Computers & Industrial Engineering 167 (2022) 108029

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

System-level effects of increased energy efficiency in global low-carbon scenarios: A model comparison

Francesco Dalla Longa [a], Panagiotis Fragkos [b], Larissa Pupo Nogueira [a], Bob van der Zwaan [a,c,d,*]

[a] TNO Energy Transition Studies, Amsterdam, the Netherlands
[b] E3 Modelling, Athens, Greece
[c] University of Amsterdam, Faculty of Science (HIMS and IAS), Amsterdam, the Netherlands
[d] Johns Hopkins University, School of Advanced International Studies (SAIS), Bologna, Italy

ARTICLE INFO

Keywords:
Integrated assessment modelling
Paris agreement
Climate policy
Energy efficiency
Model comparison

ABSTRACT

Supporting investments in energy efficiency is considered a robust strategy to achieve a successful transition to low-carbon energy systems in line with the Paris Agreement. Increased energy efficiency levels are expected to reduce the need for supply-side investments in controversial technologies, such as carbon dioxide capture and storage (CCS) and nuclear energy, and to induce a downward push on carbon prices, which may facilitate the political and societal acceptance of climate policies, without adversely affecting living comfort and sustainable development. In order to fully reap these potential benefits, economies need to design policy packages that balance emission reduction incentives on both the demand and the supply side. In this paper we carry out a model-comparison exercise, using two well-established global integrated assessment models, PROMETHEUS and TIAM-ECN, to quantitatively analyze the global system-level effects of increased energy efficiency in the context of ambitious post-COVID climate change mitigation scenarios. Our results confirm the expected benefits induced by higher energy efficiency levels, as in 2050 global carbon prices are found to decline by 10%–50% and CO_2 storage from CCS plants is 13%–90% lower relative to the “default” mitigation scenarios. Similarly, enhanced energy efficiency reduces the additional average yearly system costs needed globally in 2050 to achieve emission reductions in line with the Paris Agreement. These additional costs are estimated to be of the order of 2 trillion US$ – or 1% of global GDP – in a well-below-2 °C scenario, and can be reduced by 6–30% with the adoption of higher energy efficiency standards. While the two models project broadly consistent future trends for the energy mix in the various scenarios, the effects may differ in magnitude due to intrinsic differences in how the models are set up and how sensitive they are to changes in energy efficiency and emission reduction targets.

1. Introduction

The global energy system aims to provide useful energy and mobility services to various end users, including consumers and businesses. The development of energy demand determines the size of future energy supply and the corresponding investment costs, and thus directly influences the assessment of climate change mitigation challenges (Wilson et al., 2012). Large increases in energy consumption may put an additional burden to the energy supply sector to further reduce emissions (Grubler et al., 2018). Accordingly, most global mitigation scenarios tend to focus on supply-side options (IPCC, 2014; Rogelj et al., 2018) and commonly require the large-scale uptake of negative emission technologies, such as those based on carbon capture and storage (CCS) in combination with bio-based fuels. These technologies, however, face large uncertainty and critical limitations related to e.g. their high costs, the availability of suitable sites for CO_2 storage and land for growing bioenergy crops (which might in some cases compete with food production needs), and sustainability of upscaling their deployment (Fuss et al., 2018; Nemet et al., 2018). On the other hand, there exist a high potential for reducing energy consumption in end-use sectors, without adversely affecting the comfort of living for the population, by deploying enhanced energy efficiency solutions, technologies, and practices. Pursuing such enhanced efficiency options on the demand-side provides a complementary avenue to achieving climate change mitigation targets

* Corresponding author.
E-mail addresses: francesco.dallalonga@tno.nl (F. Dalla Longa), fragkos@e3modelling.com (P. Fragkos), larissa.nogueira@tno.nl (L. Pupo Nogueira), bob.vanderzwaan@tno.nl (B. van der Zwaan).

https://doi.org/10.1016/j.cie.2022.108029

Available online 19 February 2022

that may reduce the necessity to invest heavily in expensive and uncertain low-carbon technologies on the supply side, while also reducing the pressure on exploitation of primary energy resources – including renewable resources – to provide human needs like housing and mobility (Grubler et al., 2018).

In the Paris Agreement under United Nations Framework Convention on Climate Change (UNFCCC), governments agreed to a long-term target of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit temperature increase to 1.5 °C (UNFCCC, 2015). This requires large and rapid changes in the energy system towards net-zero emissions by or slightly after 2050 (Van Soest et al., 2021). In this study, we explore the role of energy efficiency as a no-regret strategy for deep decarbonization at the global level in the post-COVID era, as it may provide multiple environmental and economic benefits. In the short-term, energy efficiency offers a low-hanging fruit to reduce emissions while providing a strong stimulus to domestic labor markets (e.g. in the construction business), as it typically creates more domestic jobs per million of expenditure relative to other types of energy investments (IEA, 2020a). In the medium term, energy efficiency reduces the need for supply-side investment and the costs of transformation, which may lead to an increase in the social acceptance of climate policies (Van Vuuren et al., 2018). Finally, in the long term, accelerated efficiency improvements lower the need for expensive and risky technologies like CCS and other Carbon Dioxide Removal (CDR) options. Therefore, energy efficiency provides a resilient, low-cost, and low-risk pathway towards the net-zero transition, while offering important co-benefits such as improved air quality and health (Rauner et al., 2020) and reduced energy trade bills for major economies like the EU, China, Japan, and India (Reuter et al., 2020).

Policy makers are increasingly recognizing the important role of energy efficiency in national low- emission strategies. For example, specific targets for energy efficiency are set by the EU for 2030 as part of the "Clean Energy for All Europeans" policy package, the revised Energy Efficiency Directive and the recent Fit for 55 package. Following this, several EU Member States have legislated policies targeting energy efficiency, while ambitious efficiency measures have been put in place in non-EU countries (e.g. Japan, Canada, USA) in the form of fuel efficiency standards, energy appliance labeling or implementation of stringent building standards. The importance of energy efficiency for reducing emissions is widely recognized: 143 out of 189 Parties explicitly mention energy efficiency in their Nationally Determined Contribution (NDC) plans (IEA, 2016). However, while many options and technologies to increase energy efficiency are readily available in all sectors, current deployment levels are below those required to meet the Paris Agreement goals. At the time of writing, annual investments in energy efficiency amount to 290 billion US$ (IEA, 2020b), while a pathway to achieve net zero emissions by 2050 is estimated to require annual efficiency-related investment of 1.3 trillion US$ by 2030 (IEA, 2021).

Most analyses of the role of energy efficiency in climate mitigation scenarios are currently based on bottom-up detailed assessments with large technological granularity (e.g. Hummel et al., 2021; Fleiter et al., 2018; Swan et al., 2009). However, these often lack the connection with the global climate target narrative and cannot capture system-level effects, including changes in energy prices, supply and/or consumer behavior. Therefore, there is a need to expand Integrated Assessment Models (IAMs) to appropriately represent the technical and behavioral details related to energy efficiency (Brugger et al., 2021; Grubler et al., 2018; Fotiou et al., 2019), while capturing system level effects (e.g. demand–supply interactions, sectoral shifts and spillovers, carbon price and system costs) in a holistic, comprehensive and consistent energy-environment-economy framework. In this way, potential linkages, synergies and trade-offs between ambitious climate targets and energy efficiency policies can be systematically assessed.

In this study we investigate a set of scenarios to meet the Paris goals using two well-established IAMs: PROMETHEUS and TIAM-ECN. Both models rely on the same modelling paradigm: estimating the cost-optimal global energy mix based on a detailed bottom-up description of the energy system, a specific regional disaggregation and an estimated development of future sectoral energy demand driven by exogenous projections of economic and population growth. At the same time, the inner workings of the two models are different, since each model is characterized by a set of unique design choices and assumptions (e.g. the equations used to calculate the objective function, the parametric description of processes and technologies, the way in which interactions between sectors are represented). Because of this diversity one can expect that the models will respond differently to changes in input parameters and policy settings. We refer to this feature as the sensitivity of a model to a certain input. By systematically varying a set of key input parameters (related to climate targets and energy efficiency) to define our scenarios in each model, we can take advantage of the unique models' sensitivities to assess the robustness of the trends observed in the outcomes. We can thus derive policy-relevant recommendations for a cost-efficient and socially acceptable transition to a decarbonized economy, identify uncertainties in our results, and highlight aspects that should be investigated in more detail.

The paper is structured as follows: Section 2 describes the methods used in this work, including the IAMs used and the definition of scenarios based on alternative climate targets and assumptions for energy efficiency. In Section 3, we present the main model outcomes in terms of decarbonization pathways, low-emission strategies shared by the different scenarios, and specific insights useful to inform the design of climate and energy efficiency policies. Finally, Section 4 discusses the main findings and provides policy-relevant conclusions.

2. Methodology

In this paper – as is common-practice in most studies of this type (see e.g. Bertram et al., 2021; Riahi et al., 2021; IPCC, 2018; van der Zwaan et al., 2016) – the term 'model comparison' means that the outcomes of different models are compared, based on a set of common output variables, under consistent scenario assumptions. The main drivers of the models are harmonized (in our case population and GDP), along with the energy system representation (e.g. installed capacities, CO_2 emissions) in the start year of scenario simulations. Each model, however, retains its specific assumptions and granularity in terms of technology portfolio, sectoral representation and regional disaggregation. In this type of analysis 'model comparison' does not mean providing a detailed comparison of models in terms of their inputs, granularity, energy flows, technologies, etc. The 'comparison' is done exclusively on a limited series of selected output variables, which can be reported in a consistent manner for all models involved. The differences in terms of outcomes reflect thus both the differences in representation of the energy system, as well as the differences in the inner workings of each model. In this section we briefly introduce the main characteristics of PROMETHEUS and TIAM-ECN, and we provide the interested reader relevant literature references for more details on how the models are set up, and how they have been used in previous studies. We then describe our scenario framework.

