Energy-socio-economic-environmental modelling for the EU energy and post-COVID-19 transitions

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Abstract

Relevant energy questions have arisen because of the COVID-19 pandemic. The unforeseen drastic reductions in emissions motivated by the pandemic shock are expected to be temporary as long as they do not involve structural changes. However, the COVID-19 consequences and the subsequent policy response will affect the economy for decades, becoming crucial to face present challenges such as the fight against climate change and energy transition. The COVID-19 experience brings lessons for dealing with future scenarios of considerable load reduction and higher renewable production. Focusing on the EU, this discussion article argues that recovery plans are an opportunity to foster significant changes and, finally, deepen the way towards a low-carbon economy, improving employment, health, and equity. Long-term alignment with the low-carbon path and the development

of a resilient transition towards renewable sources should guide instruments and policies, conditioning aid to energy-intensive sectors such as transport, tourism, and the automotive industry. However, the potential dangers of short-termism and carbon leakage persist. The current energy-socio-economic-environmental modelling tools are particularly valuable to widen the scope and deal with these complex problems. The scientific community has to assess disparate, non-equilibrium, and non-ordinary scenarios, such as sectors and countries lockdowns, drastic changes in consumption patterns, significant investments in renewable energies, and disruptive technologies, as well as to incorporate uncertainty analysis. All these instruments will allow evaluating the cost-effectiveness of decarbonization options and potential consequences on employment, income distribution, and vulnerability.

1. Introduction

The COVID-19 pandemic has caused profound and unforeseen effects in all spheres of human life around the planet. Measures to prevent the spread of the pandemic, primarily the confinement of citizens and the lockdown of non-essential economic activities, have led to a dramatic decline in GDP (gross domestic product) and employment. The European Union (EU) experienced a 6.1% contraction of the GDP in 2020, with an unemployment rate of 7.0% (7.3% in April 2021) and a public deficit of 6.9% (EC, 2021a, 2021b, 2021c). Simultaneously, global CO_2 emissions estimates decreased by 17% in early April 2020, which is associated with an annual decrease of 4.2-7.5% (Le Quéré et al., 2020). In the European Union, CO_2 emissions from fossil fuel combustion decreased by 10% in 2020 compared to the previous year (EC, 2021d).

To cope with the economic impacts of the pandemic, the European Commission (EC) and Governments of the Member States (MS) have announced and developed a number of recovery plans. From the long-run perspective, the EC and the MS work on designing stimulus packages to boost the economic recovery, the so-called Green Recovery Plans (GRPs). In the face of the COVID-19 crisis, the EC indicated that it will continue promoting its flagship project, the European Green Deal (EGD) [1], the most comprehensive proposal for economic transformation. The Next Generation EU (NGEU) fund is at the core of the recovery policy in the EU. This temporary recovery instrument consists of more than €800 billion to help repair the immediate economic and social damage brought about by the coronavirus pandemic. The aim of this plan is to foster a greener, more digital, more resilient Europe and better fit for the current and forthcoming challenges. In parallel, and in order to benefit from the NGEU, the MS have submitted to the EC their National recovery and resilience plans (EC, 2021e), outlining how they will invest the funds, and how they will contribute to a sustainable, equitable, green and digital transition. The reforms and investments included in the plans should be

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[1] Discussions around the Green New Deals have more than a decade (Barbier, 2010a, 2010b; Bauhardt, 2014; Patel and Goodman, 2020; UNEP, 2009), retaking the media scene now as proposal for the post-COVID-19 crisis (Galvin and Healy, 2020; Micale and Macquarie, 2020; Salter, 2020).

implemented by 2026. The NGEU fund will operate from 2021 to 2023, and will be tied to the regular long-term budget of the EU, running from 2021 to 2027. The EU's long-term budget, coupled with NGEU, will be the largest stimulus package ever financed in Europe with a total budget of €2 trillion.

Political economy may tell us more about how this will play out in the end (depending on, e.g., the interest of well-positioned lobbies and/or large firms, the need to take advantage of planned projects, the built or needed infrastructure, etc.). According to Cowen (2021), energy policy is often judged by three criteria (cost, reliability, and effect on carbon emissions), while suggesting an alternative approach based on which green energy policies can get the support of most special-interest groups and the fewest forces in opposition. Academic, online and political debates are then greatly modulating and adapting the above principles. Still, according to Pianta et al. (2021), surveys about the next 5 years to policymakers and stakeholders from 55 different countries and sectors suggest that expectations that the COVID-19 pandemic will accelerate decarbonization efforts are widely shared, similarly to what citizens seem to reveal (EU, 2020).

