissions including LULUCF relative to 2010 levels within the range of [−75—58%]. Our emission pathway is well in line with this range as the emission level in 2050 is lower by −76% from 2010 levels. Our simulations do not include LULUCF emissions but as the historical and projected CO₂ emissions from land use for the EU28 are found negative (Den Elzen et al. 2015), our projections are still well in line the 450-ppm CO₂eq range.

PRIMES model, as described in the previous section, and with the introduction of the corresponding PRIMES carbon price. For the non-EU regions, we develop two alternative policy scenarios depending on the level of ambition of their mitigation action. In the *EU-WB2°C* scenario with GEM-E3, we simulate the full implementation of the conditional NDCs for all G20 countries through the introduction of carbon prices, covering the economic sectors that are described in the respective NDC documents (i.e., for the EU28, we impose the carbon price on all emitting sources and not only on ETS sectors). The specific targets assumed for all regions along with our quantification of NDC targets in relation to 2010 emission levels are shown in Table S.5 in the Supplemental Material. For the rest of the model regions that are not covered in the latter table, we do not assume additional climate policies beyond the Reference. For the period after 2030, for non-EU countries, we assume that the fragmented climate action continues with the same ambition by implementing the same emission reduction rates compared with the Reference levels as in 2030 in all subsequent years.

In the second policy scenario (*WB2°C_Global*), we implement a stylized, global mitigation action in line with a well below the 2 °C target. A recent literature has established the link between carbon budgets and long-term climatic targets (Rogelj et al. 2015a, b, 2016; Luderer et al. 2018 and in Supplementary Text 1), thus enabling an assessment of 2 °C consistent pathways with different model types. For the implementation of this scenario in our global GEM-E3 model, we take stock of this research and use a carbon budget of 810 Gt CO₂ for the period 2016–2100 (Luderer et al. 2018), which refers to a warming limited below 2 °C in twenty-first century with a higher than 67% chance. In particular, we use the optimal emission pathway⁸ for the 2016–2050 period that corresponds to the carbon budget that is consistent with the 2 °C target, as this is described in Luderer et al. (2018). The pathway to 2050 corresponds to a global CO₂ budget of 675 Gt CO₂, excluding LULUCF. The emission constraint is achieved with the introduction of a global, economy-wise carbon price on all gases and sources from 2025 onwards, while in the period before 2025, the Reference policies are implemented. Although the carbon budget only refers to CO₂ emissions, the carbon price is applied to all non-CO₂ GHGs, thus ensuring comparable mitigation efforts across gases (Rogelj et al. 2015b). In both scenarios simulated with GEM-E3 model, the tax revenues from the introduction of the carbon price are recycled back to the economy via a reduction in indirect taxation.

3 Results

3.1 GHG emissions

EU28 GHG emissions are projected to continuously decouple from economic growth, as climate and energy policies are in place already in the Reference scenario. In the latter scenario, the EU28 sees an important decrease of GHG emissions compared with 2015 levels, the highest among all regions (Table S.6 of the Supplemental Material). Given the already ambitious decarbonization efforts in the Reference scenario, the EU28 NDC in 2030 is achieved with a 9% reduction of GHG emissions from Reference. While all emitting sectors and gases

⁸ Here, we also use the outputs of IMAGE model for consistency reasons. We calculate the GHG (excl.LULUCF) emission pathway for 2016–2050 for the corresponding scenario (2C with 1000 Gt CO₂ for 2011–2100) found in the CD-LINKS database and impose this global emission constraint to GEM-E3 model. The database will be available here when it is made public: <https://db1.ene.iiasa.ac.at/CDLINKSDB/>.

contribute to the emission abatement efforts, CO₂ emission reductions are dominant, with energy supply contributing by 36% and transport by 18% of total reductions in 2030. We find that the industrial sectors only contribute by 8% to total emission reductions, indicating that marginal abatement costs in the power, transport, and buildings sectors are generally cheaper and that deeper emission reductions will require more measures by the industrial sector.