2.1. Models

We use for our analysis two well-established IAMs: PROMETHEUS and TIAM-ECN. PROMETHEUS is a global energy system model capturing the complex interlinkages between energy demand and supply, technology development and deployment, energy prices and CO2 emissions at global and regional level (Fragkos and Kouvaritakis, 2018). The model simulates the development of the global energy system in different forward-looking scenarios until 2050 exploring alternative socio-economic, policy or technology pathways (Fragkos, 2021). It divides the world into 10 regions and has a distinct representation of major emitters, including the EU, China, the US, and India. The model includes the main end-use sectors, including transport (different modes),

Table 1
Model scenarios.

Scenario	Climate targets	Energy efficiency	Carbon price
REF	No additional targets beyond current 2030 climate policies	Endogenous	Endogenous
2DC	Global 2016–2050 carbon budget of 850 Gt CO_2 (compatible with a below-2 °C target)	Endogenous	Endogenous
2DC_eff	Global 2016–2050 carbon budget of 850 Gt CO_2 (compatible with a below-2 °C target)	Exogenously increased in all sectors to levels higher than in 2DC	Endogenous
TAX_eff	No additional targets beyond current 2030 climate policies	Exogenously increased in all sectors to levels higher than in 2DC	Exogenous, based on 2DC scenario
1.5DC	Global 2016–2050 carbon budget of 600 Gt CO_2 (compatible with a below-1.5 °C target)	Endogenous	Endogenous

industries and buildings, while energy supply and transformation (e.g. power generation, refineries, resource extraction, hydrogen production) are modelled in a bottom-up way based on explicit technologies and processes. PROMETHEUS has been used to provide scenarios focusing on international fossil fuel prices (Capros et al., 2016), the impacts of specific mitigation options like CCS (Fragkos, 2021), Nationally Determined Contributions and low-emission strategies in major emitters (Fragkos and Kouvaritakis, 2018), energy system transformation to 1.5 °C (Fragkos, 2020, Marcucci et al., 2019), assessment of the emission and energy system impacts of COVID-19 and recovery plans (Rochedo et al., 2021), and analysis of the role of comprehensive policy measures and portfolios to bridge the gap towards the Paris goals (Van Soest et al., 2021).

TIAM-ECN (IAMC, 2021) is an IAM, built upon the TIMES model generator, that operates at the global level. The TIMES framework and its global realization – TIAM – are well described in e.g. Loulou and Labriet (2008), Loulou (2008) and Syri et al. (2008), and we refer the interested reader to these publications for an overall description of their main characteristics and their mathematical formulation. Here we focus on the features that are specific to TIAM-ECN and particularly relevant for the present paper. As all TIMES-based models, TIAM-ECN is a bottom-up linear optimization model that finds the cost-optimal regional energy mix within scenarios defined through a set of exogenous constraints. TIAM-ECN possesses an input database consisting of several hundreds of processes both for energy production (supply side) and consumption (demand side). It encompasses energy conversion in the main economic sectors, i.e. resource extraction, fuel production, electricity generation, transportation, residential and commercial buildings, and industry. In its most recent implementation, TIAM-ECN divides the global energy system in 36 national or supra-national regions (Kober et al., 2016; van der Zwaan et al., 2018). TIAM-ECN has been used to create long-term scenario projections at global and regional level for specific sectors, such as transportation (Rösler et al., 2014) and electricity generation (Kober et al., 2016), for certain technology classes, such as CCS (Dalla Longa et al., 2020) and off-/mini-grid power production (Dalla Longa et al., 2021a), and for climate change (Kober et al., 2014) and technology diffusion (van der Zwaan et al., 2013; van der Zwaan et al., 2016).

In the context of this paper, assumptions for future development of the main socio-economic drivers – population and GDP growth – in PROMETHEUS and TIAM-ECN have been harmonized in order to provide a robust and consistent framework for model comparison. Projections for population and GDP growth are based on the second Shared Socioeconomic Pathway (SSP2) developed by the global integrated assessment modelling community (Fricko et al., 2017). The SSP2 GDP trajectory has been modified to better reflect the short-term impacts from COVID-19 and the expected developments in the post-COVID era (see the Appendix for an overview of our modified SSP2 trajectory at the global level). In order to obtain this modified GDP trajectory, we consulted several short-term GDP projections from official sources and international organizations, including DG ECFIN (Summer 2021), OECD Economic Outlook (November 2020), and World Bank Global Economic Prospect (June 2021). We settled for the projections derived from the OECD Economic Outlook (OECD, 2020), which entail for the year 2020 a global GDP that is 8% lower than pre-COVID forecasts (i.e. 4.5% below 2019 levels). The GDP projections further assume a V-shape growth recovery after 2021, assuming a strong and effective vaccination programme and no further major outbreaks after 2021 (see Dafnomilis et al., 2021, for a detailed analysis).

Both IAMs can be utilized to provide an improved understanding of the impacts that energy and environmental policies at national and global levels may have on the sectoral energy mix, CO_2 emissions, energy investment and costs at the global level. They can both simulate the effects of various policy instruments, including price signals (e.g. carbon prices, energy or carbon taxation, energy or technology subsidies), policies promoting the use of renewable energy and energy efficiency, technology standards and phase-out policies (Capros et al., 2016; Fragkos et al., 2018; Kober et al., 2016). The modelling frameworks are well equipped to quantify the medium- and long-term effects of ambitious energy efficiency policies in the context of the Paris Agreement goals.

2.2. Scenarios

This paper aims at exploring the effects of a strong push in energy efficiency across all sectors on the global energy system under stringent climate change control policies. For this purpose, we design five scenarios based on specific assumptions with regard to (i) climate change mitigation targets, (ii) energy efficiency improvements, and (iii) carbon price developments. These scenarios are then implemented in PROMETHEUS and TIAM-ECN. Table 1 presents a summary of the key assumptions used in each scenario.

The first scenario, REF, is based on the continuation of existing energy and climate policies, in consistency with Roelfsema et al. (2020). The energy system develops in line with current trends, including already legislated climate policies until 2030 and further cost improvements in low-carbon technologies. Beyond that, we impose no binding climate change mitigation targets and no technology or sector-specific increases in energy efficiency. Slightly higher overall energy efficiency levels are still achieved endogenously throughout the modeling horizon due to the fact that energy intensity of GDP is assumed to keep improving at rates close to historical values in each region. This scenario represents a projection of current system trends into the future and serves as a benchmark with which to compare the results of the remaining scenarios. By systematically varying some key model parameters, in the other scenarios we explore possible realizations of a low-carbon global energy system until 2050.

In the 2DC scenario we assume that the world will settle on a cost-optimal trajectory compatible with a well-below 2 °C increase in global average temperature, in line with the Paris Agreement goal (COP-21, 2015). Global CO_2 emissions from fossil fuels and industrial operations in the 2016–2050 period are exogenously limited to a budget of 850 Gt CO_2 (in line with Mc Collum et al., 2018). Emission certificates can be traded through a universal carbon pricing mechanism across regions and sectors. The carbon price emerges endogenously in the models as the dual variable related to the maximum allowed CO_2 emissions by 2050, and it applies uniformly to all regions and sectors. No efficiency improvements are assumed beyond those induced by carbon pricing (and those already assumed in REF based on continuation of historic trends).

The 2DC_eff scenario is a variant of 2DC in which we impose an

Table 2
Assumptions for the increased efficiency scenarios 2DC_eff and TAX_eff.

Sector	Technology category	Average efficiency increase	Average capital cost increase
Industry	All	10%	10%
Residential	All	20%	10%
Commercial	All	20%	10%
Transport	Electricity	15%	10%
	Biomass	10%	10%
	Gas	10%	10%
	Oil	10%	10%
	Hydrogen	20%	10%

increase in energy efficiency to be realized between 2020 and 2050 in the most widespread technology classes across all demand sectors. Higher efficiency is typically accompanied by an increase in the corresponding capital costs for a technology category, as discussed in e.g. Fotiou et al. (2019). Our assumptions, detailed in Table 2, are largely based on the 2020 EU Reference scenario report (EC, 2021a). 2DC_eff aims at illustrating the possible effects of a consumers' shift towards purchasing the most energy efficient technologies in the market. Such a shift could be induced by ambitious policy measures targeting, among others, the gradual phase-out of low-efficiency energy appliances in favor of high-efficiency technology standards, the implementation of energy labelling directives for residential and commercial buildings, the increase in renovation rates (e.g. induced by subsidies), and the application of stringent energy efficiency standards in industry and in the transport sector.