A critical question is how to shape the GRPs to rapidly deliver jobs and improve citizens' quality of life without compromising the fight against climate change and contributing to sustainable and resilient societies (Shan et al., 2020). This article, complementary to the discussions on carbon pricing and COVID-19 (Mintz-Woo et al., 2020), how the disease impacts the ongoing energy transitions (Sovacool et al., 2020), and the role of international governance in the recovery (Obergassel et al., 2020), discusses the challenges and potential of the GRPs, highlighting the value of energy systems modelling for informing policymakers in managing an efficient, secure, and fair energy transition. It is organised into five main sections, each raising a challenge of the post-COVID-19 plans for recovery and energy transition in the EU.

2. How have the energy system, the associated environmental pressures, and the European policy agenda changed with the COVID-19 crisis?

In the period of tightest restrictions against COVID-19, most of Europe experienced a notable load drop. Interestingly, while coal, oil and nuclear power generation considerably decreased in most countries, the production of renewables increased, proving that intermittent renewables are a reliable resource in critical times (Werth et al., 2021). Likewise, energy trade between countries increased. As a result, CO_2 emissions fell by 17 million tonnes in April 2020, a drop that had not been registered since 2006 (Le Quéré et al., 2020). Schumacher et al. (2020) estimated that greenhouse gas (GHG) emissions reductions from changes in EU consumption accounted for 6% in the EU, and around 1% globally.

However, unless the future economic recovery is tilted towards green stimulus and reductions in fossil fuel investments (Forster et al., 2020), the decline in 2020 is unlikely to persist in the long term, as it does not reflect structural changes in economic systems, nor do they seem to have much effect on global climate change in the medium term (IEA, 2021; Linares, 2020). Nevertheless, studies on the impact of the COVID-19 on health, economy and the environment serve to analyse possible scenarios of considerable load reduction and higher renewable production[2]. In this context, the permanence of changes depends on how production and consumption patterns evolve (e.g., teleworking and tourism), the scope of the energy transition, and, ultimately, to what extent climate change is taken into account when planning economic responses after COVID-19. This framework is genuinely at stake, particularly in the post-pandemic EU with the GRPs.

3. How is the European energy transition linked with the GRPs?

The European energy transition appears intimately connected with the GRPs by the common goal of decarbonisation. The energy transition as an engine of recovery can lead to large investments in clean energy technologies. According to the priorities of the GRPs, mobilisation of funds will mainly focus

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[2] See CAT (2020), EC (2020), Guan et al. (2020), Illanes and Casas (2020), McKibbin and Fernando (2020), OECD (2020), Oxford Economics (2020), amongst others.

on the renovation of buildings, renewables and hydrogen, and clean mobility; a share of 30% will be spent on fighting climate change (EC, 2021f).

As pointed out by Escribano et al. (2020), the set of EU policies can provide the regulatory certainty that the private sector needs to embrace the low-carbon transition as a recovery opportunity (Campiglio, 2014). Additionally, the EU has built a framework for aligning financial and climate goals through the Sustainable Finance Action Plan (EC, 2018), and the recently published EU taxonomy for sustainable activities (OJEU, 2020). These initiatives should aim to neutralise any attempt to reverse the trend towards energy and climate policies and regulations, aligning recovery plans and energy transition.

The IEA proposes greater cooperation, coordination based on the national energy and climate plans (NECPs) and working on the integration of the energy market, cross-border trade, and developing stronger signals from the price of carbon (IEA, 2020a)[3]. Cooperation mechanisms included in the European Renewable Energy Directive (OJEU, 2018) enable EU countries to work together to meet their targets more cost-efficiently. The EGD is an opportunity to deepen measures affecting the EU pooling investments in key innovative technologies. In general, GRPs should accelerate and prioritise some of the action plans contemplated in the NECPs. Governments' role will be very relevant in innovative public procurement processes setting the benchmark for companies (Lindström et al., 2020; EC, 2014).

4. Are there specific opportunities for the energy transition (e.g., more investment for more employment-generating electricity production technologies) with these plans?

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[3] Reasonable concerns may emerge on the fact that carbon taxes could derive into further austerity policy and hence not actually be a “recovery” measure. The recovery package designed by the EU requires some reforms for the funds to be released, including fiscal reforms of which carbon taxes may be a part. Actually, carbon taxes, particularly in the sectors not included in the ETS (Emissions Trading System), may be required as one of the policies needed to reduce emissions, and hence ensure that the recovery is aligned with the Green Deal. Carbon border taxes (or alternative mechanisms, such as climate contribution) are also needed to prevent relocation, and to help fund the decarbonization of industry and the recovery package. Both of them can (and probably should) include redistributive measures (such as refunds to households) to prevent the austerity that may create negative impacts on households.