By the middle of the century, EU28 GHG emissions fall by 34% compared with 2015 levels in both the PRIMES and GEM-E3 Reference scenarios (see Fig. S.1 in the Supplemental Material) as a result of the existing policies and technological advancements. The emission trajectory of the EU-WB2°C scenario in 2050 shows a reduction of GHG emissions by 61% below Reference levels and 74% below 2015 emissions, reaching 1176 Mt CO₂eq. Already in the Reference scenario, the CO₂ emissions of the energy supply sector in 2050 fall to 16% of total GHG from 29% in 2015. In the EU-WB2°C, these emissions fall to 8% of total, as the energy supply sector is almost fully decarbonized by 2050 falling to just below 100 Mt CO₂eq. The major contributing sector in the 2050 emission reductions is transport, contributing with 33% of the total reductions (Fig. 1). Nevertheless, transport CO₂ emissions continue to hold the same share in total 2050 emissions as in the Reference (30% of total), in particular due to the emissions from freight and air transport activities that are difficult to abate. The largest share (38%) of the remaining 2050 GHG emissions in the EU-WB2°C is attributed to non-CO₂ emissions, for which abatement is more costly or more related to behavioral changes (e.g., dietary shifts). Overall, we find that emission reductions consistent with a cost-optimal trajectory towards the 2 °C stabilization (see Section 2.2 and Van Soest et al. 2017; Duscha et al. 2018) are achievable with the existing technologies and do not require negative emission technologies like power supply with BECCS (Biomass with CCS), in contrast with the findings of Rodriguez et al. (2016).

Regarding the global GEM-E3 scenarios, we note that in the Reference scenario, only EU28 and Japan register GHG emission levels in 2050 below 2015 levels (see Table S.6 in Supplemental Material). The level of ambition of the EU28 Reference scenario is notably

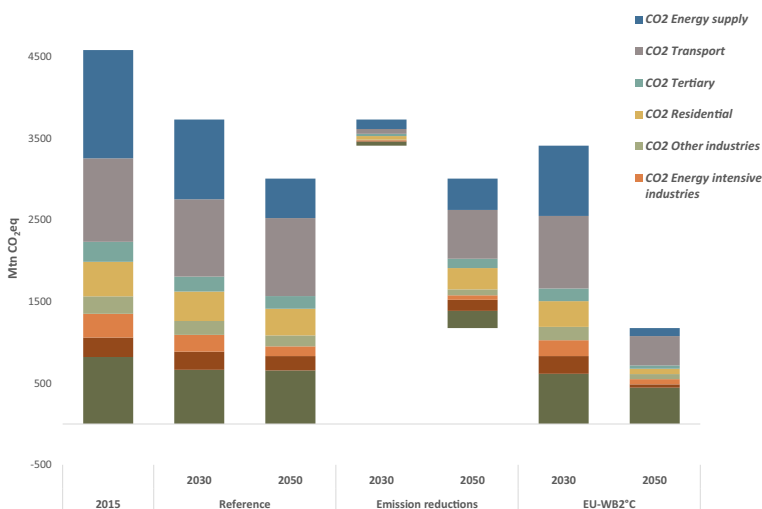


Fig. 1 CO₂ emissions by source and total non-CO₂ GHGs in PRIMES Reference and EU-WB2°C scenarios and corresponding emission reductions. All figures exclude LULUCF emissions. Source: E3MLab; PRIMES model

much higher than of the rest of the regions, making the EU28 economic system more carbon-efficient and thus enabling a less abrupt transition under the action of the WB2°C_Global scenario. In particular, in the global mitigation scenario, GHG emission reductions from Reference in 2050 are equal to 48%, noticeably lower than the reductions seen in other regions, as the system is already becoming decarbonized in the Reference scenario. Similarly, the achievement of the EU28 NDC implies less effort when compared with the GEM-E3 Reference scenario, in contrast to other regions such as Australia, Canada, and the USA (see Table S.6 in Supplemental Material). However, in the global NDC scenario in 2050, the EU28 achieves the highest reductions from Reference as all other regions maintain their NDC ambition levels. We note that the relative ambition of emission reductions across regions is a key driver of macroeconomic impacts, as will be discussed in Section 3.3.