In TAX_eff we maintain the assumptions on increased energy efficiency reported in Table 2. In this scenario, however, global emission reductions are achieved by exogenously imposing a carbon price that is equal to that in the 2DC scenario, rather than by directly capping the release of CO_2 in the atmosphere. The scenario aims at simulating the effects of increasing efficiency standards and legislation in the context of ambitious carbon pricing towards 2 °C in order to assess whether this

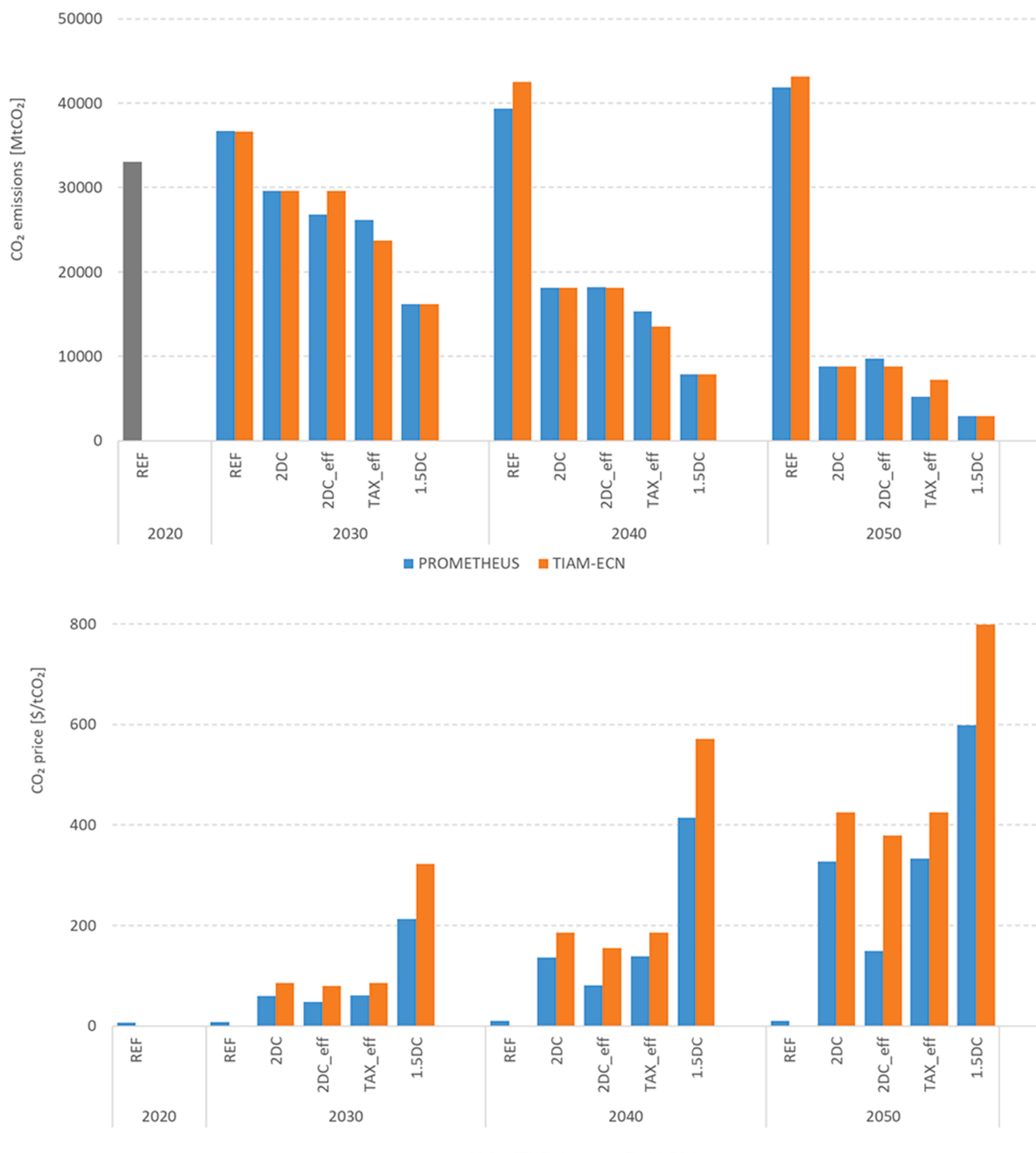

Fig. 1. CO_2 emissions (top panel) and carbon price (bottom panel).

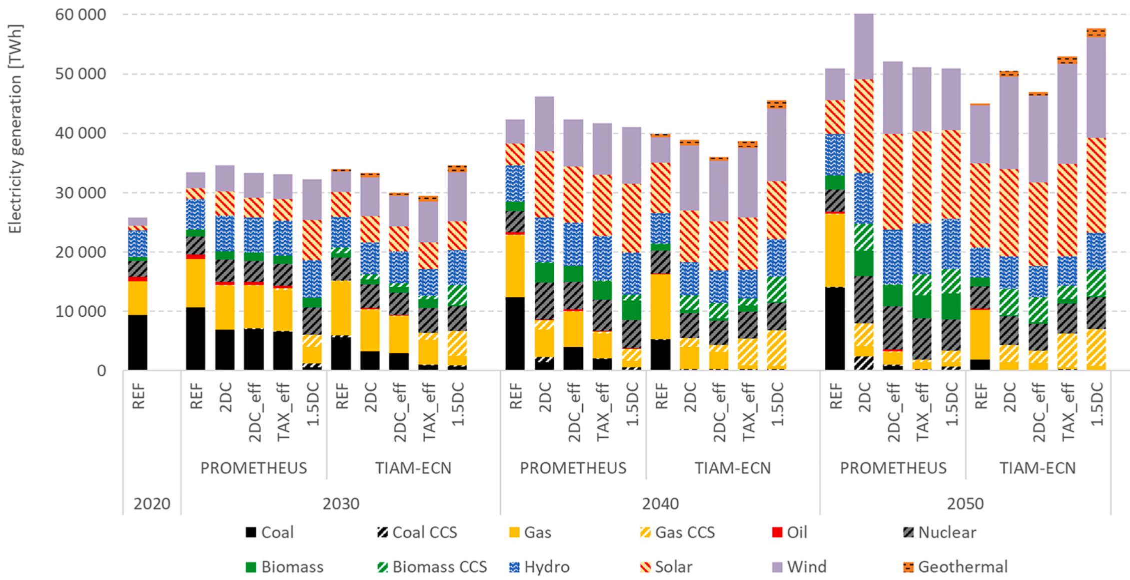

Fig. 2. Global power generation mix.

policy combination can pave the way towards meeting the more ambitious 1.5 °C Paris goal.

Our final scenario – 1.5DC – is analogous to 2DC, but we assume a more stringent 2016–2050 global carbon budget of 600 Gt CO_2, resulting in a maximum temperature increase of 1.5 °C by the end of the century (IPCC SR1.5, Rogelj et al., 2018). This scenario is meant to explore the impacts that are triggered when all countries work together to limit the global temperature increase to levels below 1.5 °C as per the more ambitious climate goal proposed in the Paris Agreement (COP-21, 2015), by implementing a universal carbon pricing scheme in all regions and sectors.

3. Modelling results

In this section we present the main scenario-based outcomes of PROMETHEUS and TIAM-ECN over the period 2020–2050.

3.1. CO_2 emissions and carbon prices

Fig. 1 shows the projections for energy-related CO_2 emissions (top panel) and carbon price (bottom panel) obtained with PROMETHEUS and TIAM-ECN. In the REF scenario both models project a limited increase of global CO_2 emissions over the 2020–2050 period, despite the robust growth of global economic activity (Fricko et al., 2017), indicating a relative decoupling of emissions from GDP growth. This decoupling is triggered endogenously by the adoption of low-carbon technologies (e.g. PV panels, wind turbines, electric vehicles) and high-efficiency processes, induced by their respective future cost reductions. The current climate policies and targets assumed in REF are realized in both models through a series of exogenous constraints on the minimum and maximum shares of, respectively, low-carbon and fossil fuel-based technologies in the energy mix at regional and sectoral level. PROMETHEUS also explicitly simulates the strengthening of the European Emission Trading System (resulting in the small increase in global average carbon price observed in REF in Fig. 1), while for TIAM-ECN no carbon markets are assumed in REF – hence no carbon price is calculated by the model.

In the 2DC and 2DC_eff scenarios, ambitious climate policies to limit global carbon emissions are applied. Mid-century global CO_2 levels in the 2DC scenarios are 80% lower than in REF for both models. The emission cap imposed in these scenarios triggers an endogenous increase in carbon price which applies uniformly to all regions and economic sectors to achieve emission reductions when and where it is most cost-efficient, thus ensuring that the global climate goal is achieved with the lowest possible costs. By comparing the bars relative to 2DC and 2DC_eff in the bottom panel of Fig. 1, one can notice that the required carbon price is, in both model projections, lower in the increased energy efficiency scenario, showing that the implementation of ambitious efficiency policies, standards and regulation may reduce the need for high carbon pricing to achieve the same mitigation target. This is expected to have a positive effect on the social acceptance of ambitious climate policies, as energy (or carbon) taxation has regressive distributional impacts, posing a disproportionately high cost burden to low-income households (Fragkos et al., 2021), and often raises social concerns (see e.g. Vona, 2019). In PROMETHEUS, the required carbon price appears to be more sensitive to the implementation of higher efficiency standards than in TIAM-ECN, as the former includes a more detailed description of energy end use technologies and related efficiency measures, while TIAM-ECN has a higher granularity in representing energy supply. This is especially evident in 2050 as the carbon price in 2DC_eff is less than half of that in 2DC for PROMETHEUS, whereas for TIAM-ECN the reduction is only 10%.

The TAX_eff scenario combines the carbon pricing of 2DC with the increased energy efficiency improvements of 2DC_eff, and thus achieves further reductions in global emissions relative to 2DC and 2DC_eff. These are projected to vary in 2050 from 83% to 86% below REF levels for, respectively, TIAM-ECN and PROMETHEUS. In comparison with the 2DC scenario, CO2 emissions in TAX_eff are 35% and 20% lower for, respectively, TIAM-ECN and PROMETHEUS. In TAX_eff the carbon price is imposed exogenously in order to trigger emission reductions without applying a CO_2 cap. This scenario illustrates that utilizing energy efficiency policies and standards could prove an effective way to bridge the effort gap between a “well below” 2 °C scenario and a below 1.5 °C one without requiring very high CO_2 prices until 2050. To further emphasize this point, in our final scenario, 1.5DC, we impose a constraint on global carbon budget compatible with a 1.5 °C climate control target. In this scenario both models project that global CO2 emission levels in 2050 would be more than 90% lower than in REF – hence very close to reaching net zero by 2050 – but the corresponding carbon prices are nearly twice as high as in 2DC and TAX_eff.

Fig. A2 in the Appendix complements the data presented in Fig. 1 by providing a sector-level overview of emission reductions in the various scenarios.