There are several clear synergies between energy transition and job creation (IRENA, 2019) and improved health. For instance, pollution associated with fossil fuel combustion takes premature lives annually while increasing the respiratory risk associated with diseases such as COVID-19 (Vandyck et al., 2018). Environmental and social ratings have been resilient during COVID-19 featuring higher returns, and renewable energy technologies may yield environmental and health benefits (Guerriero et al., 2020).

The IEA estimates that investing 0.7% of global GDP could create or save 9 million jobs a year in improving the efficiency of buildings, grids, and renewables, but also in improving the energy efficiency of manufacturing, food, and agriculture, textiles, infrastructure for low-carbon transport (which should also be of low-carbon concrete and steel, e.g. for railway), and more efficient vehicles (with the reasonable substitution of the vehicle park based on its useful life) with enhanced electricity grids (IEA, 2020b).

In the business field, there have been "winners" in the COVID-19 crisis (e.g., technology, distribution, food and pharmaceutical companies). Their expansion offers the chance to include them in the fight against climate change actively. For instance, electronic commerce is here to stay. Therefore, distribution companies must develop the modal shift towards electric vehicles (Shahmohammadi et al., 2020). In the same vein, technology-based electricity-intensive companies should be encouraged to keep low carbon footprints, penalising possible carbon leakage in carbon-intensive countries (Ortiz et al., 2020; Jiborn et al., 2018) and including carbon border adjustment mechanisms (as intended by EGD for selected sectors by 2021).

GRPs need to target not only the most relevant sectors in terms of emissions and economic growth (e.g., airlines committed to reducing their emissions in the medium term, or industries focused on fossil fuels that do not have much time to live in their current configuration) but also, significantly, critical activities in which the conditionality of aids can be very effective towards decarbonisation (e.g., the power sector or the automotive sector). The allocation of GRPs stimuli is crucial, because it could increase global five-year emissions by -4.7% to 16.4% depending on the structures and strength of incentives (Shan et al., 2021), and a "green GRP" could outperform an equivalent stimulus package while reducing global energy CO_2 emissions by 10% (Pollitt et al., 2020).

Further opportunities arise from the investment in renewable electricity, hydrogen and energy storage technologies, which are set to play a fundamental role. Promoting home-grown technology production becomes relevant for job creation. In strategic sectors for Europe, such as electricity and digital technologies, efforts may be made towards developments in the field of management, control, security, and digitisation. In production technologies such as photovoltaics, aspects such as adaptation to urban environments, integration in buildings, and advances in high-efficiency cells remain as opportunities. Hydrogen research, especially electrolysers, can be a differential technological factor. Concentrated solar technology for electricity production is an example of such technological leadership that could be promoted, being entirely consistent with the spirit of the objectives of the EGD, supporting high-value-added and sustainable economic activity in southern European countries like Spain, heavily hit by the crisis (Banacloche et al., 2020).

The renovation of buildings offers an excellent opportunity to contribute to the economic recovery of the construction sector. The solutions to improve the thermal insulation of façades in existing buildings would not only redirect sectoral activity and avoid job losses but also fight against energy poverty. Likewise, the tourism sector has great potential to decarbonise and become more resilient if the necessary investments are made. It seems reasonable to implement plans at a regional and local level aimed at improving energy efficiency, circular economy, and public awareness.

5. Are there specific dangers to the energy transition, e.g. economic recovery measures that could indirectly generate more pressure on the energy and environmental system?

According to IEA (2020c), the energy investment has been reduced by 20% in 2020 due to supply chain disruptions, lockdown measures, restrictions on people and goods' movement, and emerging financing pressures. Moreover, some key lobbyists and stakeholders have expressed short-term priorities for sustaining employment and economic growth of any kind. If so, there is a risk of targeting aid to specific emission-intensive industries, incentivising vehicles' purchase, or protecting traditional tourism, which would perpetuate unsustainable production and consumption patterns. In the context of low oil prices, aggravated by the reduction in demand due to the pandemic, such interventions would dangerously delay fossil fuels' substitution.

Furthermore, the potential rebound effects resulting from technology innovations and energy efficiency improvements cannot be ignored (Greening et al., 2000; Sorrell et al., 2009; Antal and van den Bergh, 2014). Several instruments and interventions should be considered to mitigate the magnitude of the rebound effects: policies that promote changes in consumer behaviour and sustainable lifestyles, environmental taxation, non-fiscal measures to increase the effective price of energy services, or the development of new business models (Maxwell et al., 2011).

