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The interplay among COVID-19 economic recovery, behavioural changes, and the European Green Deal: An energy-economic modelling perspective

Gabriele Cassetti\(^a\), Baptiste Boitier\(^b\), Alessia Elia\(^a\), Pierre Le Mouël\(^b\), Maurizio Gargiulo\(^a\), Paul Zagamé\(^b,c\), Alexandros Nikas\(^d,e\), Konstantinos Koasidis\(^d\), Haris Doukas\(^d\), Alessandro Chiodi\(^a\)

\(^{a}\) FASMA S.r.l., Via Livorno, 60, 10144, Turin, Italy
\(^{b}\) EURECO, 9 Rue de Chateaudun, 75009, Paris, France
\(^{c}\) Université Paris 1 Panthéon-Sorbonne, 12 Pl. du Panthéon, 75231, Paris, France
\(^{d}\) School of Electrical & Computer Engineering, National Technical University of Athens, Iroon Polytechniou 9, 15780, Zografou, Athens, Greece

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**ABSTRACT**

In the EU, COVID-19 and associated policy responses led to economy-wide disruptions and shifts in services demand, with considerable energy-system implications. The European Commission’s response paved the way towards enhancing climate ambition through the European Green Deal. Understanding the interactions among environmental, social, and economic dimensions in climate action post-COVID thus emerged as a key challenge. This study disaggregates the implications of climate ambition, speed of economic recovery from COVID-19, and behavioural changes due to pandemic-related measures and/or environmental concerns for EU transition dynamics, over the next decade. It soft-links two large-scale energy-economy models, EU-TIMES and NEMESIS, to shed light on opportunities and challenges related to delivering on the EU’s 2030 climate targets. Results indicate that half the effort required to reach the updated 55% emissions reduction target should come from electricity decarbonisation, followed by transport. Alongside a post-COVID return to normal, the European Green Deal may lead to increased carbon prices and fossil-fuel rebounds, but these risks may be mitigated by certain behavioural changes, gains from which in transport energy use would outweigh associated consumption increases in the residential sector. Finally, the EU recovery mechanism could deliver about half the required investments needed to deliver on the 2030 ambition.

1. Introduction

Aiming to curb the spread of COVID-19 in late 2019 – early 2020, many governments imposed restrictive measures such as curfews, travel restrictions, quarantines, self-isolation and social distancing, or even lockdowns and economic shutdown [1–3]. Despite their early effectiveness [4–6], these further enabled an already impending severe global economic recession [7,8]. In the European Union (EU), both the pandemic and these early policy responses had a considerable socio-economic impact [9,10], despite large economic support measures. Among other consequences, fossil CO\(_2\) emissions significantly dropped in 2020 [11,12] and energy markets and systems were largely disrupted [13–15].

Rapid availability of vaccines allowed some optimism over the end of the pandemic, but socioeconomic recovery remains uncertain [16,17] due to concerns over the long-term efficiency and regional availability of vaccines [18,19] and the emergence of new variants of the virus [20]. Major economies rushed to devise short-to-long-term support schemes, such as the American Rescue Plan [21] or the NextGenerationEU program [22]. Activists and academics alike seized the moment and made strong cases for drawing insights from this emergency to help manage the global climate crisis [23] and to capitalise on recovery efforts to boost climate action [24–26], by refraining from grey stimulus like in the aftermath of the 2008–2009 global financial crisis [27] and pushing fiscal recovery plans towards more sustainable development paths [28,29].

In the EU, the NextGenerationEU (NGEU) program was launched to reinforce the planned 2021–2027 Multiyear Financial Framework. In tandem with the European Green Deal (EGD) launched by the von der Leyen Commission [30] just months before the COVID-19 outbreak, the
program dictates that at least 37% of total financial support—via several mechanisms, the most relevant being the Recovery and Resilience Facility (RRF)—promote green investment. Part of the RRF scheme is subject to amendments, following the EU’s energy planning in response to Russia’s 2022 invasion of Ukraine (‘REPowerEU’), which notably includes accelerating the diffusion of renewable energy, supply diversification, and energy demand reductions, aiming to reduce the bloc’s reliance on Russian fossil fuels [31]. Currently taking shape in the ‘Fit for 55’ package [32], the EGD aims inter alia to cut greenhouse gas (GHG) emissions by at least 55% in 2030 in comparison with 1990 [33], raising the ambition from the previous –40% target for the same year [34].

At the same time, COVID-19 and restrictive measures brought about shifts in EU citizens’ lifestyles and pro-environmental behaviours [35] and consumption patterns [36], of which some have been temporary and associated with the pause of economic and social activities, while others (e.g., work-from-home and relevant transportation implications) may stick around and have long-term impact on the EU energy system. Such shifts notably represent changes (e.g., transport demand reduction [57]) that have broadly been considered as viable options towards (European) carbon neutrality [38–46].

Along those three axes (i.e., impact of COVID on climate ambition, green recovery efforts, and behavioural shifts), recent studies on climate policy focused on analysing long-term impacts of the COVID-19 pandemic at the global level [15, 41, 42], while the European Commission has instigated impact assessments at the EU level [33, 43] and other studies focused on the national level [44–46]. From a recovery perspective, studies have focused on the impact of fiscal stimuli and green recovery packages on global [47] and national emissions [48, 49], as well as their broader macroeconomic impacts [50], while on the social domain of lifestyle changes and behavioural shifts, studies mostly emphasised reduced demand scenarios [51, 52]. Despite recent calls to enhance modelling efforts across the environment-social-economic nexus in light of the COVID-19 pandemic [53], especially on the demand side [54, 55] and the impact of extremes [56], a handful of studies have focused on individual aspects. Dalla Longa et al. [57] analysed post-COVID, well-below-2°C scenarios accounting for behavioural aspects, assuming a V-shape growth recovery after 2021. Similarly, Hainsch et al. [58] analysed selected areas of the EGD, also without accounting for the impact of the speed of recovery, and with ambitious assumptions over the contribution of behavioural transformations [59].

explored a global 1.5°C-consistent pathway focusing on energy demand changes, considering GDP uncertainty to account for the speed of recovery, without elaborating on the impact of either the recovery packages or the climate ambition context.

To the best of the authors’ knowledge, no research has hitherto investigated the combination of (i) the pace of post-COVID-19 economic recovery; (ii) the EU climate ambition; and (iii) the potential long-term transformations in citizen behaviour induced by the pandemic and/or environmental concerns. This study introduces an integrated scenario assessment of key energy and economic dynamics to investigate the interplay of these three drivers in an organic manner, aiming to explore potential long-term implications of the recovery from COVID-19 for EU transition dynamics over the next decade. It further analyses the EU energy transition economics with the NGEU program and benchmarks EGD-related investment requirements against the NGEU program to provide high-level estimates of the challenges, for a series of employed scenarios. To deliver on this goal, our research soft-links a macroeconomic model (NEMESIS) and an EU-wide energy system model (EU-TIMES), passing detailed economic data from the former to the latter. Visions of the two models are then compared against one another to understand divergences and gain richer insights. We present the modelling framework in the next section and discuss the results of the scenario analysis in Section 3, before concluding the study with key takeaways and prospects in Section 4.