3.2 Decarbonization pillars

The EU28 energy system undergoes a drastic transformation in order to achieve the rapid emission reductions described in the section above. The main indicators of the decarbonization process are presented in Fig. 2 for both the Reference and EU-WB2°C scenarios. The efforts required to move from the Reference projections towards a decarbonized system are more striking in 2050 than in 2030.

We find that energy efficiency (Fig. 2a) is key in the decarbonization process, as the energy intensity of GDP in 2050 in the EU-WB2°C scenario is projected 60% lower than that of 2015. Dedicated measures, such as the renovation of commercial and residential buildings, the eco-design regulation, the introduction of best available techniques in industry, and the emission standards for cars, aim towards increasing energy savings in combination with the increasing use of more efficient energy carriers like electricity. As a



Fig. 2 Key EU28 decarbonization indicators expressed through the energy intensity improvements (a), the share of renewables in primary energy demand (b), the share of electricity in final energy demand (c), and the carbon intensity of the power supply sector (d). Source: E3MLab; PRIMES model

result of dedicated measures, we find that around 40% of the savings in the total final energy consumption come from the residential sector and 35% by the transport sector. Final energy demand of the buildings sector is reduced by 44% in 2050 when compared with Reference levels (Fig. 3d).

High penetration of renewable energy is also pivotal. The share of renewables in primary energy supply in 2050 reaches 50% in the EU-WB2°C scenario up by 22 percentage points from Reference (Fig. 2b). This is to the detriment of oil and gas, while in both Reference and EU-WB2°C scenarios, coal use in 2050 is dropping substantially from 2015 levels (Fig. 3c). Renewable energy penetration is most prominent in the power sector, especially by the deployment of wind and solar power technologies, and is also notable in the transport sector and to a less degree the buildings sectors. We find a limited growth in biomass-fueled power generation, as the use of biomass feedstock sector in biofuel production is more cost-effective. The role of advanced biofuels for the decarbonization of transport is key, particularly in the case of aviation and freight.

Already in the Reference, carbon prices and dedicated renewable energy targets lead to a penetration of renewables (including large hydro) equal to 45% in power supply production in 2030 and 50% in the scenario while by 2050, renewables dominate the EU28 power mix, reaching 67% in the EU-WB2°C scenario (Fig. 3a). Nuclear power supply holds a share close to 20% in both scenarios both in 2030 and 2050, driven mostly by the retrofitting of old plants rather than the construction of new ones. The development of CCS technology in 2050 is marked but limited, mainly due to acceptability issues and other licensing issues for storage sites. The carbon intensity of the EU28 power system falls by 74% from 2005 levels in the Reference scenario and is almost decarbonized in the EU-WB2°C scenario (Fig. 2d).

The penetration of renewables is also driven by the decarbonization effort in the transport sector, as the use of biofuels in the total final energy demand rises from 6% in 2030 to 38% in