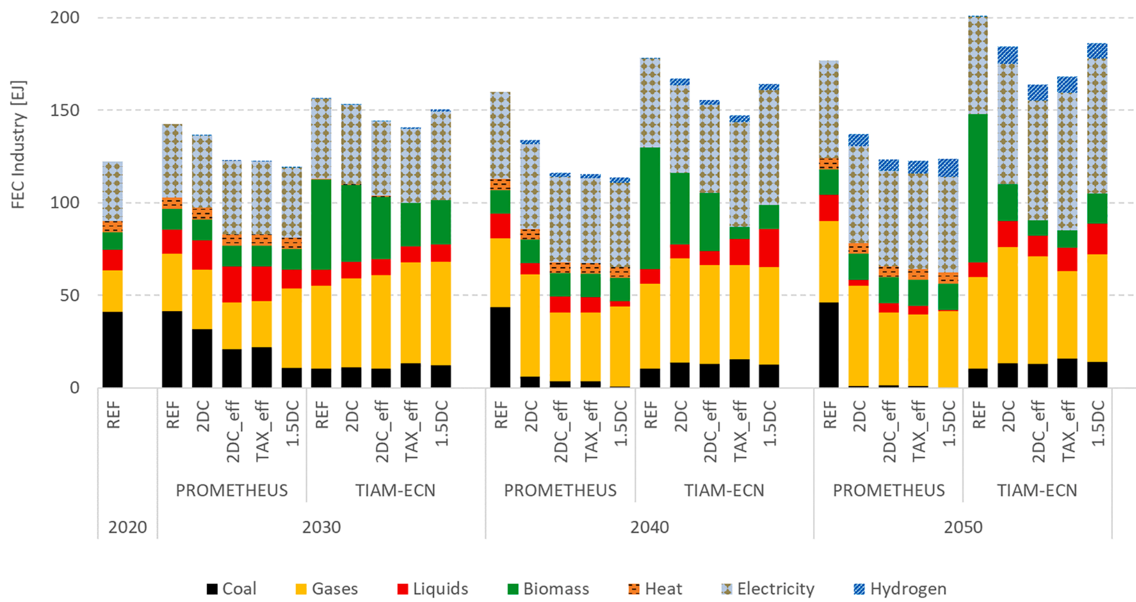

Fig. 3. Final energy consumption by energy carrier in industry.

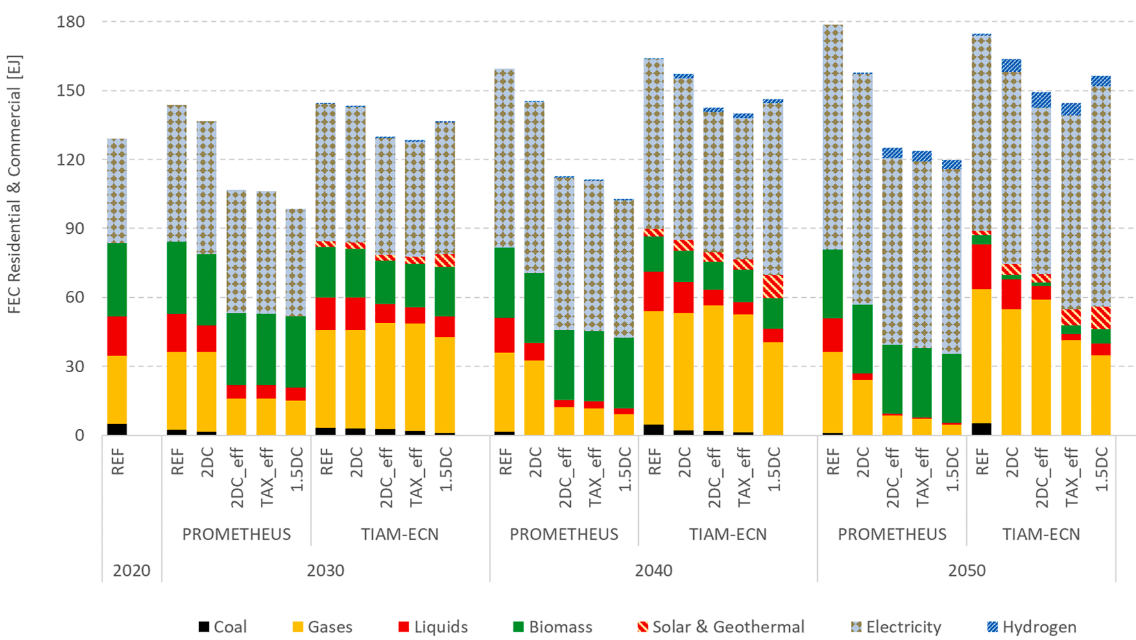

Fig. 4. Final energy consumption in residential and commercial buildings.

3.2. Power sector

In Fig. 2 we present the global power generation mix. For all scenarios, both models project a steady increase in electricity production between 2020 and 2050 with an average annual growth between 2% and 3% (depending on model and scenario assumptions) triggered by growing living standards (due to rising incomes) combined with increasing electrification of energy services. The relative magnitude of the increase in electricity generation requirements and the projected technology mix differ in the two models, mainly as a result of different assumptions in technology cost developments, technology potentials, carbon price levels, and different sensitivity levels to changes in the parameters that define our scenarios. In REF, global electricity generation grows to 50,000 TWh/yr by the middle of the century for PROMETHEUS, against the 45,000 TWh/yr projected by TIAM-ECN. The main contributors to the electricity mix in the REF scenario in 2050 are solar, wind, hydro, natural gas and nuclear. In the REF scenario, due to the lack of ambitious climate policies, PROMETHEUS projects that coal-based generation maintains a share of 28% by 2050 (albeit reduced from 39% in 2015), while this source is almost completely phased out in TIAM-ECN due to the high uptake of renewable energy (especially solar and wind) at levels considerably higher than in PROMETHEUS. In both models, nuclear energy, hydro and biomass provide a small, but non-negligible, amount of electricity over the 2020–2050 period. In the 2DC scenario electricity generation increases with respect to REF by respectively 20% and 10% for PROMETHEUS and TIAM-ECN as electricity use expands in buildings, transport and industries to substitute for fossil fuels which are penalized by high carbon pricing. Both models project a larger renewable-electricity production than in REF, with the share of renewables in 2050 increasing from 40% (REF) to over 70%

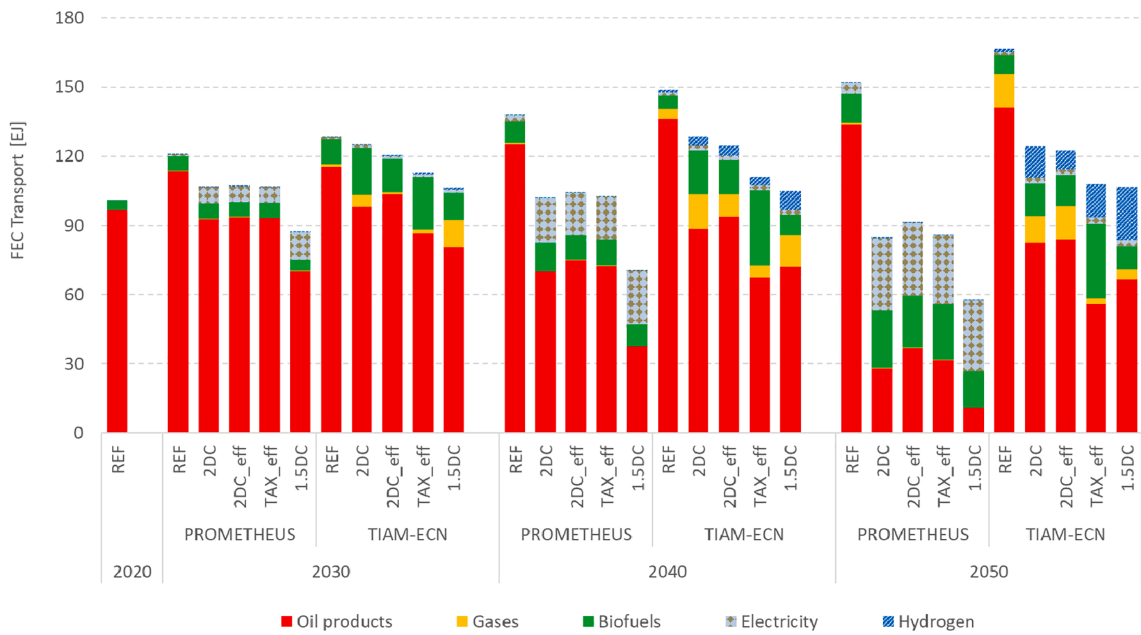

Fig. 5. Final energy consumption mix in transport.

(2DC) and from nearly 70% (REF) to slightly more than 80%, respectively, in PROMETHEUS and TIAM-ECN. Both model projections also feature the adoption of carbon capture and storage (CCS) technologies combined with biomass and fossil fuels – while the utilization of the latter carriers without CCS is almost completely phased out – and an increase in the use of nuclear energy. TIAM-ECN also projects a small contribution from geothermal energy. In 2DC_eff, total electricity production in 2050 reverts back to slightly over the REF level for both models, as a result of the increased efficiency assumptions that induce an overall reduction of electricity requirements especially in buildings and industries. In the 2DC_eff PROMETHEUS projection, electricity production from CCS technologies is negligible, while for TIAM-ECN it is only slightly smaller than in 2DC. Overall 2050 electricity generation levels in TAX_eff and 1.5DC remain roughly the same as in 2DC_eff for PROMETHEUS, indicating that the policy measures simulated in these two scenarios trigger a degree of electrification and energy efficiency in the energy system that is of the same order of magnitude of that triggered in the 2DC_eff scenario. The situation is different in the TIAM-ECN projections. These show higher total electricity production, reaching 53,000 and 58,000 TWh/yr, respectively, in TAX_eff and 1.5DC. In both models, the power sector is almost completely decarbonized by mid-century in all ambitious mitigation scenarios. This decarbonization is triggered by high carbon pricing and the emergence of low-cost clean alternatives to fossil fuel-based generation, especially renewable energy and CCS technologies.