2. Methods and tools

2.1. Models

The methodology developed to perform the study is based on a set of scenarios for the EU and the UK (“EU+” hereafter) and the soft-linkage of two modelling tools (Table 1).

More information can be found in the I2AM PARIS platform, for both NEMESIS and EU-TIMES, including details on their economic rationale and solution, calibration, supported measures and technologies, sectors represented, and recent case studies.

2.2. Scenario design

The baseline scenario of this study reflects a pre-COVID-19 case, where potential GDP growth projections are part of a set of harmonised assumptions [68] developed to drive the assessment of “Where are We Headed?” [64] (WWH), considering climate efforts and pledges before the 2021–2022 update of Nationally Determined Contributions [69]. In this outlook the socioeconomic assumptions are harmonised using the EUROPOP database for population [70], the 2018 Ageing Report for GDP per capita [71], as well as technoeconomic assumptions for representative technologies based on the European National Energy and Climate Plans (NECP) reports [72] for power and buildings, and fossil fuel prices projections from 2019 World Energy Outlook CP scenario.

Table 1

| Short description of the two models of the study. |
|-----------------------------------------------|
| **NEMESIS** A sectorally detailed macroeconomic model, with a demand-driven, neo-Keynesian core, specifically designed for the EU [60, 61]. It is a system of economic models for every European country (including the United Kingdom), devoted to study how European economies will evolve in the medium-to-long term, considering the international economic context (economic development, exchanges and interest rates, etc.), sector-specific dynamics (capital cost, labour and materials productivity, inter-industrial exchanges, etc.) and major structural policies such as fiscal, climate and/or energy policy [62]. On the supply side, the model is represented by nested constant elasticity of substitution production functions, while inter-sectoral exchanges are captured by conversion matrices. NEMESIS includes a detailed energy-environment module that allows the model to deal with climate mitigation policies, at EU and EU-national level [63, 64], by detailing energy consumption by source as well as by integrating a technology-rich representation of power generation technologies. In particular, as a primarily economic model but with a detailed energy-environment module, it is well-equipped to calculate the impact of economic activity and the implementation of economic instruments, such as shocks to some of the exogenous variables, to emissions and energy price formation. An enhanced version of the open source JRC-EU-TIMES model [65]. It is a multi-region European version of TIMES and represents the EU Member States and neighbouring countries. TIMES (an acronym for The Integrated MARKAL-EFOM System) is an economic model generator, computing a dynamic inter-temporal partial equilibrium for the (multi-) regional energy and emission markets, providing a technology-rich basis for representing energy dynamics over a multi-period time horizon. It aims to supply energy services at minimum global cost, maximising the total surplus defined as the sum of surplus of the suppliers and consumers, by simultaneously making decisions on equipment investment and operation, primary energy supply, and energy trade for each region modelled. It essentially provides the optimal mix and competitive technologies (capacity and activity) and fuels at each period under various policy scenarios. To drive scenarios, the model requires estimates of end-use energy service demands (e.g., car road travel; residential lighting; steam heat requirements in the paper industry; etc.), the existing stocks of energy related equipment in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials. The EU-TIMES model, in particular, is designed for analysing the role of energy technologies and innovation needs for meeting European energy and climate policy targets [64]. It can consider policies affecting the entire energy system, sectors, as well as (sets of) various technologies/commodities [66, 67]. |
This means that, throughout the entire modelling study, both models start with a set of fully harmonised data regarding socioeconomic and technoeconomic assumptions (see Refs. [64,68], which also list the detailed reference energy system for the EU), including the list of policy instruments, technologies, and carriers considered.

Starting from this WWH baseline, our scenario protocol focuses on the 2020–2030 decade and is built on three key drivers: (i) the economic outlook in the EU+, pre- and post-pandemic; (ii) the impacts of climate action in the EU+; and (iii) the potential long-term transformations due to behavioural changes induced by environmental concerns and COVID-19.

Regarding the first driver, the aim of the economic layer is not to forecast the European economy up to 2030 (as, e.g., in Ref. [74]) but to allow considering the short-to long-term consequences of the COVID-19 pandemic on the different economic activities in the EU+ and to assess how it can influence the European energy system when coupled with the 2 other drivers. Two economic futures for the post-COVID-19 European economy are considered in this study, on top of the WWH case: a “Full economic Recovery” (COVID-FR), assuming that well-designed public support mechanisms implemented during the pandemic and particularly after the crisis are efficient to support a complete economic recovery in 2025 [75]; and a “Limited economic Recovery” (COVID-LR), due to persistent socioeconomic impacts of the COVID-19 pandemic in the longer run; economic activity in the EU + does not manage to return to the pre-COVID-19 GDP levels by 2030. Thus, in the WWH context, the set of socioeconomic and technoeconomic input assumptions are drawn from Ref. [64], whereas the COVID-FR and COVID-LR scenarios diverge in terms of GDP trajectories and sectoral dynamics.

The second driver is represented by the European climate action for 2030. To comply with the Paris Agreement, the European Commission updated its climate change mitigation strategy in the EGD, among others reinforcing the GHG emissions reduction target for 2030 to −55% relative to 1990 levels [30]. In this context, we analyse two options for the EU climate action: (i) a current policy (CP) that includes all the measures and policies included in the EU 2030 Climate and Energy Framework [76] and (ii) a more ambitious context (EGD) that refers to the latest 2030 climate perspective aiming to reduce GHG emissions by at least 55% by 2030 in comparison to 1990 levels, as reflected in the ‘Fit for 55’ policy package currently being formalised [32].

Finally, the third layer looks at the potential impacts of behavioural changes (Beh) on transformations that could affect the EU+ energy system in the long term. At the time of writing this paper, some travel- and work-related confinements due to—and practices emerging during—COVID-19 remain in place, despite originally seen as temporary/contingency measures before a ‘complete return to normal’. In this direction, our scenario design assumes that behavioural changes may persist in the longer term, addressing safety and/or emerging environmental concerns. These include ‘work from home’ and ‘limited international travel’ assumptions, either due to COVID-19 restrictions or sustainability considerations. The assumed types of behavioural changes are discussed in detail in Section 2.4.

The combination of these three drivers lead to six different scenarios, as summarised in Table 2.

### 2.3. Modelling framework

Both models employed in this study can individually deliver outputs on the European energy system and climate change mitigation (e.g. Ref. [64]). However, to take advantage of the different capabilities of the two models, we soft-link them, considering that a single modelling tool cannot address all aspects of the complex energy-economy dynamics as well as that greater insights can be gained by drawing on the strengths of multiple modelling tools.