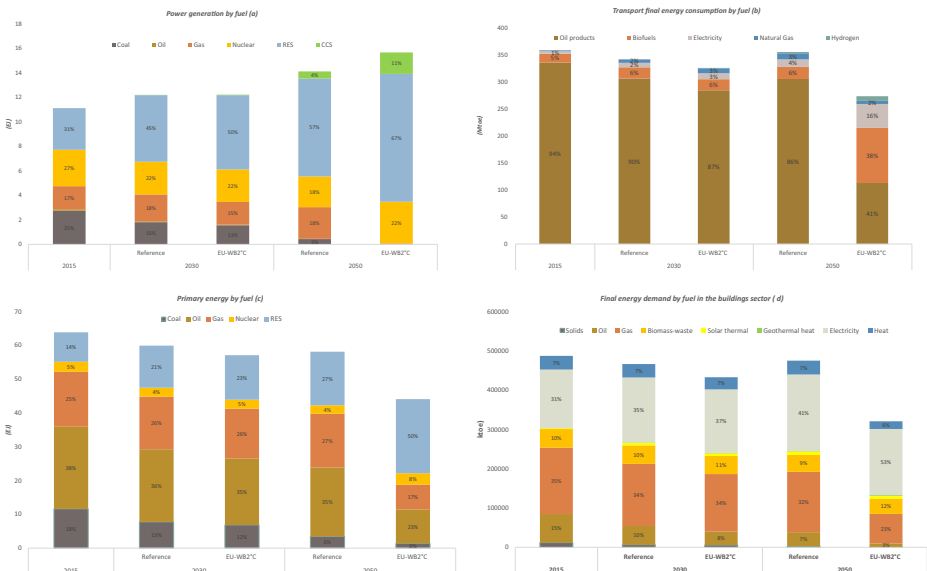


Fig. 3 The EU28 power mix (a), final energy consumption by fuel in the transport sector (b), primary energy by fuel (c), and final energy demand by fuel in the buildings sector (d), all presented for years 2015, 2030, and 2050. Source: E3MLab; PRIMES model

2050 in the decarbonization scenario (Fig. 3b). The introduction of advanced biofuels is the main option to reduce emissions in the non-electrifiable modes of road freight, aviation, and maritime transport. Nevertheless, the main driver for GHG reductions in transport is the regulation of the test cycle emissions performance of light-duty vehicles (LDVs). As manufacturers have to respect stricter regulation, they promote more efficient vehicles and increase the availability of low emissions vehicles in their portfolios. An additional key driver in 2050 is the electrification of transport which quadruples from Reference levels to 16% of total transport final energy demand, thus providing a clean alternative to fossil fuels as the power sector would have been largely decarbonized.

Overall, the electrification of final energy demand is another crucial element of the transformation process, going to 24% and 35% in 2030 and 2050 respectively in the EU-WB2°C scenario (Fig. 2c). Electricity demand grows towards 2050 (Fig. 3a), particularly due to the electrification of the transport sector and also due to the increased use of electricity for heat production in the buildings sector. In 2050, in the EU-WB2°C scenario, electricity serves more than half of the final energy demand of the buildings sector (Fig. 3d).

3.3 Macroeconomic impacts

Moving to a low-carbon system involves a drastic transformation of production processes and consumption preferences. This transition is capital-intensive and can thus carry a cost for all economic agents. The carbon and energy efficiency of the system is improved through the adoption of new technologies and practices that are resource-intensive and potentially more expensive than the conventional ones, especially in the short to medium term. In addition, unabated emissions are subjected to high carbon taxes, creating an extra economic burden to consumers, while earlier investments in fossil fuel sectors result in stranded assets that occupy a share of the finite resources of the economy. Global economic activity can be adversely affected due to the resource requirements of climate mitigation policies (IPCC 2014). Yet, on a regional level, changes in key macroeconomic indicators can be either positive or negative depending on potential competitiveness gains, impacts on interregional trade, and new investment dynamics. We highlight that this assessment of macroeconomic impacts is only partial as accounting for the costs corresponding to the avoided climate damages and the significant co-benefits for air pollution, noise, and other externalities which could largely over-compensate the small direct economic costs.