3.3. Demand sectors

In Figs. 3–5 we analyze scenario projections of final energy consumption (FEC) in the three main demand sectors: industry, residential and commercial buildings, and transport. The REF projections in Fig. 3 show that FEC in industry undergoes a steady increase reaching values of 175 and 200 EJ/yr for PROMETHEUS and TIAM-ECN, respectively, driven by increasing industrial activity (following socio-economic developments increasing the need for materials and industrial products) and the lack of ambitious climate policies. The main industrial fuels remain the same throughout the modeling horizon: natural gas, coal, oil, biomass and electricity, with a small contribution from heat. The PROMETHEUS projection shows in REF only small changes in the relative shares of industrial fuels in future decades (gas and electricity slightly increasing, coal and oil products slightly decreasing), while in TIAM-ECN coal is almost completely replaced by natural gas and biomass already from 2030.

The application of ambitious climate control policies causes a decrease of total industrial FEC in both models, as more efficient technologies start to be utilized and more efficient energy carriers (e.g. electricity) increasingly replace the inefficient use of coal and oil products. Both models thus identify accelerated energy efficiency improvements and fuel switching as the main instruments to achieve industrial decarbonization. In general, PROMETHEUS projects larger FEC reductions relative to REF (up to 31% in TAX_eff) than TIAM-ECN (up to 19% in 2DC_eff). While for PROMETHEUS the emission constraint and efficiency assumptions mainly induce a reduction in fossil fuel consumption, for TIAM-ECN the use of hydrogen also emerges as an important transformation pathway for industry, especially in hard-to-abate sectors like Iron and Steel. The application of CCS in biomass and fossil fuel-based industrial processes in the low-carbon scenarios is also projected in both models (not shown in Fig. 3) as will be discussed later in this section.

In Fig. 4 we present FEC projections for residential and commercial buildings. In the REF scenario energy consumption from buildings grows steadily at similar rates for both models, as a consequence of our assumptions on population and GDP growth, increasing urbanization and rising income and living standards in developing economies. The main difference between the two REF model projections in 2050 is that PROMETHEUS is more optimistic than TIAM-ECN with regard to the replacement of natural gas with technologies based on electricity and biomass. The application of emission and efficiency constraints in the low-carbon scenarios causes a reduction of total FEC in buildings - triggered by an increased rate and depth of renovation, a more rational use of energy and the uptake of more efficient fuels and equipment - and the emergence of electricity and hydrogen for heating, accompanied, in the TIAM-ECN case, by a growth of solar thermal and geothermal technologies. As for industry, also in the residential and commercial sectors PROMETHEUS projects larger FEC decreases than TIAM-ECN. Maximum FEC reductions with respect to REF levels in 2050 are projected at 33% and 17% for, respectively, PROMETHEUS (1.5DC) and TIAM-ECN (TAX_eff). Our analysis is in line with Levesque et al. (2018) who have shown that global energy demand from buildings can be reduced by up to 47% in a highly-efficient scenario compared to a

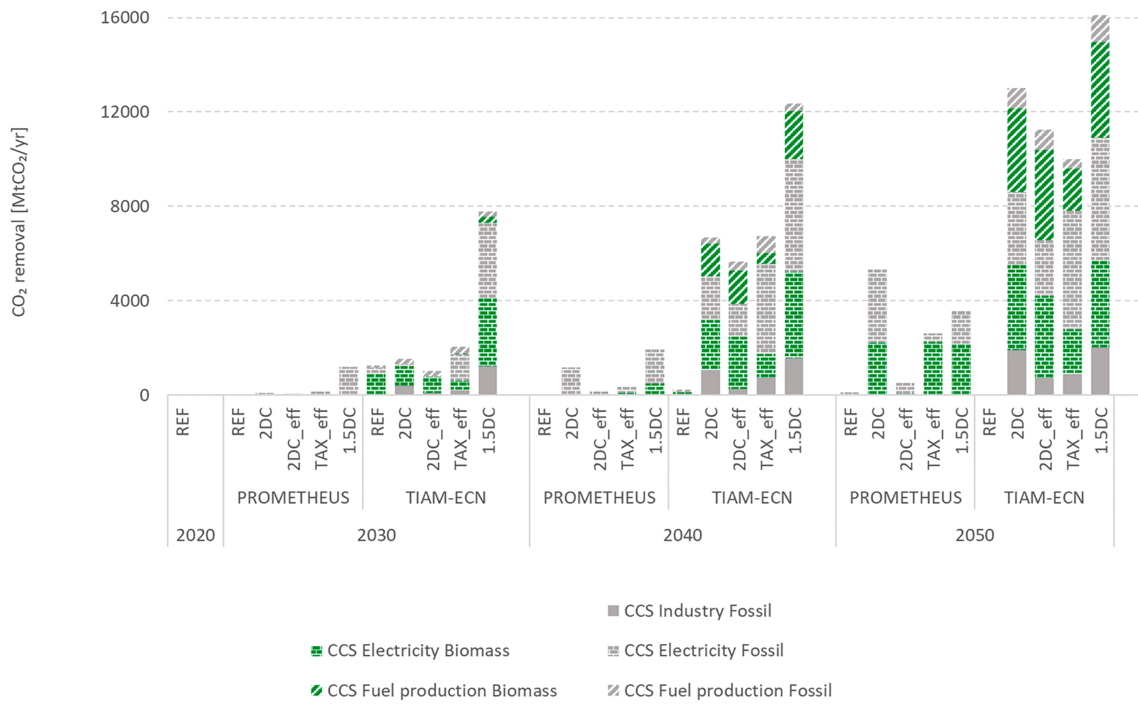

Fig. 6. Uptake of CO_2 removal technologies.

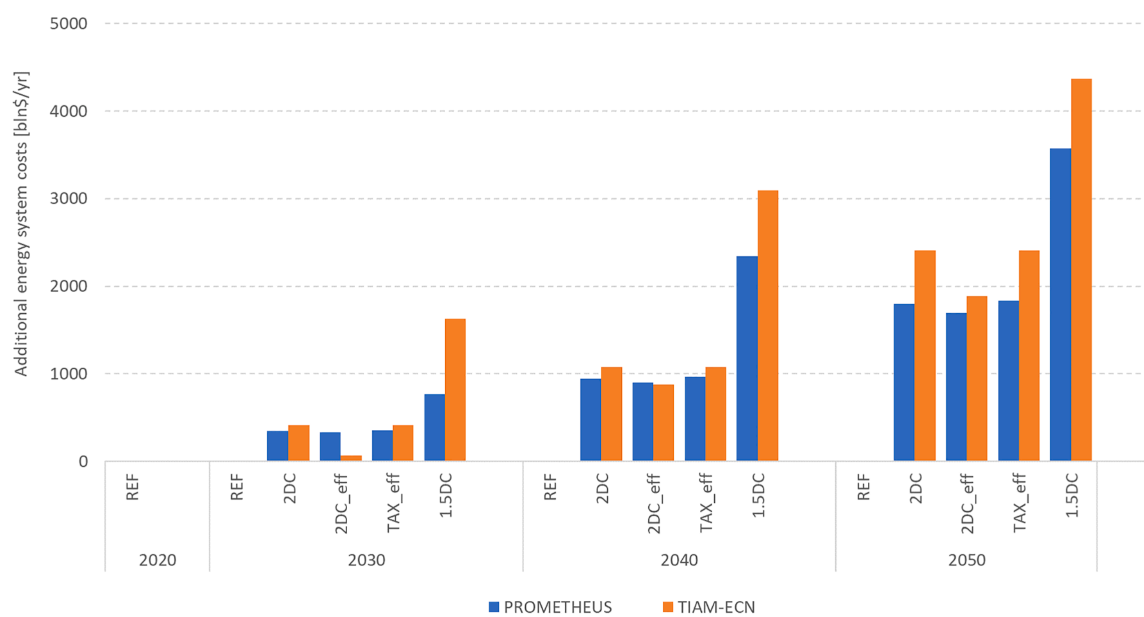

Fig. 7. Additional energy system costs with respect to REF.

scenario following current trends. In 2050 the emergence of hydrogen in the PROMETHEUS projection is only triggered by the application of high energy efficiency requirements (2DC_eff, TAX_eff) or by a very stringent emission cap (1.5DC), whereas TIAM-ECN projects that hydrogen also penetrates the residential and commercial sectors in 2DC. While the use of oil in buildings is completely phased out by 2050 in most low-carbon scenarios in the PROMETHEUS projections, TIAM-ECN maintains a small amount of oil consumption in all scenarios. This is mainly occurring in developing economies, such as several countries in Sub-Saharan Africa that lack the means to deploy the required infrastructure to support a full-scale switch to cleaner alternatives by mid-century (see e.g. van der Zwaan et al., 2018).

Fig. 5 shows the model-based projections for final energy consumption in the transport sector. As in the other two demand sectors, the REF projection displays in both models a steady growth between 2020 and 2050, reaching 150 and 165 EJ/yr for PROMETHEUS and TIAM-ECN, respectively. This is triggered by the increasing living standards, rising GDP and the increasing motorization trends in developing regions, combined with the lack of policies to reduce emission footprint and facilitate the switch to transport modes requiring less energy (e.g. public transport, biking and walking). Oil products remain the dominant transport fuel in the REF projections, with biofuels, natural gas, electricity and (only for TIAM-ECN) hydrogen each gaining a small share in the transport energy mix, as conventional vehicles with internal combustion engines (ICEs) are projected to remain predominant in all transport modes. In the four low-carbon scenarios, total

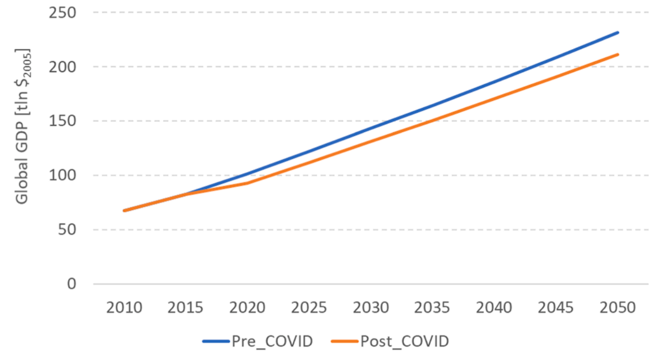

Fig. A1. Pre- and post-COVID GDP projections, expressed in 2005 international dollars.