Despite featuring a detailed representation of the European energy system, EU-TIMES requires projections for key socioeconomic drivers as inputs (e.g., GDP, sectoral added value), as most energy system models, but existing projections of the pandemic’s impact on national GDP are predominantly short-term (e.g. Ref. [74]); NEMESIS, in turn, can produce a coherent dataset of this macroeconomic data to be used as input in EU-TIMES for the entire modelling horizon. The methodology applied to soft-link the two models is thus straightforward. First, the NEMESIS model is used to project, for each scenario, economic impacts of the COVID-19 pandemic. Second, key economic variables produced by NEMESIS (namely national GDP and sector value added) are unidirectionally transferred to EU-TIMES as input drivers for energy service demands projections. EU climate policy and the effects of behavioural changes are implemented in both models to ensure a fully harmonised model setup.

The consistency of CO2 emission trajectories is checked between NEMESIS and EU-TIMES, with the latter informed by the unidirectional link between the two models, and across the scenarios to ensure that the model linkage does not produce unintentional divergence. In the CP scenarios, the similarity between the trajectories is achieved by the implementation of equivalent mitigation policies in both models. The divergence observed is coherent with model differences on their assessment of the impacts of EU climate policies. In EGD scenarios, on the other hand, consistency of emissions trajectories is ensured based on different implementations in each model. In EU TIMES, an emissions cap is imposed, with the model then generating the scenario carbon price as the marginal cost of CO2 once the optimal solution is identified. In NEMESIS, although the same caps are also imposed, the internally generated carbon prices are iteratively used to produce the model’s solution, as costs influence demand and vice versa. Despite these differences, this ensures that models deliver similar CO2 emissions trajectories in the EGD scenarios, thereby rendering further calibrations unnecessary. This also the case under the shocks implemented under the different scenarios, which include different inputs and assumptions (see Tables 1 and 2), ensuring the coherence of the CO2 emissions trajectories with the scenario design. Additional selected energy variables, including primary energy consumption by fuel (PEC) and sectoral final energy consumption (FEC) are also compared and analysed to further guarantee the coherence of modelling outputs with respect to the scenario design. In this process, the single inconsistency observed between the models, which cannot be logically attributed to different model responses, was found in final energy consumption in the transport sector when introducing behavioural changes (i.e., remote working). As such, recalibration of the parameters used to mimic the exogenous shocks was performed in NEMESIS, by lowering the elasticity of the households’ demand for transport with respect to their income, leading to the values assumed in Table 1.

This approach ensures that key strengths of both NEMESIS (i.e., in terms of macroeconomic implications) and EU-TIMES (i.e., in terms of

### Table 2

| Summary of the considered scenarios. |
|-------------------------------------|
| Scenario ID   | EU + economy | EU Climate policy | Behavioural transformations |
| WWH-CP        | Pre-COVID-19 national GDP growth (based on [71,72]) (WWH) | Current Policy (2020–2030 EU Climate and Energy Framework) | None |
| WWH-EGD      | European Green Deal – 2030 Climate Target | Moderate (Beh) |
| WWH-EGD      | European Green Deal – 2030 Climate Target | Moderate (Beh) |
| COVID-FR-EGD | Full economic recovery (COVID-FR) | None |
| COVID-LR-EGD | Limited economic recovery (COVID-LR) | None |
| COVID-FR-EGD-Beh | Full economic recovery (COVID-FR) | Important (Beh) |
| COVID-LR-EGD-Beh | Limited economic recovery (COVID-LR) | Important (Beh) |
technology dynamics) are used to finetune the model setup and expand the scope of scenario analysis. Fig. 1 provides a high-level outline the modelling framework.

2.4. Scenario implementation

Post-COVID economic development is quantified in NEMESIS: the economic impact of the pandemic in 2020 is based on the EC’s economic forecast [9], including household final consumption, public consumption, gross fixed capital formation, exports, and imports for each Member State. Impacts are further differentiated by economic sector with quarterly data from Eurostat for every Member State (Eurostat code: nami_10) [77]. Calibration for 2020 consists in introducing gap variables in behavioural equations in the model: (i) household consumption by purpose, to mimic the impact of non-pharmaceutical interventions imposed on households, (ii) employment and income, to consider job retention schemes implemented by public authorities, and (iii) intra- and extra-EU + demand, to reproduce the reduction in trades of goods and services. Post-2020, according to scenarios, these gap variables are either completely or partially phased out and with different temporality.

NEMESIS runs three different scenarios, a pre-COVID-19 scenario (WWH) with an EU average annual GDP growth of 1.3% between 2021 and 2030; and two post-COVID-19 scenarios, one with full recovery (FR) in 2025 and another with limited recovery (LR), considering an EU + GDP loss of 3.9% compared to pre-COVID-19 levels (Table 3). For the FR scenario, the European economy strongly upturns in 2022 allowing EU + economies to align the GDP with the pre-COVID-19 economic trajectory by 2025. The methodology assumes that behaviour changes observed in 2020 production and consumption patterns are only temporary and completely vanish in 2025. Consequently, post-2025 economic growth in EU + realigns with the GDP growth assumed before COVID-19, with annual GDP growth of 1.2%. In the LR case, the EU + economy displays slower recovery until 2023 and -0.2% of GDP growth annually, post-2025, leading to lower GDP (2.9% and 3.9% below WWH/baseline levels in 2025 and 2030, respectively). Previous research (e.g. Refs. [78,79]) has shown that large economic recessions have had impacts on long-term productivity growth, as a consequence of a “hysteresis” effect [80]. Despite differences between previous economic crises and the COVID-19 case, the latter may impact long-term human capital productivity following the temporary closure of educational institutions and the delayed entry of young students in the labour market [81]. Thus, in the LR case, we assumed a productivity growth loss of 0.15% per year in the long run compared with the pre-COVID situation [82]. These projections of the European economy up to 2030 are thereafter implemented in the EU-TIMES model, for which they constitute an exogenous driver.

Following the strong disruptions to the fossil fuel markets, different trajectories have been projected for fossil fuel prices to 2030. Here we assume two trajectories according to the current economic outlook. The FR scenario assumes a transitory shock on fossil fuel markets, with prices rapidly returning to their pre-crisis levels (by end of 2022), whereas the LR scenario expects lower prices: about 14% for oil and 6% for natural gas and coal, in 2030, following the latest available projections by the International Energy Agency [15]. These trajectories avoid directly aligning with the current fuel price spikes as a result of the (policy responses) to the ongoing Russia-Ukraine conflict and the consequent energy crisis, especially in the EU, aiming to avoid making highly uncertain assumptions and retain the capacity to disaggregate the impact of COVID-19 from the combination of crises.

Regarding EU climate action, we assume a CP case, implementing the policies currently in place (~43% in the EU ETS by 2030 with regard to 2005, the Effort Sharing Regulation for non-EU ETS sectors, a RES target of 32% in final energy consumption by 2030, the 32.5% energy efficiency target for 2030, the current nuclear capacity and phase-out/renovation plans considering the classification of nuclear energy investments as green in the EU Taxonomy [83], and national coal phaseout plans; see details in Ref. [64]), and an EGD case, on top of current policies, with a 55% (relative to 1990) CO2 emissions reduction target in 2030 in line with the EU’s long-term strategy [84] towards net-zero by 2050. Both models need assumptions about non-CO2 emissions and LULUCF emissions. For the CP case, we use projections from the EC [85]; for the EGD case (Table 4), we use the Commission’s impact assessment of the 2030 Climate Target Plan [33]: the projected land-use, land-use change, and forestry (LULUCF) GHG sink of about ~225 MtCO2eq in 2030 corresponds to the sector’s maximum contribution to the ~55% target [86]. We also assume that the UK continues to participate in the EU Emissions Trading System (EU ETS) and other EU climate policies, post-Brexit.