In 2030, in the *EU-WB2°C* scenario, a global implementation of NDCs is achieved. Due to the high asymmetry of emission reduction targets across regions (Table S.6 in Supplemental Material), the EU28 registers competitiveness losses. Reductions in exports lead to a GDP loss of 0.15% of Reference levels (Fig. 4a and Table S.12 in Supplemental Material). We find that it is not the energy-intensive sectors that become less competitive—on the contrary, the exports of these sectors slightly increase—but rather the rest of manufacturing goods and service sectors (Fig. 5a and Table S.9 in Supplemental Material). European energy-intensive industries can further improve their exporting capacity as they are more resilient to emission reduction policies than their competitors by being less carbon-intensive already in the Reference scenario. In terms of sectoral production, losses from the sectors of manufacturing goods and services are not counterbalanced by the increasing production of electric vehicles and other clean energy technologies.

In 2030, in the *WB2°C_Global* global climate action scenario, GDP falls by 0.17% below Reference levels, similar to the *EU-WB2°C* scenario. Exports in 2030 fall, as in the *EU-WB2°C*

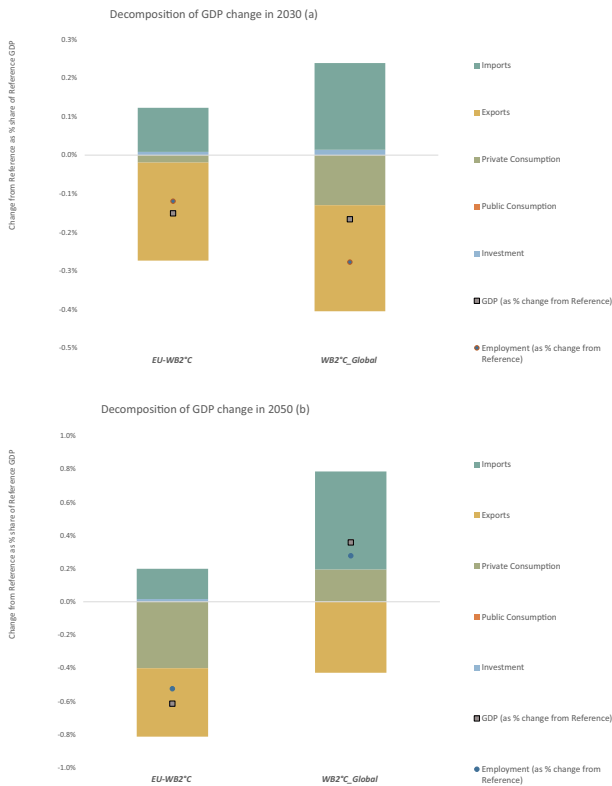


Fig. 4 Decomposition of EU28 GDP changes in both EU-WB2°C and WB2°C_Global scenarios relative to Reference for 2030 (a) and 2050 (b). The contribution of each GDP component is its change from Reference levels expressed as a share of Reference GDP. GDP and employment (markers only) are expressed in % change from Reference levels. Source: E3MLab, GEM-E3 model

scenario, but in this case, not only due to a deterioration of the EU28 competitiveness but also due to a reduction in global demand for goods and services. However, as imports drop as well, there is a counterbalancing effect in the overall trade balance. Thus, the main driver of lower activity levels is the reductions in private consumption (Fig. 4a), which are, however, a result of changes in relative competitiveness. For example, a decline in the exports of the biggest employing sector, the services (Fig. 5 and Table S.9, S.10 in Supplemental Material), results in lower income and thus lower levels of overall consumption. Overall, despite the higher production levels in certain sectors, such as electric cars, other clean energy technologies, and energy-intensive goods, the reduced external demand for certain, labor-intensive, EU goods and services drives GDP to lower levels. In Fig. 5, we show the changes in EU28 exports for aggregate sectors, and the respective share of this change in total EU28 exports. Our findings confirm that competitiveness impacts are central to climate policy assessment, as is discussed in policy debates on environmental regulation and in a large part of academic literature (e.g., see Dechezlepretre and Sato 2017).