consumption shrinks as a result of switching to more efficient vehicles. Maximum reductions of, respectively, 60% and 35% are achieved in PROMETHEUS and TIAM-ECN in the 1.5DC scenario. The fuel mix is altered in different ways in the two models. In 2DC, 2DC_eff and TAX_eff, PROMETHEUS projects a total fuel consumption in the transport sector of around 90 EJ/yr by mid-century (close to current levels), fulfilled in nearly equal parts by oil products, biofuels and electricity. Energy use is further reduced to 60 EJ/yr in the 1.5DC scenario, mainly by phasing out most of the ICE and hybrid fleets combined with a rapid expansion of electric vehicles in passenger transport and hydrogen fuel cells especially in road freight transport, aviation and navigation. In the TIAM-ECN projections the decrease in total FEC with respect to REF is in general less pronounced than for PROMETHEUS: fuel consumption in 2050 is slightly above 120 EJ/yr for both 2DC and 2DC_eff, while a further decrease down to about 105 EJ/yr is triggered in TAX_eff and 1.5DC. The consumption of oil products is severely reduced in all low-carbon scenarios, and natural gas is almost completely phased out in TAX_eff and 1.5DC. Biofuels continue to provide a substantial contribution to the fuel mix, up to over 30 EJ/yr in TAX_eff. The share of electricity in the transport mix remains small (below 3%) in all scenarios, while hydrogen becomes a prominent transport fuel with shares up to 20% in the 1.5DC scenario. Electricity emerges as the main decarbonization fuel for transport in the PROMETHEUS mitigation scenarios, whereas this role is fulfilled by hydrogen in the TIAM-ECN projections. This difference is caused by diverging assumptions in the evolution of costs for batteries and fuel cells for, respectively, electric vehicles (BEV) and hydrogen ones (FCEV). While BEVs are currently more widespread than FECVs, since both their respective underlying storage technologies have experienced significant cost declines in recent years, a large uptake of hydrogen-based transportation might also materialize in the near future, alongside or in competition with the growth of the electric vehicles fleet (Rösler et al., 2014; Capros et al., 2019). For this reason, we find it valuable to present the outcomes of the two models without trying to further harmonize our cost assumptions, as they represent two different – but equally realistic and self-consistent – possible realizations of the future transport fuel mix under ambitious mitigation policies.

3.4. CO_2 removal

In Fig. 6 we plot the projections for CO_2 removal in the various scenarios. The main mechanism for removing CO_2 from the atmosphere considered in this study is the deployment of CCS technologies in the electricity generation, industry and fuel production sectors, which is triggered by high carbon pricing. As Fig. 6 shows, CCS processes are used in all low-carbon scenarios, in quantities that depend on the model used and the scenario-specific assumptions. In general PROMETHEUS is less optimistic than TIAM-ECN with regard to the potential spread of CCS technologies, relying instead more heavily on energy efficiency improvements to achieve decarbonization targets. The former model projects the utilization of CCS exclusively in the power sector, while the latter deploys it also in industry and fuel production. Maximum CO_2 capture levels are reached in 2050 in the carbon cap scenarios: 5 $GtCO_2$/yr in 2DC and 16 $GtCO_2$/yr in 1.5DC for PROMETHEUS and TIAM-ECN, respectively. The efficiency push in the "_eff" scenarios causes a significant decrease in the need for CCS deployment. While this reduction is consistently projected by both models, its magnitude varies across models and scenarios. In 2DC_eff, CO_2 removal in 2050 is 90% and 13% lower than in 2DC for, respectively, PROMETHEUS and TIAM-ECN; thus the PROMETHEUS projection indicates that in the presence of strong energy efficiency measures, there is little need for CCS uptake, as carbon prices stay considerably lower than in 2DC. In the same year, in TAX_eff, the relative reductions with respect to 2DC are 50% and 23% for

Table A1
Modified 2020 GDP growth rates at country/regional level (from OECD economic outlook, consulted in November 2020).

	2020 GDP growth rate [%]
Argentina	−12.9
Australia	−3.8
Austria	−8.0
Belgium	−7.5
Brazil	−6.0
Bulgaria	−4.1
Canada	−5.4
Chile	−6.0
China (People's Republic of)	1.8
Colombia	−8.3
Costa Rica	−5.6
Czech Republic	−6.8
Denmark	−3.9
Dynamic Asian Economies	−4.6
Estonia	−4.7
Euro area (17 countries)	−7.5
Finland	−4.0
France	−9.1
Germany	−5.5
Greece	−10.1
Hungary	−5.7
Iceland	−7.7
India	−9.9
Indonesia	−2.4
Ireland	−3.2
Israel	−4.2
Italy	−9.1
Japan	−5.3
Korea	−1.1
Latvia	−4.3
Lithuania	−2.0
Luxembourg	−4.4
Mexico	−9.2
Netherlands	−4.6
New Zealand	−4.8
Non-OECD Economies	−3.0
Norway	−1.2
OECD - Total	−5.5
Other oil producers	−6.5
Poland	−3.5
Portugal	−8.4
Rest of the World	−4.3
Romania	−5.3
Russia	−4.3
Slovak Republic	−6.3
Slovenia	−7.5
South Africa	−8.1
Spain	−11.6
Sweden	−3.2
Switzerland	−4.7
Turkey	−1.3
United Kingdom	−11.2
United States	−3.7
World	−4.2
EEU	−4.8

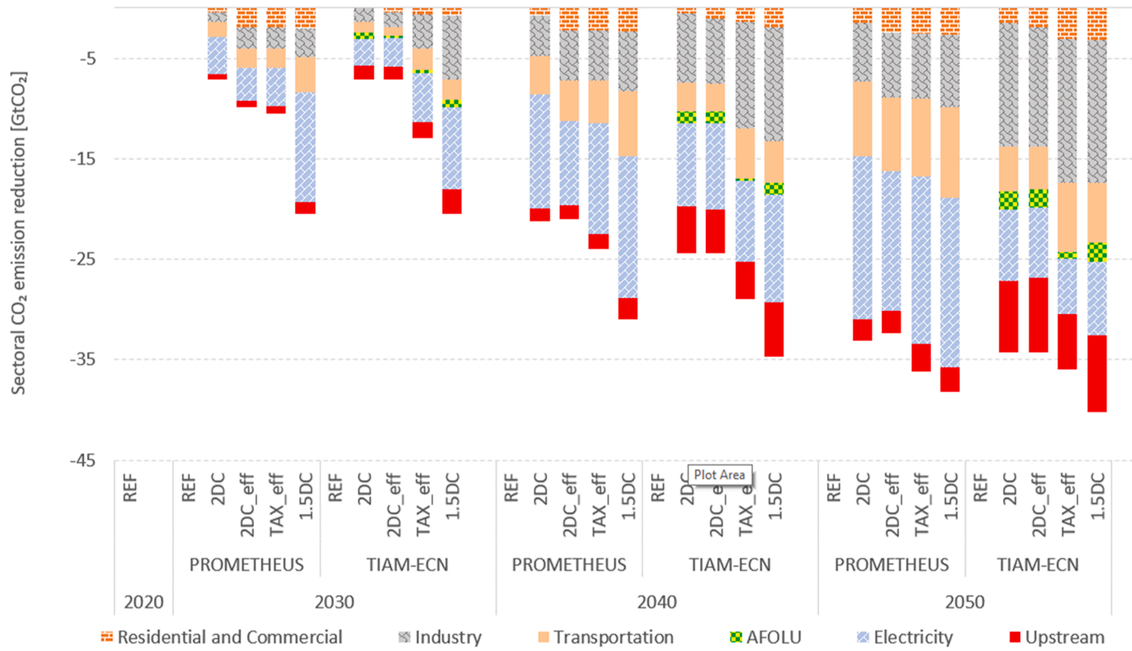

Fig. A2. Sectoral CO_2 emission reduction with respect to the REF scenario.

PROMETHEUS and TIAM-ECN, respectively, showing that deep emission reductions can be achieved through accelerated uptake of renewable energy, low-emission vehicles and energy efficiency.

3.5. System costs

Fig. 7 presents additional energy system costs with respect to REF for all mitigation scenarios. Ambitious climate control targets in 2DC and 1.5DC drive system costs up by forcing additional investments in low-carbon technologies, clean vehicles and energy efficiency. As shown in (Fragkos, Kouvaritakis, 2018), energy system costs generally increase with the mitigation effort. For PROMETHEUS additional global energy system costs in 2050 for 2DC and 1.5DC are, respectively, 1.8 and 3.6 tln $/yr, while for TIAM-ECN they are, respectively, 2.4 and 4.4 tln$/yr. PROMETHEUS generally projects lower additional costs than TIAM-ECN. This is directly related to the lower energy use projected by the former model in all end-use sectors, resulting from its detailed and disaggregated representation of end-use technologies with different levels of efficiencies, in line with Fotiou et al. (2019). In both models, the imposition of energy efficiency policies on top of the climate objective in the 2DC_eff scenario causes on the one hand the use of (expensive) high-efficiency end-use processes and more efficient technologies, cars, appliances and equipment in the demand sectors – which leads to an increase in system costs – and on the other hand a reduction in fossil fuel consumption and carbon price – which push system costs down. The two effects result in 2050 in additional costs that are 6% and 30% lower with respect to the 2DC scenario for, respectively, PROMETHEUS and TIAM-ECN. Both model projections thus consistently indicate that stimulating the adoption of high-efficiency technologies on top of a climate mitigation target might reduce overall energy system costs to meet the same climate target.