The two main behavioural changes considered involve the diffusion of home-/remote-working and travel limits, driven by (i) the impulse from the contingent situation of the pandemic, and (ii) lifestyle changes due to environmental concerns (increasing awareness that such changes can positively contribute to mitigation). According to IEA [15], behavioural changes required to achieve a net-zero transition involve a wide range of sectors and modes. However, since the underlying uncertainty is currently very high, here we limit our analysis to the residential and transport sectors. In the former, an increased number of people are expected to work from home in 2030 compared to 2020, encompassing limited private transport for commuting different work habits. Similarly, increased decarbonisation costs and environmental concerns in society

Fig. 1. Soft linkage of NEMESIS with EU-TIMES. A detailed list of the socio- and techno-economic assumptions can be found in Ref. [68], while assumptions on fossil fuel prices, GDP, and emissions caps can be found in the supplementary material ³ (see also Data Availability section).
may reduce flights [39], while the proliferation of teleconferences [33]. Emissions projections in CP [85] and EGD [30], LULUCF emissions projections Source: Historical data from the European Environmental Agency [87], non-CO

Table 4

| CO₂ emissions caps according to EU + climate action context. | 1990 | 2005 | 2030 |
|-------------------------------------------------------------|------|------|------|
|                                                                  | CPA (40% w/o LULUCF & Int’ bunkers) | CPA (55% w/o LULUCF & Int’ bunkers) | EGD (55% w/o LULUCF & Int’ bunkers) |
| CO₂ w/o LULUCF & Int’ bunkers                                | 4.65 | 4.61 | 2.96 |
| CO₂ Int’ bunkers                                              | 0.18 | 0.29 | –   |
| Non-CO₂ w/o LULUCF & Int’ bunkers                            | 1.18 | 0.93 | 0.66 |
| LULUCF                                                       | –0.25 | –0.32 | –0.23 |
| Total w/o LULUCF & Int’ bunkers                              | 5.65 | 5.24 | 3.39 |
| Total w/LULUCF & Int’ bunkers                                | 5.58 | 5.22 | –   |

Source: Historical data from the European Environmental Agency [87], non-CO₂ emissions projections in CP [85] and EGD [30], LULUCF emissions projections [33].

may reduce flights [39], while the proliferation of teleconferences during lockdowns may have accelerated the reduction of business flights in the long term. Table 5 describes key behavioural change assumptions, and how these are interpreted and translated into the models.

3. Results

3.1. CO₂ emissions depending on the recovery speed

We first assess the impacts of varying climate ambition for 2030 in a pre-COVID-19 economic context. The WWH-CP and WWH-EGD scenarios analyse transformations required by the EU + energy system to move from the 2020–2030 EU Climate and Energy Framework policies (i.e., –40% GHG emissions by 2030 compared to 1990) to the updated target (~55%), considering a pre-crisis economic and demand outlook.

Fig. 2 compares the EU + CO₂ emissions trajectories from energy and industrial processes, identifying which sectors contribute the most to mitigation. From 3.7 GtCO₂ in 2019, both models reach the ~55% reduction target in the WWH-EGD scenario, with 2.24 Gt of CO₂ emissions in 2030, while showing slightly different CO₂ emissions in the WWH-CP scenario (2.98 and 2.84 GtCO₂ in EU-TIMES and NEMESIS, respectively). First, the EGD target is binding while the CPs attempt to push mitigation to the highest potential each policy can achieve, which explains the convergence in the level of emissions reached under the EGD pathway and the small divergence in the respective CP performance (more susceptible to model differences). Second, sectoral differences are also explained by the national burden sharing in those sectors, as framed in the Effort Sharing Regulation (ESR), as such burden is not constraining in some Members States. Also, CO₂ emissions from international bunkers are not included in the CO₂ emissions perimeter in the WWH-CP scenario, but they are in WWH-EGD. Third, the technological representation in EU-TIMES is much more detailed; this was the motivation behind the soft linkage of the two models in the first place and justifies the differences in certain sectors (e.g., industry) as well as the less homogeneous/linear trajectory from NEMESIS.

Both models agree that power generation and supply are the main sectors driving decarbonisation: by 2030, these sectors drive a reduction due to environmental concerns.

Behaviour changes due to COVID-19 pandemic

• Remote working: considering the 40% reduction potential [88,89], we assume that 25% of workforce work remotely, with commuting taking 40% of total passenger journeys for 3 days per week [90,91]. The increase in residential energy demand is calculated as one third of the decrease in transport. Therefore, the change is modelled by projecting 6% less private car commuting and 2% higher energy demand in households. Same increase is accounted for electricity consumption and space heating demand [13]. The effect on the tertiary sector is not modelled due to lack of estimates in the literature.

• Environmental concern and increased prices in aviation: the former is interpreted as passengers having a higher awareness of the environmental impact (CO₂ emissions) of the sector, thereby accepting to reduce the number of their trips. At the same time, the adoption of low-carbon fuels (e.g., biofuels) is meant to increase the ticket price. The combination of these two effects is modelled by projecting 34% lower demand in the aviation sector in 2030 [13] (in NEMESIS, demand for aviation is influenced by prices, the effect of environmental concerns in not imposed a priori in this case)5.

• Travel restrictions: this is modelled by projecting an additional 10% lower energy demand in aviation in 2030 compared to the reduction due to environmental concerns (above).

behaviour, and justifies the differences in certain sectors (e.g., industry) as well as the less homogeneous/linear trajectory from NEMESIS.

Both models agree that power generation and supply are the main sectors driving decarbonisation: by 2030, these sectors drive a reduction of 275 MtCO₂ in NEMESIS and 404 MtCO₂ in EU-TIMES. Contributions to decarbonisation are foreseen also from end-use sectors: EU-TIMES shows 2030 mitigation potentials from the transport, industry, and building sectors (both residential and commercial) of 141, 117, and 80 MtCO₂ respectively (132, 66, and 117 MtCO₂ respectively, for NEMESIS) (Fig. 2). Overall, both models indicate that the EGD requires coordinated contribution from all energy sectors, meaning no single silver-bullet solution exists. These results are comparable with the Commission’s 2030 Climate Target Plan impact assessment [33], with the...
Fig. 2. EU + CO₂ emissions from energy and industrial processes - comparison between WWH-CP and WWH-EGD scenarios for (a) EU-TIMES and (b) NEMESIS. Transportation includes international EU + aviation emissions; industry includes industrial processes emissions; agriculture is only related to energy (AFOFI sector: IPCC category 1A4c).
strongest contributions lying in power and supply representing 60% of total CO\(_2\) mitigation effort. However, the European Commission expects smaller contribution from industry and transportation, compared to our analysis, a fact largely explained by more ambitious emissions cuts in these sectors in the Commission’s baseline (current policy) scenario.