The pandemic also has the potential to change consumer preferences, alter social institutions, and rearrange the structure and organization of production. Greening et al. (2000) refer to these potential effects as transformational rebound effects. No theory exists to predict the sign of these effects, which in the longer term could lead to higher or lower energy consumption, as well as to changes in the mix of energies used in production and consumption throughout the economy. In this regard, it is worth recalling the take-back in GHG emissions observed after the economic-financial crisis of 2008-2009, or in leisure travel after the 9/11 terrorist attacks.

6. What type of energy modelling can be particularly useful to address current challenges and to anticipate advantageous situations and trade-offs from these plans?

The COVID-19 pandemic has caught the world in the transition to a sustainable low-carbon energy system and economy, and it raises new challenges to the existing ones. Environmental-energy-economic models must adapt and report on the specific dimensions of those challenges. Modelling energy transition in a post-COVID era must go beyond typical technical variables to meet environmental and social goals, flexibility and uncertain parameters and indirect effects of increasing renewables use (Tovar-Facio et al., 2021). Modellers are increasingly claimed to include aspects such as uncertainty derived from agents' interactions or evolution in their behaviour, ability to integrate shocks in both demand and supply, and non-enforcement of Say's Law or equilibrium or quick adjustment in markets and sectors (Shan et al., 2021; Pollitt et al., 2020). The integration of social indicators with a perspective of global supply chains to identify winner and losers from policy actions or inaction can be crucial to improve models' relevance to the real world. To this end, insights from political economy –regarding individuals not just as rational optimisers, mass movements, public opinions, confidence and quality of institutions, trade linkages of sectors and trade policy, among others– can be helpful, although hard to model due to data availability (Peng et al., 2021).

In the Appendix, we display some examples of current efforts in multidisciplinary energy modelling to address the challenges of a sustainable energy transition, some of them already applied to the implementation of Energy and Climate Plans in the Spanish context. Input-Output Tables (IOT) and the extended Multiregional Input-Output (MRIO) models provide a systemic, multisectoral, multiregional view, in which it is possible to include different indicators for policy advice (Wood et al., 2020; Vanham et al., 2019; Wiedmann and Barrett, 2013): environmental impacts (emissions), resource needs (water, land), socio-economic impacts (employment, qualifications), and social risks along the value chains. They can help to define and quantify synergies and trade-offs between different measures and investments. They are also useful to assess the resilience of the economy (and in a sense, of the energy sector) to situations such as pandemic experiences since it allows modelling the closures of sectors/countries or the resource/employment needs of specific sectors by identifying bottlenecks and hotspots including all phases of the global production chain. On the demand side, they allow elaborating scenarios of change in consumption patterns. Besides, MRIO-disaster models deal explicitly with disequilibrium shortfalls in supply and demand in different markets and sectors (Shan et al., 2021).

Energy systems modelling based on simulation/optimisation, such as TIMES (The Integrated MARKAL-EFOM System, IEA-ETSAP, 2020), is the one chosen by, e.g., the Spanish Government to establish the narratives of the energy system for long-term energy planning (Loulou et al., 2005). In the same fashion as Computable General Equilibrium (CGE) models have been criticized for assuming optimal ("rational") behaviour, introducing optimising behaviours in the energy sector but not anywhere else in the modelling would be inconsistent as well. Additionally, depending on the scale of application and the dimension of analysis, we should implement other modelling types. Linking MRIO models and energy systems optimisation models with methodologies such as Life Cycle Sustainability Assessment (LCSA) allows understanding the implications of alternative investment options in broader sustainability aspects (Navas-Anguita et al., 2020). LCSA typically consists of an environmental life cycle assessment (LCA), a life cycle costing, and a social life cycle assessment (S-LCA) within a consistent, holistic framework (UNEP/SETAC Life Cycle Initiative, 2011). In this regard, we note that decarbonization and sustainability are expected to continue to be the drivers for policy action, especially regarding energy systems.

Environmental-Energy-Economic integrated assessment models (E^3 IAMs) are useful tools to provide ex-ante information on the potential impacts of recovery plans, but, to that end, they must be able to report on the specific dimensions of the challenge. Accordingly, models should inform on employment, income (distributional), and environmental impacts of different green policies portfolios. Full multi-agent econometric input-output models should be included in the economic part of the IAMs, as done in the WILIAM model, an IAM with detailed representations of the economic, socio-demographic, resources (energy, materials, land, water) and environmental spheres[4].

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[4] Developed in the LOCOMOTION (https://www.locomotion-h2020.eu) project. The economic module of the model departs from a structure inspired in the FIDELIO model (Kratena et al., 2013, 2017) and the DENIO model, used for the economic, employment, social and public health impact of the Spanish Integrated Energy and Climate Plan 2021-2030 (MTE, 2020).