4. Discussion and policy recommendations

In this paper we explore a set of alternative mitigation pathways compatible with the Paris Agreement goals, under different scenario assumptions, using two established global IAMs: PROMETHEUS and TIAM-ECN. The analysis shows that the Paris goals are technologically possible but require large-scale, structural transformations in energy systems and societies at the global scale. The necessary changes should be driven by accelerated uptake of multiple mitigation strategies, including renewable energy deployment, electrification of end-uses, energy efficiency, hydrogen and CCS. The remaining carbon budget consistent with 1.5 °C or 2 °C goals highly influences the speed and magnitude of the required energy system transformation. To meet strong climate targets, global CO_2 emissions should peak before 2025, followed by a steep reduction induced by the decarbonization of the power sector, driven by the expansion of renewable energy and the phase-out of coal. Our analysis highlights the importance of strengthening climate action and revising upwards the ambition of current policies and NDCs, while developing the required clean energy infrastructure in the 2020–2030 decade.

Considering the main outcomes from the two models in the various combinations of climate mitigation and energy efficiency policies that our low-carbon scenarios entail, several pillars to achieve global decarbonization targets can be identified. First, a large expansion of energy generation from renewable sources is projected for all sectors, and is especially prominent in the power generation sector, which in some cases becomes almost carbon-free by 2050 (see e.g. the TIAM-ECN projection for TAX_eff scenario in Fig. 2). Second, the dependence of end-use energy services from fossil fuels can be lessened through an increase in electricity shares across the demand sectors, complemented by the deployment of low-carbon fuels (e.g. advanced biofuels and hydrogen) when electrification is neither technically feasible nor economically efficient (e.g. high-temperature industrial processes). Third, energy demand savings through uptake of enhanced energy efficiency technologies or through improved thermal insulation of buildings proves to be a robust strategy to reduce CO_2 emissions across the economy, as it is endogenously triggered by high carbon prices in the cost-optimal 2DC and 1.5DC scenarios. Fourth, the deployment of carbon removal technologies, such as CCS, is necessary in order to achieve ambitious decarbonization targets. CCS requirements are, however, considerably lower if ambitious energy efficiency policies are implemented, thus reducing society's reliance on a costly and risky technology, currently not used at scale.

Policies combining the promotion of high energy efficiency with a carbon cap (as in 2DC_eff) can lead to lower carbon prices – possibly accompanied by lower energy system costs – than those focusing solely on capping emissions. Utilizing energy efficiency policies together with a moderate carbon price (as in TAX_eff) could provide the required additional effort to move from a well-below-2 °C future down to a well-below-1.5 °C one, without requiring very high CO_2 prices. This, in turn, might increase the likelihood of social acceptance and support of ambitious climate policies (Fragkos et al., 2021). Our analysis shows that the adoption of high efficiency standards can contribute to mitigating the environmental, economic, ethical and social risks that emerge from relying on currently immature carbon removal technologies, such as CCS (Van Vuuren et al., 2018). The extent to which enhanced energy efficiency can reduce the need for CCS deployment is, however, highly uncertain, and may well vary between extremes as low as 13% and as high as 90%. The diffusion of high energy efficiency technologies also leads to lower supply-side investments and may bring important co-benefits, e.g. in terms of job creation (see e.g. IEA, 2020a), reduced air pollution and lower dependency on energy imports. Our analysis, using two leading IAMs under a range of policy and technology assumptions, confirms the findings of previous literature, showing that scenarios driven by energy demand reductions provide a robust alternative to technology-driven scenarios, possibly entailing some significant economic, social, and environmental benefits (Creutzig et al., 2018; Mundaca et al., 2019; Grubler et al., 2018). The energy efficiency assumptions simulated here are not considered extreme and thus do not reduce living standards of consumers (Rao et al., 2017) and do not constrain thermal comfort, the use of appliances, transport activity and industrial production (Levesque et al., 2018).

Despite the expected economic, health and environmental benefits of enhancing energy efficiency across the economy, the transition to a net-zero emissions world still requires a large transformation of the global energy and transport systems, as well as of human. For example, the uptake of already-existing clean technologies should be upscaled (e.g. solar PV, wind, BEVs and FCEVs, heat pumps), while new mitigation technologies have to emerge (e.g. advanced biofuels, green hydrogen), driven by targeted investments.. Simultaneously, human behavior needs to change through modal shifts to less-emitting transport options, more rational use of energy, and uptake of more efficient fuels and equipment. All these changes cannot be realized easily, and require increased funding, ambitious and early action by governments, businesses and citizens, increased low-carbon innovation, lifestyle changes, and strong policy signals targeting the cost-efficient and just transformation of the global economy. In the quest towards achieving the Paris long-term temperature goals, energy efficiency can be considered a robust and efficient strategy to reduce both demand and supply-side emissions, as well as the required carbon price.

In order to go a step further in understanding and quantifying the direct and indirect effects of high energy efficiency policy in combination with climate targets, more detailed modeling is needed. This can partly still be achieved with IAMs, by enhancing the granularity of the analysis along several dimensions. First, an assessment of our scenarios at regional level would bring additional insights in how the energy mix might change across different latitudes and economies, especially focusing on major emitters (USA, Europe, China and India). This should be combined with a region- and sector-specific analysis of mitigation costs, i.e. additional system costs per unit of CO_2 emission reduction achieved, in different scenarios and time periods. Second, some of the uncertainties highlighted in this paper may be partly removed by improving the IAM representation of some key technologies and processes in the energy demand sectors. These include demand response mechanisms, consumer characterization, mode-shifting in transport, building-stock classification, deep dwelling renovation options, decarbonization pathways in specific industrial subsectors (especially in energy-intensive manufacturing), and material flows supporting enhanced circularity in the economy (Capros et al., 2019). Third, while the energy efficiency improvement factors we adopted in this study (see Table 2) are well within the range of what is technically achievable, more detailed results can be obtained by further specifying energy efficiency increases at the process level. The factors in Table 2 are suitable for the illustrative scenario analysis presented in this paper, targeting large geographic areas and adopting a long-term perspective. A technology-specific assessment of possible energy efficiency improvements at the regional level is needed in order to devise suitable policy instruments to stimulate the adoption of high-efficiency technologies. In addition, our scenario design assumes global cooperation to achieve the climate targets starting by 2025, which is optimistic given the current international policy landscape. Thus, new research should explore the impacts of delayed or regionally fragmented climate action, while also assessing the feasibility of transformation not only in technical terms, but also integrating societal, governance and political economy considerations (Brutschin et al., 2021). Finally, (enhanced) IAM analysis should be complemented by detailed modeling at urban and suburban scale, possibly also including elements for which IAMs are not particularly well-suited, such as consumer behavior, lifestyle changes and representation of short-term targets and policy instruments at (sub-)national level. Improving the way some of these aspects can be simulated in different types of models (including, but not limited to IAMs) is the core focus of the WHY research project (WHY, 2021). As the tools developed in WHY evolve including granular representation of technical and behavioral aspects, we will integrate them in our IAMs in order to address some of the open questions presented here.

In this study we consider the global post-COVID context in terms of an adjusted global GDP projection in our models. This adjustment stylistically accounts for the expected long-term economic trends by triggering a reduction the final energy demand in all regions and (sub) sectors. In our scenarios, however, we do not explicitly take into account other possible long-term impacts related to the COVID pandemic. For example, in 2020 and 2021, with the emergence of remote working and schooling, energy use has partly shifted from the commercial to the residential sector, while the demand for specific transport (e.g. in aviation and in private cars) has decreased significantly during general lock-down periods. If this pattern persists in the future, it may trigger significant changes in the energy system, and correspondingly require specific policy adjustments. Similarly, the COVID outbreak also affected energy use in the transport and industrial sectors. It is still uncertain whether these changes in the demand sectors will lead to long-term impacts on the energy system (see e.g. Kikstra et al., 2021). Analyzing this in detail falls beyond the scope of our present study, and we defer it to future research.

Our model comparison analysis shows that pushing enhanced energy efficiency can be an effective strategy to pursue ambitious emission reduction objectives and pave the way for the transformation required to meet the Paris goals. From a policy perspective, however, achieving efficiency acceleration remains a challenge. Large upfront investments are needed in order to expand the deployment of high-efficiency processes and scale up the implementation of renovation strategies in the residential and commercial sectors. Advancing the uptake of high efficiency end-use technologies, such as household appliances and passenger vehicles, may prove particularly difficult for low-income households, and policy makers are already concerned about this, as shown in the EU 'Fit for 55′ policy package (EC, 2021b). Energy efficiency policies should be designed so as to target a just and inclusive energy transition, paying special attention to the social groups that are most at risk of energy poverty (see e.g. Dalla Longa et al., 2021b). Important policy measures in this regard are those that explicitly address behavior and lifestyle changes (educational campaigns, among others). These should always complement traditional economic instruments, such as offering economic support (e.g. subsidies and low-cost loans) and enforcing the adoption of building or technology standards.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the European Commission for funding the research behind this publication through the WHY project (Horizon 2020 Programme, Grant Agreement no. 891943).

Appendix

Fig. A1 presents the post-COVID global GDP projection used in this paper. This has been obtained by the authors based on the SSP2 projection from Fricko et al. (2017), also shown in the plot. The short-term GDP assumptions have been modified to include the socio-economic impacts of COVID-19 and recovery plans. The short-term GDP assumptions were modified to better account for recent socio-economic developments and are consistent with GDP trajectories presented in detail in (Dafnomilis et al., 2021) (see Table A1).

In Fig. A2 we present sector-level emission reductions with respect to REF. Both models project that the largest reductions occur in the power generation, industry and transport sectors. The latter two sectors' contributions become more sizeable towards the middle of the century. For PROMETHEUS the electricity sector provides the largest contribution in all time periods and scenarios while for TIAM-ECN Industry becomes the most prominent contributor in 2050. TIAM-ECN also projects a substantial role for the Upstream sector, mainly driven by the possibility to deploy CCS technologies in fuel production, as also evident from Fig. 6. While emission reduction in the residential and commercial sectors are relatively small, it is worth noticing that, in the 2050 TIAM-ECN projection, the moderate carbon price assumed in the TAX_eff scenario triggers, for these sectors, a drop in emissions of approximately the same magnitude as that observed in the 1.5DC scenario. This is yet another indication that carbon pricing in combination with enhanced energy efficiency can prove an effective strategy to decarbonize the residential and commercial sectors.