The WWH-EGD pathway is then used to benchmark scenarios considering different economic recovery trajectories, namely COVID-FR-EGD and COVID-LR-EGD. These foresee limited implications for emissions trajectories (which are driven by policy targets), but considerable implications at sectoral level. In Fig. 3, the difference at sectoral

Fig. 3. EU + CO\(_2\) emissions from energy and industrial processes - difference at sectoral level between post COVID-19 pandemic scenarios (COVID-FR-EGD and COVID-LR-EGD) and pre-pandemic scenario (WWH-EGD) in (a) EU-TIMES and (b) NEMESIS. The total CO\(_2\) emissions trajectory between EGD scenarios is unchanged in EU-TIMES.
level is benchmarked with the WWH-EGD scenario.

In EU-TIMES, COVID-LR-EGD presents a marked reduction in transport (−63 MtCO₂) with an increase in other sectors in 2022 (45 MtCO₂ in industry and 9 MtCO₂ in others). These differences are then softened, as short-term COVID-19 implications phase out. However, the building sector maintains a small positive balance increasing its emissions by 21 MtCO₂. In COVID-FR-EGD, swift recovery would result in less visible impacts on sectoral CO₂ emissions². In 2022, the scenario shows a reduction in emissions from transport (−16 MtCO₂) and a negligible increase in other sectors (2 MtCO₂ in buildings, 7 MtCO₂ in industry, 8 MtCO₂ in power and supply). In 2030, power generation and supply emits 16 MtCO₂ more, while emissions from other sectors slightly reduce.

NEMESIS confirms that major impacts of the pandemic on energy-related emissions are expected in the short-term: CO₂ emissions are 12% lower (−460 MtCO₂) in 2020 in both post-COVID scenarios (compared to WWH-EGD). In 2020, the transport sector reduces its emissions by 310 MtCO₂, and emissions also drop considerably in power and supply (−119 MtCO₂) as well as industry (−47 MtCO₂). Moving towards 2030, the EU + CO₂ emissions tend to realign with the WWH-EGD scenario—faster in the full recovery case (COVID-FR-EGD).

We also assess the CO₂ emissions intensity of primary energy consumption (PEC) (Table 6). In the short run, both models display declining values; however, NEMESIS is better equipped to consider short-term shocks such as those from the pandemic as a macroeconomic model [92] and considering that it runs on an annual basis—this, also, explains the higher resolution in figures and tables, including Table 6. Results indicate that confinement significantly affected the activity of the transport sector and, considering its role in total energy consumption and oil share in its energy mix, this decline leads to a short-term reduction of CO₂ intensity. In EGD scenarios, post-COVID CO₂ intensity declines markedly (1.47 and 1.94 MtCO₂/Mtoe in EU-TIMES and NEMESIS, respectively) compared to the WWH-CP scenario (1.91 and 2.15 MtCO₂/Mtoe in EU-TIMES and NEMESIS, respectively).

Furthermore, in both models, CO₂ intensity is slightly higher in the limited (COVID-LR-EGD) than in the full recovery case (COVID-FR-EGD). The reason lies in the slightly lower fossil fuel prices in the former case, which in turn leads to different primary energy consumption (Sections 2.4 and 3.2).

We also look at the carbon prices (marginal CO₂ abatement cost) produced by the two models in each scenario (Table 7). Despite inter-model differences in carbon price values (with EU-TIMES requiring a much higher carbon price than NEMESIS to reach the same target), the carbon price is consistently defined between the two models, which both expect a considerable increase with the implementation of the EGD (WWH-EGD). Behavioural changes due to environmental concerns (WWH-EGD-Beh) have a positive effect in EU-TIMES (−16% in the marginal CO₂ abatement cost relative to WWH-EGD), with only a downturn in NEMESIS (−2%). Post-COVID scenarios indicate a reduction in carbon prices in both models, even for a full economy recovery. This drop is larger when introducing behavioural changes (COVID-FR-EGD-Beh): −20% in EU-TIMES and −9% in NEMESIS, compared to WWH-EGD, which is consistent with the 19% drop in carbon prices by 2030 for a 1.5 °C-consistent low energy demand recovery pathway estimated by Ref. [59]. Here, lower demand for transportation services reduces the CO₂ emissions reduction burden, and mostly in aviation, which is particularly challenging to decarbonise. In the limited recovery case (COVID-LR-EGD), NEMESIS shows the lowest carbon prices among all EGD scenarios. Lower economic activity in the EU + (−3.9% of GDP, see Table 3) in COVID-LR-EGD leads to carbon prices being 11% lower than in the WWH-EGD scenario. This carbon price is also lower in EU-TIMES, but in line with the WWH-FR-EGD scenario, indicating that the recovery does not necessarily negatively impact delivering on climate targets. In brief, results from both models suggest that reinforced mitigation ambition in the EU (i.e., the −55% target) will contribute to a threefold (NEMESIS) to fivefold (EU-TIMES) increase of carbon prices, but this burden may be somewhat alleviated by lifestyle changes (here remote working and less flights).

### Table 6

| Emissions intensity on PEC (CO₂ emissions/Primary Energy Consumption) [Mt CO₂/Mtoe] EU-TIMES | 2019 | 2022 | 2025 | 2027 | 2030 |
|---|---|---|---|---|---|
| WWH-CP | 2.30 | 2.34 | 2.18 | 2.07 | 1.91 |
| WWH-EGD | 2.30 | 2.11 | 1.88 | 1.75 | 1.47 |
| COVID-LR-EGD | 2.20 | 2.17 | 1.91 | 1.78 | 1.50 |
| COVID-FR-EGD | 2.20 | 2.13 | 1.89 | 1.78 | 1.48 |
| WWH-EGD-Beh | 2.30 | 2.13 | 1.91 | 1.78 | 1.52 |
| COVID-FR-EGD-Beh | 2.30 | 2.17 | 1.92 | 1.80 | 1.53 |

| NEMESIS | 2019 | 2020 | 2021 | 2022 | 2025 | 2027 | 2030 |
|---|---|---|---|---|---|---|---|
| WWH-CP | 2.38 | 2.38 | 2.37 | 2.35 | 2.29 | 2.24 | 2.15 |
| WWH-EGD | 2.38 | 2.38 | 2.34 | 2.31 | 2.19 | 2.10 | 1.94 |
| COVID-LR-EGD | 2.38 | 2.30 | 2.35 | 2.33 | 2.23 | 2.14 | 1.98 |
| COVID-FR-EGD | 2.38 | 2.30 | 2.36 | 2.32 | 2.20 | 2.11 | 1.95 |
| WWH-EGD-Beh | 2.38 | 2.38 | 2.34 | 2.30 | 2.19 | 2.09 | 1.93 |
| COVID-FR-EGD-Beh | 2.38 | 2.30 | 2.35 | 2.31 | 2.19 | 2.09 | 1.93 |