The electrification of global and EU road transport has important macroeconomic impacts, also for the EU. This is due to the assumption in our Reference scenario that the EU holds a high share of production in the global market of electric vehicles. Hence, in the policy scenarios, EU can reap some benefits from the expansion of the global and domestic EV

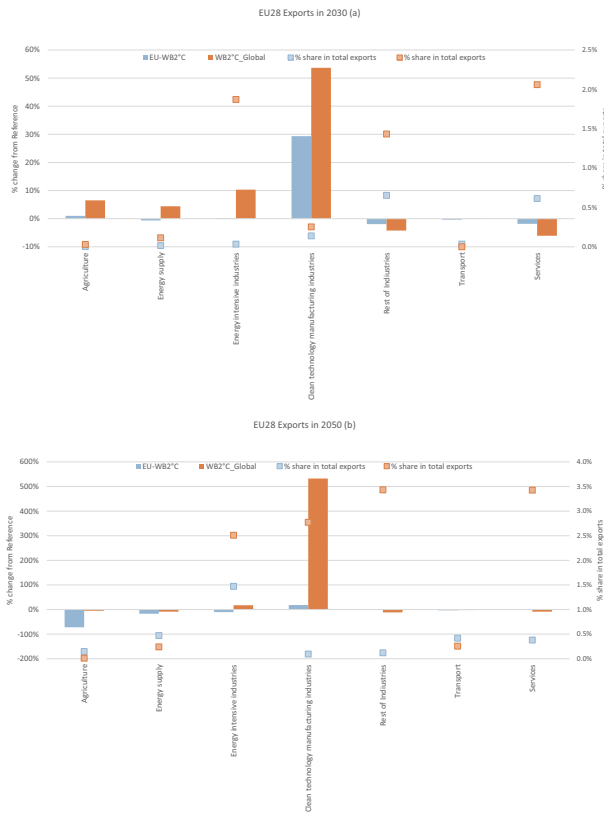


Fig. 5 EU28 exports in 2030 (a) and 2050 (b) in both EU-WB2°C and WB2°C_Global scenarios, expressed in % changes from Reference scenario (bars) for aggregate sectors. Square markers indicate the importance of each respective absolute change expressed as a share of total exports. Source: E3MLab, GEM-E3 model

market. We find that the macroeconomic impacts are directed by several effects, including the differences in the value chain of the emerging market. The additional demand for new car stock spurs economic activity but as the production process of electric vehicles differs significantly from that of conventional cars (UBS 2017; ING 2017; IEA 2017), the sectors that benefit from such a transition vary. This is captured by the GEM-E3 model analysis through the representation of a separate representative firm with distinct production processes for the two different types of passenger cars. In particular, when compared with conventional cars, electric cars feature a different demand for intermediate goods and require less intermediate input of services (Fries et al. 2017). In Table S.13, in the Supplementary Material, we provide the assumptions for the production process in the GEM-E3 model. This lower intermediate demand for services partially explains the reduction in global demand for services in the global policy scenario.

Despite the considerably higher global mitigation efforts in 2050 in the *WB2°C_Global* scenario, where global GHG emissions fall by 72% from Reference, the EU28 registers economic gains. A driving force of this positive impact is the lower emission reductions from Reference levels of the EU28 compared with other GEM-E3 regions, as shown in Table S.6. Due to the very low EU28 energy and GHG intensities, among the lowest globally, that are the result of EU28 climate mitigation policy region already in the Reference scenario, the EU28

effort is lower than that of the rest of the regions. Once a global carbon tax is introduced, the EU28 economy is well equipped, and, although GHG reductions from 2015 levels are among the highest globally (Table S.6), the reductions from Reference levels are less demanding. This is in sharp contrast with the highly fragmented *EU-WB2°C* scenario, where EU28 achieves the highest emission reductions compared with the Reference and thus shows a negative impact on GDP. An additional driver of positive economic impacts is the learning-by-doing effect which leads to reductions in the purchase cost of electric vehicles and other emerging clean energy technologies. Thus, penetration of clean technologies can be more prominent (see Table S.18) and the overall energy system transformation can be less costly.