References

Bertram, C., Riahi, K., Hilaire, J., et al. (2021). Energy system developments and investments in the decisive decade for the Paris Agreement goals. *Environmental Research Letters, 16*, Article 074020.

Brugger, H., Eichhammer, W., Mikova, N., & Dönitz, E. (2021). Energy Efficiency Vision 2050: How will new societal trends influence future energy demand in the European countries? *Energy Policy, 152*, Article 112216.

Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., et al. (2021). A multidimensional feasibility evaluation of low-carbon scenarios. *Environmental Research Letters, 16*, Article 064069.

Capros P., De Vita A., Tasios N., et al., 2016, "EU Reference Scenario 2016, Energy, transport and GHG emissions, Trends to 2050".

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., et al. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy, 134*, Article 110960.

COP-21, 2015, In: Paris Agreement, United Nations Framework Convention on Climate Change, Conference of the Parties 21, Paris, France.

Creutzig, F., Roy, J., Lamb, W. F., et al. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change, 8*(4), 260–263.

Dafnomilis I., Chen H.H., Elzen M., Fragkos P. et al., 2021, "Targeted green recovery measures in a post-COVID-19 world enable the energy transition", Research Square, DOI: 10.21203/rs.3.rs-667715/v1.

Dalla Longa, F., Detz, R., & van der Zwaan, B. (2020). Integrated assessment projections for the impact of innovation on CCS deployment in Europe. *International Journal of Greenhouse Gas Control, 103*, Article 103133.

Dalla Longa, F., & van der Zwaan, B. C. C. (2021a). Heart of light: An assessment of enhanced electricity access in Africa. *Renewable and Sustainable Energy Reviews, 136*, 11039.

Dalla Longa, F., & van der Zwaan, B. C. C. (2021b). Exploring the complex origins of energy poverty in The Netherlands with machine learning. *Energy Policy, 156*, Article 112373.

DG ECFIN, 2021, "Summer Economic Forecast 2021", https://ec.europa.eu/info/business-economy-euro/economic-performance-and-forecasts/economic-forecasts/summer-2021-economic-forecast_en.

EC, 2021a, "EU Reference Scenario 2020: Energy transport and GHG emissions – Trends to 2050", European Commission, Brussels, Belgium.

EC, 2021b, "'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality", COM(2021) 550, European Commission, Brussels, Belgium.

Fleiter, T., Rehfeldt, M., Herbst, A., Elsland, R., Klingler, A.-L., Manz, P., et al. (2018). A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. *Energy Strategy Reviews, 22*, 237–254.

Fotiou, T., de Vita, A., & Capros, P. (2019). Economic-Engineering Modelling of the Buildings Sector to Study the Transition towards Deep Decarbonisation in the EU. *Energies, 12*(14), 2745.

Fragkos, P. (2020). Global Energy System Transformations to 1.5 °C: The Impact of Revised Intergovernmental Panel on Climate Change Carbon Budgets. *Energy Technology, 8*(9), 2000395.

Fragkos, P., & Kouvaritakis, N. (2018). Model-based analysis of intended nationally determined contributions and 2 °C pathways for major economies. *Energy, 160*, 965–978.

Fragkos, P. (2021). Assessing the role of carbon capture and storage in mitigation pathways of developing economies. *Energies, 14*(7), 1879.

Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., & Charalampidis, I. (2021). Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union. *Energy, 237*(125), Article 121591.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., et al. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change, 42*, 251–267.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, et al. (2018). Negative emissions-Part 2: Costs, potentials and side effects. *Environmental Research Letters, 13*, 6.

Grubler, A., Wilson, C., Bento, N., et al. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy, 3*, 515–527.

Hummel, M., Büchele, R., Müller, A., Aichinger, E., Steinbach, J., Kranzl, L., et al. (2021). The costs and potentials for heat savings in buildings: Refurbishment costs and heat saving cost curves for 6 countries in Europe. *Energy and Buildings, 231*, 1–19.

IEA, 2016, "Energy Technology Perspectives 2016. Towards Sustainable Urban Energy Systems", Paris, France.

IEA, 2020a, "Sustainable Recovery report", IEA, Paris https://www.iea.org/reports/sustainable-recovery.

IEA, 2020b, Energy Efficiency 2020.

IEA, 2021, "World Energy Investment Outlook", IEA, Paris, France (Vol. 23).

IPCC, 2018, "Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty".

Kikstra, J., Vinca, A., Lovat, F., et al. (2021). Climate mitigation scenarios with persistent COVID-19-related energy demand changes. *Nature Energy, 10*.

Kober, T., Falzon, J., van der Zwaan, B. C. C., Calvin, K., Kanudia, A., Kitous, A., et al. (2016). A multi-model study of energy supply investments in latin america under climate control policy energy economics. *Energy Economics, 56*, 543–551.

Kober, T., van der Zwaan, B. C. C., & Rösler, H. (2014). Emission certificate trade and costs under regional burden-sharing regimes for a 2C climate change control target. *Climate Change Economics, 5, 1, 1440001*, 1–32.

Levesque, A., Pietzcker, R. C., Baumstark, L., De Stercke, S., Grübler, A., & Luderer, G. (2018). How much energy will buildings consume in 2100? A global perspective within a scenario framework. *Energy, 148*, 514.

Loulou, R., & Labriet, M. (2008). ETSAP-TIAM: The TIMES integrated assessment model, Part I: Model structure. *Computational Management Science, 5*(1–2), 7–40.

Loulou, R. (2008). ETSAP-TIAM: The TIMES integrated assessment model, Part II: Mathematical formulation. *Computational Management Science, 5*(1–2), 41–66.

Marcucci, A., Panos, E., Kypreos, S., & Fragkos, P. (2019). Probabilistic assessment of realizing the 1.5 °C climate target. *Applied Energy, 239*, 239–251.

Mundaca, L., Ürge-Vorsatz, D., & Wilson, C. (2019). Demand-side approaches for limiting global warming to 1.5 °C. *Energy Efficiency, 12*, 343–362.

Nemet, G., Callaghan, M., Creutzig, F., Fuss, S., et al. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters, 13*, 6.

OECD, 2020, "OECD Economic Outlook, Interim Report Coronavirus (COVID-19): Living with uncertainty".

Riahi, K., Bertram, C., Huppmann, D., et al. (2021). 2021, "Cost and attainability of meeting stringent climate targets without overshoot". *Nature Climate Change, 11*, 1063–1069.

Rao, N. D., & Min, J. (2017). "Decent living standards: Material prerequisites for basic human wellbeing. *Social Indicators Research*, 1–20.

Rauner, S., Bauer, N., Dirnaichner, A., et al. (2020). Coal-exit health and environmental damage reductions outweigh economic impacts. *Nature Climate Change, 10*, 308–312.

Reuter, M., Patel, M., Eichhammer, W., Lapillonne, B., & Pollier, K. (2020). A comprehensive indicator set for measuring multiple benefits of energy efficiency. *Energy Policy, 139*, Article 111284.

Rochedo, P. R. R., Fragkos, P., Garaffa, R., Couto, L. C., Baptista, L. B., Cunha, B. S. L., et al. (2021). Is Green Recovery Enough? Analysing the Impacts of Post-COVID-19 Economic Packages. *Energies, 14*, 5567.

Roelfsema, M., van Soest, H.L., Harmsen, M. *et al.* "Taking stock of national climate policies to evaluate implementation of the Paris Agreement", 2020, Nature Communications, 11, 2096.

Rösler, H., van der Zwaan, B. C. C., Keppo, I. J., & Bruggink, J. C. C. (2014). Electricity versus hydrogen for passenger cars under stringent climate change control. *Sustainable Energy Technologies and Assessments, 5*, 106–118.

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 degrees C. *Nature Climate Change, 8*, 325.

Swan, L. G., & Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews, 13*, 1819–1835.

Syri, S., Lehtilä, A., Ekholm, T., Savolainen, I., Holttinen, H., & Peltola, E. (2008). Global energy and emissions scenarios for effective climate change mitigation – Deterministic and stochastic scenarios with the TIAM model. *Int Journal of Greenhouse Gas Control, 2*(2), 274–285.

UNFCCC, 2015, "FCCC/CP/2015/L.9/Rev.1: Adoption of the Paris Agreement", Paris, France, 1-32.

van der Zwaan, B. C. C., Rösler, H., Kober, T., Aboumahboub, T., Calvin, K. V., Gernaat, D. E. H. J., et al. (2013). A cross-model comparison of global long-term technology diffusion under a 2°C climate change control target. *Climate Change Economics, 4*(4), 1–24.

van der Zwaan, B. C. C., Kober, T., Calderon, S., Clarke, L., Daenzer, K., Kitous, A., et al. (2016). Energy technology roll-out for climate change mitigation: a multi-model study for Latin America. *Energy Economics, 56*, 526–542.

van der Zwaan, B. C. C., Kober, T., Dalla, L. F., van der Laan, A. J., & Kramer, G. J. (2018). An integrated assessment of pathways for low-carbon development in Africa. *Energy Policy, 117*, 387–395.

van Soest, H. L., Aleluia Reis, L., Baptista, L. B., et al. (2021). Global roll-out of comprehensive policy measures may aid in bridging emissions gap. *Nature Communications, 12*, 6419.

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., et al. (2018). Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change, 8*, 391–397.

Vona, F. (2019). Job losses and political acceptability of climate policies: Why the 'job-killing' argument is so persistent and how to overturn it. *Climate Policy, 19*(4), 524–532.

WHY, 2021, https://www.why-h2020.eu/.

Wilson, C., Grübler, A., Gallagher, K. S., & Nemet, G. F. (2012). Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change, 2*, 780–788.

World Bank, 2021, "Global Economic Prospects", https://openknowledge.worldbank.org/bitstream/handle/10986/35647/9781464816659.pdf.