### Table 7

| Carbon price in €/tCO₂ | EU-TIMES | NEMESIS |
|---|---|---|
| WWH-CP | 120 | 59 |
| WWH-EGD | 607 | 187 |
| COVID-LR-EGD | 508 | 184 |
| COVID-FR-EGD | 571 | 181 |
| COVID-FR-EGD-Beh | 437 | 170 |
| COVID-LR-EGD | 575 | 166 |

* Average weighted carbon prices among Member States and between ETS and non-ETS.
Fig. 4. EU + primary energy consumption variation in post-pandemic scenarios compared to the pre-pandemic trajectory (WWH-EGD) in (a) EU-TIMES and (b) NEMESIS.
of the two models (e.g., EU-TIMES includes extra-EU aviation consumption); however, both models are in line with the range of existing studies (with EU-TIMES being on the higher and NEMESIS on the lower end); e.g., Tsinopoulos et al. [97] reviewed a set of scenarios in line with inland consumption [38]. Tsiropoulos et al. [97] reviewed a set of scenarios in line with inland consumption from transportation to the residential sector. Yet, notably, increase of environmental awareness, namely with a switch in energy consumption from transportation to the residential sector. While, in NEMESIS, CO2 emissions increase by 15% in the WWH case and 21% in the COVID-19 scenario. Notably, NEMESIS finds negligible impacts from behavioural changes on FEC mitigation.

3.3. The role of awareness- and COVID-related behavioural changes

Fig. 5 displays the EU + final energy consumption (FEC) in the transport sector in both models, assessing the impact of behavioural changes on pre-COVID-19 and post-COVID full recovery trajectories (WWH-EGD-Beh vs. WWG-EGD and COVID-EGD-Beh vs. COVID-EGD, respectively). Total transport FEC expected decreases in all scenarios. In NEMESIS, reductions occur for all fuels, in particular oil. Similarly, in EU-TIMES, jet-kerosene is the main fuel reducing consumption, due to less sky travel, followed by hydrogen and, for some years, natural gas and gasoline. The drop of fossil fuel consumption in these scenarios contributes to a reduction of CO2 emissions in transportation by 12% for both WWH and COVID analysis in EU-TIMES (3% and 6%, respectively, in NEMESIS).

A similar comparison is drawn for the residential sector (Fig. 6): impacts driven by behavioural changes instead lead to a 3.6–5.5% increase in FEC in EU-TIMES (3.4–6.7% in NEMESIS). Consumption increases for all fuels (except for “other RES” in EU-TIMES, which primarily accounts for ambient heat from heat pumps), especially natural gas, which contributes to a CO2 emissions increase in the residential sector. Compared to scenarios without behaviour changes, in EU-TIMES, CO2 emissions increase by 15% in the WWH case and 21% in the COVID-EGD-Beh case; while, in NEMESIS, CO2 emissions grow by 3% and by 7%, respectively.

Results show that pandemic may accelerate trends foreseen by the increase of environmental awareness, namely with a switch in energy consumption from transportation to the residential sector. Yet, notably, the net impact of this interplay (demand reduction in transport and increase in the residential) remains environmentally positive, meaning there is a net reduction in energy consumption among the two sectors. Fig. 7 shows how the EU + FEC would be affected by including EGD-compliant policy and behavioural changes (WWH-EGD-Beh) – i.e., excluding the impacts of the pandemic (and recovery type). In the short-term (2022), EU-TIMES shows higher contributions from behavioural changes to energy savings than those from climate policy: from a total of 1.3% in FEC reduction, only 0.5% is due to increased climate ambition in the EGD. In NEMESIS, however, energy savings are driven mostly by that ambition, even in the short-term; by 2030, the model shows that the only contributor to FEC cuts is the EGD (about three-quarters in EU-TIMES, instead).

Fig. 8 shows how FEC is affected by behavioural changes driven by COVID-19. In EU-TIMES, results show that the impacts on FEC reduction due to COVID-induced behavioural changes are more important in the near-term, even more than the temporary economic impact of the pandemic in 2022, with the EGD policy framework eventually outperforming all other factors in the latter part of the decade. NEMESIS, on the other hand, highlights how the COVID-induced economic recession made a big impact right after the pandemic’s outbreak; thereafter, the progressive economic recovery in the EU + reduces the drop of FEC with almost no impact after 2023, whereas the reinforcement of climate ambition drives some energy efficiency gains, reaching a FEC reduction of 128 Mtoe in 2030. Notably, NEMESIS finds negligible impacts from behavioural changes on FEC.

3.4. Changes in investment requirements due to COVID-19 & behaviour shifts

Both models provide indicators for investments required to achieve EGD ambition. In NEMESIS, investment refers to the gross fixed capital formation based on the European national accounting framework [99]; whereas, in EU-TIMES, it follows a technoeconomic approach based on technology investment overnight costs.

In NEMESIS, the comparison of EU total gross fixed capital formation between pre- and post-COVID-19 scenarios allow the assessment of investment losses caused by the pandemic. Until 2022, NEMESIS finds an 860 bn€ loss of EU investments in COVID-EGD (994 bn€ in COVID-EGD) relative to WW-EGD. In addition, the comparison of total investments required between WW-EGD and WWH-CP provides insights into investment needs for shifting GHG emissions from −40% to −55% in 2030 (with respect to 1990), which are about 410 bn€ throughout the decade (Table 9). A large chunk of investment losses due to COVID-19 lies in the building sector (537–619 bn€), which includes services and households’ investments. This sector is followed by industry (198–221 bn€), for which the model has found already similar investment needs to deliver on the EGD (195 bn€) for the decade—almost double those for transportation and the built environment.

EU-TIMES investment indicators concern gross investment requirements in the energy system (Table 9). WWH-EGD features the highest cumulative investment, confirming the economic effort required to achieve the EGD -55% target: in comparison with WWH-CP, it corresponds to an additional whole-system investment of ~530 bn€ until 2030. The sectors requiring most investments differ from NEMESIS, as EU-TIMES highlights transportation (188 bn€) and power (184 bn€), in line with the CO2 emissions results. Behavioural changes (WWH-EGD-Beh) feature the potential to reduce the total amount by an impressive 86% (459 bn€), with the largest chunk being in the transport sector. This hints at behavioural changes reducing energy demand enough to considerably cut needs for advanced mitigation technologies, such as electric vehicles and hydrogen technologies, which have a remarkable impact on the investments.

The role of behavioural changes appears even bigger, when considering the COVID-19 impact: COVID-EGD-Beh requires 966 bn€ less than WWH-EGD, again with the transport sector reducing most investments. COVID-EGD-Beh, in fact, requires even less investments.
than the WWH-CP scenario (−434 bn€2010).