In 2050, in the *WB2°C_Global* scenario, estimations show an increase in private consumption and an improved net trade balance, thus leading to an overall increase of GDP (Fig. 4b). On a sectoral level, the transition towards a low-carbon economy and the respective diversification of sectoral production is prominent. Domestic production of low-carbon technologies increases substantially and almost compensates the reduced demand for conventional equipment and fuels. Domestic production is not only directed to the domestic market but also for exports, particularly for electric vehicles, as the EU holds a market share already in the Reference scenario. Combined with an improved competitiveness of European energy-intensive goods, the total domestic production increases. In addition, the increasing demand for domestically produced energy carriers like electricity substitutes imported fossil fuels and brings positive effects to the economy. Total exports of goods and services are estimated to fall as global economic activity is depressed, but the sharp drop in fossil fuel imports has a beneficial effect to the overall trade balance of EU28, which is found to improve by 0.1% of GDP. By conducting a sensitivity analysis, we can confirm that the EU28 trade balance is positively affected under the *WB2°C_Global* scenario in 2050 even with varying assumptions on the Armington elasticity of substitution (see Table S.14 and Table S.15 in Supplemental Material).

We note that the macroeconomic impacts of climate policies are greatly affected by the type of recycling of carbon tax revenues, if such a tax is foreseen. Recycling carbon tax revenues is in line with current practices found existing emission trading or carbon tax schemes (Carl and Fedor 2016). In our simulations, this revenue is considerable as it reaches almost 2% of EU28 GDP (see in Table S.8 of the Supplemental Material the level of the respective carbon prices). In GEM-E3 simulations, carbon tax revenues are recycled so that the government budget is only impacted by direct and indirect macroeconomic effects of the examined policies. For the simulations described in this paper, we have used a recycling scheme that reduces the level of indirect taxation of all goods and services, both domestic and imported. This mechanism creates a counterbalancing force to the increasing costs of production. If other recycling schemes are enabled, like for example a reduction of social security contributions, the macroeconomic results may differ substantially and can even register an increase in total employment levels, as seen in Fragkos et al. (2017).

4 Conclusions

In this paper, we explore the transformation of the EU28 energy and economic system under a decarbonization pathway to 2050. For this purpose, we employ a dedicated modeling toolbox, following a one-way soft link approach between a technology-rich energy system model, PRIMES, and a large hybrid CGE model, GEM-E3. We assess the macroeconomic

implications of the European decarbonization pathway under two different global climate action trajectories, one assuming a global implementation of NDCs and another assuming a coordinated and ambitious global climate action in line with a well below 2 °C climate stabilization. Overall, our assessment provides insights for an evidence-based preparation towards the next UNFCCC processes and other climate decision-making. We note that equity and fairness considerations are beyond the scope of this paper but are nevertheless crucial for a well-informed policy debate and can thus be the focus of future analysis.

The transition to a low-carbon system requires considerable adjustments in all production and consumption patterns and an overall transformation of the energy system. We find that this can be achieved with the existing technology portfolio. Clean energy technologies features significant cost reduction potentials through learning by doing and by research mechanisms. The energy supply sector is leading in early emission reductions while transport takes the lead towards 2050. By mid-century, the power sector is almost fully decarbonized, thus enabling low-carbon transport services through increased electrification. Our projections indicate that RES deployment in power generation is notable. There is also a significant use of biofuels in the transport sector and in particular in freight and aviation. Overall, we find that biomass (in particular new lignocellulosic crops) is more effectively used in transport than in power supply or other end uses. Along with the electrification of transport and the intensive penetration of RES in energy supply sectors, electrification of heat and the use of hydrogen produced from renewable power sources are also important contributors. A major pillar is ambitious energy efficiency in all sectors and in particular in the buildings and industry. Massive renovation of buildings, the eco-design regulations, and heat recovery in industry are the main enablers of efficiency progress. Energy intensity falls more than half below today's levels, while energy savings are very significant in the buildings sector and in transport where they owe mainly to electrification. Additional emission reductions, especially in view of the aspiration for a 1.5 °C climate stabilization, will require dedicated measures for the industry sector and, more importantly, abatement measures for non-CO₂ GHG and for remaining transport emissions in freight and air transport.