The range of investments needed to achieve the −55% target in 2030 is in line with European Commission estimates [32], according to which the need of additional investments in the power generation sector ranges between 110 and 165 bn€2010 between 2021 and 2030; overall additional investment requirements are higher in that assessment (590–1080 bn€2010), but it is noteworthy that our models do not include infrastructure costs.

A comparison with the EU investment capacity is interesting, considering that NGEU dictates that minimum 37% of the financing mechanism enable the climate transition. By considering only the NGEU stimulus, amounting to 750 bn€2018, the 37% green part corresponds to 277.5 bn€2018, including grants and loans. Now, comparing with the additional investment needs to go from current EU climate policies to the −55% GHG EGD target, the green part of the NGEU program could support about 55–70% of the investment needs calculated by the two models (after converting in €2018 and excluding UK). Therefore, the economic stimulus given by the NGEU program would play a critical role.

Fig. 5. EU final energy consumption in transportation - differences between scenarios with behavioural changes (WWH-EGD-Beh and COVID-FR-EGD-Beh) and their respective reference scenario (WWH-EGD and COVID-FR-EGD) for (a) EU-TIMES and (b) NEMESIS. Blended fuels include a mix of biofuels and fossil fuels according to the fuels’ quality and renewable energy directives [98]. Other oil fuels include heavy oil and LPG.
in supporting the energy transition in the EU and concretely stimulating green investments, after the COVID economic halt. Thus, it is vital that EU countries properly allocate NGEU funding to meet the EGD climate target, considering that NGEU is a considerable share of all investments required in the model findings.

4. Discussion

To comply with the Paris Agreement, the EU has revised its 2050 climate strategy [84] as well as its 2030 goals, with the EU 2030 Climate Target Plan [32]. The EGD, a set of policy initiatives upgrading the EU’s climate ambition, was launched just months before the outbreak of the COVID-19 pandemic, which has significantly affected European economies, energy systems, and citizen lifestyles.

Results point to largely similar CO₂ emissions pathways towards the newest – 55% GHG emissions reduction target in the EU by 2030, with around half the effort needed to bridge the gap from the previous – 40% target mainly concerning the power and supply sector and about 20% the transport sector; these are followed by the built environment and industry in NEMESIS—and vice versa in EU-TIMES. The pandemic appears to have limited impact on the emissions trajectories in the longer term, almost regardless of the speed of economic recovery; however, we also highlight the need for careful design and implementation of recovery plans to avoid a possible rebound of fossil fuel consumption. Furthermore, our analysis suggests that the enhanced 2030 climate ambition of the EGD could contribute to a threefold-to-fivefold increase
of carbon prices, a burden that may be alleviated by lifestyle changes, such as work-from-home and less air travel. In line with relevant insights in the literature, both models stress the role of energy efficiency for the EU energy system decarbonisation, but energy efficiency gains may be lower if the economic recovery is slow; in this case, lower fossil fuel prices may slow down the deployment of renewables and promote fossil fuels, despite the lower economic activity, while higher fossil fuel prices may cause a swift back to unsustainable options, such as coal.

The behavioural dimension here is limited to two habits induced by COVID-related confinements and already existing environmental concerns (remote working and reduced air travel): both models highlight a trade-off in energy consumption among sectors: big drops in transport are anticipated, but so is a non-negligible increase in the residential sector—nevertheless, the assumed behavioural changes would yield a net reduction in terms of energy consumption among the two sectors. Such changes can contribute to reducing energy use in ambitious mitigation, with a strong yet short-term effect early in the decade (even larger than that of the economic slowdown), and a limited-to-negligible impact on the end-of-decade mitigation, which instead is mostly driven by the EGD-related policies in place. Our results emphasise the need for further analysis of the potential contribution of behavioural changes to deep decarbonisation transitions [100,101], as well as to other environmental concerns (e.g. Refs. [102,103]).

We also find that the green part of the EU recovery instrument could potentially cover more than half of the investments required to deliver on the EGD, especially if coupled with swift economic recovery and behavioural changes, which can cut transport-related energy demand and delay the deployment of expensive technologies (e.g., hydrogen and large-scale electrification of transportation).

By analysing and comparing a set of scenarios embodying different stories for three drivers—policy ambition, speed of recovery, and behavioural shifts—the two employed models (NEMESIS and EU-TIMES) delivered converging results in certain aspects and emphasised insightful differences in others. From a methodological point of view, the detailed representation of the EU + energy system featured in EU-TIMES was reinforced to include COVID-19 impacts on GDP projections straight from a macroeconometric model (NEMESIS) running on the same, fully harmonised set of socio- and techno-economic assumptions, rather than rely on external data on—typically short-term—GDP projections based on different assumptions. Therefore, soft-linking the

![Fig. 7. Variation of FEC highlighting behaviour changes driven by environmental concerns – comparisons among WWH-CP and WWH-EGD-Beh for (a) EU-TIMES and (b) NEMESIS.](image-url)
two models, while feeding NEMESIS economic outputs into the highly
detailed EU-TIMES energy-system model, allowed a more nuanced
approach to analysing the interactions of COVID recovery, climate
ambition, and behavioural changes, as well as a more coherent
comparative analysis of model results, as opposed to running either/
each of the models separately.

A strong caveat concerning the interpretation of this study’s results
revolves around the highly uncertain political landscape, owing in large
to international conflicts (notably Russia’s 2022 invasion of Ukraine,
which at the time of writing this paper is ongoing) and the consequent
crisis in fossil fuel prices, as experienced in Europe throughout 2022.
This dynamic environment poses question marks, which are critical to
assessing current policy ambition, and which this research does not
consider for a diversity of reasons. First, the goal of this study is to
analyse the interplay between the social, economic, and climate di-

mensions in the light of COVID-19; it is, therefore, important to retain
the capacity to disaggregate the impact of the pandemic from the
combination of all these disruptions. This is hoped to help build a
realistic pre-conflict baseline pathway, against which all future studies
incorporating conflict-related fossil fuel adaptations can be compared,
in order to then understand the true impact of the Ukraine invasion.
Second, there is little confidence over how and when this situation is
expected to return to normal, especially as EU member states embrace
for a seemingly difficult winter (2022–2023), in terms of capacity and
flexibility to meet energy demand, with great implications for fossil fuel
supplies and further energy price volatility. Perhaps more importantly,
current policies and energy mixes in Europe may radically shift
depending on a continuously elaborated policy response to the conflict.
On the one hand, acceleration of RES deployment, energy savings, and
supply diversification are spelled out in Europe’s plan on eliminating its
dependency on Russian fossil fuel imports (REPowerEU); on the other
hand, European leadership appears locked-into new LNG infrastructure
and active in mobilising every readily available fossil-fuel option [104].
How and to what extent these levers are eventually pursued actively and
across the region remains greatly uncertain [105]. Finally, apart from
policy assumptions, a critical input to— and driver of the cost opti-
misation process of— energy-economic models such as the ones employed
in the study, lies in fossil fuel price projections. Although our study uses
IEA’s 2021 outlook, which constitutes the most recent authoritative
dataset, we acknowledge that this dataset was released prior to the 2022
conflict and is thus outdated. Nonetheless, by assuming different tran-
sitory shocks on fossil fuel markets building on this latest available
outlook, our scenario design attempts to reflect part of the fossil fuel
price trajectory spectrum. For all these reasons, any bold assumption

Fig. 8. Variation of FEC highlighting behaviour changes driven by pandemic-induced lifestyle shifts – comparisons among WWH_CP and COVID-FR-EGD-Beh for (a) EU-TIMES and (b) NEMESIS.
made in an attempt to establish more ‘real-world’ scenarios that consider the current dynamic environment may create a false sense of realism, since such assumptions may as well be detached from how events eventually unfold. We also acknowledge that, aside from technological-economic datasets (such as fossil fuel prices), critical socioeconomic assumptions upon which climate-economy modelling exercises are typically anchored to Ref. [106]—including but not limited to levels of international cooperation/fragmentation, structural inertia, etc.—may already be invalidated by these recent developments and need to be revisited by the modelling community [107].

5. Conclusions

This study integrated two large-scale modelling tools for the EU, namely the EU-TIMES and NEMESIS models, to assess challenges and opportunities related to delivering on the EU’s climate ambition for 2030 in consideration of the interplay between the enhanced policy ambition reflected in the EGD, the speed of economic recovery from COVID-19, and behavioural shifts induced by societal responses and sustainability concerns.

Key results and policy implications can be summarised in the following:

- The EGD can put the EU on track to meeting its updated 55% emissions reduction target. On top of the pre-pandemic baseline and the 40% target, half the gap may be bridged in the power sector, followed by transport decarbonisation.
- However, investments as part of the EU green recovery can conditionally finance only about half of this effort. Additional investments and financial instruments are required to realise a pathway to −55% in 2030, especially considering the implications of the recently announced REPowerEU plan.
- Plans, such as the REPowerEU as well as other investment schemes to potentially follow in the near-term, need to be properly designed to avoid the risk of possible fossil fuel rebounds after COVID-19, although the pandemic itself is found unlikely to impact long-term emission trajectories.

- The EGD-induced carbon price increase is expected to be threefold-to-fivefold. Behavioural changes can be instrumental here, by helping mitigate part of this burden. To realise this potential, plans need to draw from pandemic-triggered insights and encourage the continuous uptake of best practices, including but not limited to remote working and reduced (air) travel.

Despite significant effort to ensure that the scenario protocol and underlying assumptions are realistic and objectively serve the purpose of the study, future research should further elaborate on this selection. This, first and foremost, includes the consideration of a fast-evolving EU climate policy framework, with the finalisation of the ‘Fit for 55’ package; instead, our results must be interpreted as a static representation of the current policy context. Perhaps more importantly, considering that a key limitation has been the lack of representation of the latest international conflict and subsequent energy crisis despite best efforts to incorporate the latest available price projections, prospects building on this study must include the analysis of the interplay between the impacts of COVID-19 and the recent international conflict in Eurasia, by introducing different trajectories for fossil fuel prices, and drawing the impact of COVID-19 from this study to shed light on how each crisis may influence the European energy system. Accordingly, the recovery space, along with the model ensemble, can also be enhanced to include scenarios with a higher resolution in terms of the speed of the recovery, towards accounting for the inherent uncertainty. Such enhancements could consider regional disaggregation, which is another limitation of this study especially considering that the recovery is not expected to be homogeneous between the countries of the bloc, to account for the socio-economic situation of each country that could affect the allocation of the recovery funds [108].

Credit author statement

G.C., B.-B., and A.C. coordinated the modelling protocol and conceptualised the research, with contributions from all authors; all authors were involved in the model analysis, with notable contributions from G. C., A.C., A.E., M.G. (EU-TIMES), as well as B.-B., P.L.M., P.Z. (NEMESIS). G.C., B.-B., A.N., K.K., and H.D. discussed the results, with feedback from all other authors. G.C. coordinated the writing of the paper; all authors provided feedback and contributed to writing the paper.

1 https://www.i2am-paris.eu/detailed_model_doc/nemesis.
2 https://www.i2am-paris.eu/detailed_model_doc/eu_times
3 https://doi.org/10.5281/zenodo.7194864.
4 Estimates of behaviour changes are derived from the NZE scenario.
5 In EU-TIMES, demand for air transport is exogenous and depends on GDP. Thus, besides changes in passengers’ preferences due to increased awareness of air transport environmental impacts, the implementation of a carbon price on fossil fuels would increase the cost (price) of air transport (a hard-to-decarbonise sector, at least in the short-to-medium term). Thus, demand would go down, as flying would be more expensive. In NEMESIS, this mechanism is already included because the model includes a price elasticity for air transport demand; thus, we do not apply this exogenous demand reduction in NEMESIS to avoid potential double accounting.
6 EU-TIMES indicates that emissions pathways do not differ significantly compared with WWH-EGD, given its limited capability of capturing short-term shocks (the model considers average multi-year periods). NEMESIS runs on annual level resolution; hence the model is able to show implications for specific years, and rapid recovery in the following years.
7 As EU-TIMES cannot capture short-term shocks (i.e., in 2020, 2021), given its limited resolution, 2022 represents an average period between 2021 and 2023.
8 2019 values of emission intensity slightly differ in the two models.

Table 9
Cumulative EU investment deviations due to COVID-19 and EGD by sector.

| NEMESIS | Cumulative EU investment deviation from 2020 to 2022 due to COVID-19 pandemic (bn €) (w.r.t. WWH-EGD) | Cumulative EU investment deviation from 2021 to 2030 due to European Green Deal (bn €) (w.r.t. WWH-EGD) |
|---------|---------------------------------------------------------------|-----------------------------------------------------------------|
| Agriculture | −15.9 | 23.7 |
| Power and supply | −16.1 | −20.3 | −25.9 |
| Industry | −198.1 | 195.1 |
| Transportation | −103.4 | −116.1 | 110.0 |
| Buildings | −537.1 | −619.4 | 106.2 |
| Total | −870.5 | −994.4 | 409.0 |

| EU-TIMES | WWH-EGD | WWH-EGD-Beh | COVID-19 | COVID-19-Beh | COVID-19-LR-EGD |
|-----------|----------|-------------|----------|-------------|----------------|
| (w.r.t. WWH-EGD) | (w.r.t. WWH-EGD) |
| Industry | 63 | −14 | −9 | −27 | −32 |
| Residential | 24 | 1 | 12 | 1 | −16 |
| Services | 45 | −22 | 9 | −22 | −17 |
| Transformation | 28 | −13 | −2 | −6 | −6 |
| Transportation | 188 | −335 | −93 | −808 | −370 |
| Power sector | 184 | −76 | −7 | −93 | −69 |
| Total | 532 | −459 | −89 | −966 | −511 |
because they have a different base year. Therefore, values are modelled and not based on 2019 EU + energy balance.
9 Primary energy consumption equals gross inland consumption minus final non-energy consumption.

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.

Data availability
A Data Statement has been included with links to publicly available Zenodo datasets.

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