This transformation process is significantly capital-intensive. The operating expenditures decrease compared with baseline. The levelized costs of advanced, low-carbon technologies are higher than conventional ones in the early stages of transition but the gap shrinks over time as the advanced technologies profit from learning by doing. The levelized costs of solar and wind in the power sector become lower than conventional technologies already in the early stages of transition, but the balancing costs including costs of storage are significant and increase non-linearly as the renewables get very high shares in power generation. However, the cost of balancing decrease over time as the storage technologies also exhibit learning by doing, while power-to-X technologies that also provide storage services emerge and become competitive in the long term. Despite the learning-by-doing effects, the total energy system cost as borne by final energy consumers is slightly higher in the decarbonization scenario compared with a baseline. The difference is small and is less than one percentage point of GDP in the worst case. The increase in energy costs imply a crowding-out effect in the economy which acts on GDP negatively, particularly in the case of fragmented global climate action. On the other hand, the transition implies a very large substitution of imported fuel by domestically produced equipment that produce renewable energy and/or achieve energy savings in final demand sectors. This substitution exerts a significantly positive multiplying effect on activity and employment. In addition, the industry sees benefits from any relevant technological progress that is enabled by the advanced techniques, and can thus preserve or expand exports of equipment and services. Overall, the impacts of decarbonization on GDP are small. However, the

high capital intensity may raise concerns regarding the capacity of financing, particularly for low income households. Potential inequality and poverty issues are important to address within the decarbonization policy and can be relevant for future research.

We also note that accounting for the costs corresponding to the avoided climate damages and the significant co-benefits for air pollution, noise, and other externalities largely over-compensate the small direct economic costs. Our assessment shows that the macroeconomic impacts of the EU28 decarbonization strategy strongly depends on the level of mitigation action of major trading partners. While a scenario with fragmented, global implementation of NDCs shows a loss of exporting capacity and overall domestic production for the EU28, the region registers economic gains in a coordinated global mitigation action scenario. Early action and adoption of measures for the preparation towards the low-carbon transition can give a comparative advantage to the European energy-intensive and low-carbon technology sectors once a global action is attained, which may result in positive macroeconomic effects. We highlight that the recycling of carbon tax revenues can provide an important tool for the alleviation of potential negative policy impacts, as these revenues can reach 2.5% of EU28 GDP. Future research could focus on the design of dedicated and efficient policies for the optimal redirection of the carbon tax revenues that could result in positive macroeconomic impacts.

As the entire system is transforming, there are important challenges for the materialization of this transition that require a coordinated action of all stakeholders and early policy signals that will act as incentives for the timely development of infrastructure. Smart and expanded electricity grids are crucial for the penetration of intermittent renewable energy, and the aging European infrastructure calls for proactive investments that could seriously affect the cost-efficiency of climate change mitigation action. In addition, climate change mitigation is subject to a new type of consumer behavior not the least with regard to the uptake of new technologies and the requirement for an improved consumer foresight that will enable the unprecedented stepping up of building renovations. New challenges include the shift of transportation demand towards new types of transport services as well as changes in dietary choices that will enable the mitigation of non-CO₂ emissions. In tandem with the above, research and innovation can provide tremendous cost reductions for the low-carbon transition while well-designed policies can ensure a just and inclusive transition. Future research can focus further on the above and complement this paper towards an integrated analysis of European and global decarbonization pathways.

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