The E3ME macro-econometric model (Cambridge Econometrics, 2019), based on post-Keynesian theory, shows an IOT base to model sectors and countries relationships and integrates the energy system, including bottom-up sub-models of several key energy sectors. It can be used to build scenarios to reflect the critical aspects of the pandemic and allow consideration of both demand- and supply-driven impacts derived from it (Pollitt et al., 2020). Besides, the model does not assume (as, in general, CGE models do) that the economy adjusts quickly after the pandemic impact to full employment of resources and allows fundamental uncertainty affecting spending and saving behaviour.

Many models will have to adapt to the new challenges (Pfenninger et al., 2014; Solé et al., 2020) and to the new features involved with the COVID-19 crisis and the coming times with the recovery plans (Table 1). For example, they could use microdata to analyse, for specific groups of households (e.g., along with a set of socio-demographic characteristics of interest), the environmental and economic implications of different recovery policies, including distributive impacts. Another critical feature is linking the economic production and consumption functions to bottom-up energy and resources modules, looking for higher resolution models in this aspect (Prina et al., 2020).

Additional aspects to implement include the criticality of the materials expected to be essential in the energy transition, the role of citizens (such as human behaviour, types of demand and users), the use of water, visual and sound impact, market regulatory advances (e.g., with schemes which avoid speculation on energy storage), energy servitization (to check whether it brings social benefits and improves the efficiency of the system), and adaptation mechanisms. Planning capacity at the regional and city levels will be crucial to the success of national measures. These modelling developments will pose a challenge for economists (input-output regionalization, recirculation, and dynamics), systems engineers (complex simulation models with high load of artificial intelligence tools and big data to configure demands, project resources, etc.), chemical engineers, and environmental scientists (regionalization and dynamic inventories in LCA), as well as decision engineers (strategies, multi-criteria decision-making, PESTEL analysis, group work, governance models and policy design).

Table 1. Key modelling developments for analysing energy transitions in the context of post COVID-19 green recovery funds.

Advanced Feature	Description / Key aspects
Oil/gas scenarios & associated	Context of low oil prices, risks for renewables transition, but also potential for introducing further environmental taxation.
Carbon price scenarios	The IEA proposes developing stronger signals from the carbon price.
Renewables penetration	Supervening role of hydrogen, which requires developments of roadmaps, infrastructure, etc.
Electric car penetration	Different possible paths towards an electrical paradigm. Potential automotive sector redistribution.
Agents' heterogeneity / Firm heterogeneity	Use of different databases (e.g., EU surveys on consumption, income, etc., linked through statistical matching). Different demographic and socio-economic characteristics to identify potential social, environmental and economic implications of varying recovery policies, including distributive impacts, vulnerability, gender inequality, resilience, etc.
Bottom-up energy link to economic production & consumption	The monetary and physical spheres need to work together with a dual system guaranteeing full consistency. It is essential to capture the environmental effects of stimulus packages and investments.
Mobility restrictions/scenarios	COVID-19 has shown the strong effects of reduced mobility on CO_2 emissions. Different restrictions may apply and scenarios to occur.
Foreign sector closures	Alternatives depending on trade and travel restrictions.
Full Multipliers Analysis (full scope/wide range of impacts)	Evaluating different implications of getting them with input-output, social accounting matrix and computable general models. Potentialities to obtain them from bottom-up renewable energy investments via investment matrices which link to macroeconomics and hybrid models.
Several impact levels (meaningful disaggregation level)	Multiregional, national, regional, city, etc. Sectoral disaggregation to allow uneven shocks and behaviour.

Non-equilibrium states	Allowing disequilibrium shortfalls in supply and demand of different markets in the short or medium term.
Additional uncertainty analysis	Uncertainty of fossil fuel resource availability, technology penetration, etc., but also consideration of *out-of-ordinary extremes.*
Biophysical limits	The limits on the availability of non-renewable and renewable energy resources and critical materials may determine some restrictions to growth.
Assessment and feedback of the impacts of climate change	Feedback of the impacts of climate change on the economy and well-being of society. Some of these relationships can have knock-on consequences.
Multi-objective criteria	Focus the results on multi-objective criteria of well-being. (SDG, social indicators, environmental indicators, …)
Behavioural change	Change in social behaviour. Some changes in social behaviour, such as diets or transportation habits, can be decisive in the fight against climate change.

Finally, it is important to point out that “scenarios are the primary tool for examining how current decisions shape the future, but the future is affected as much by out-of-ordinary extremes as by generally expected trends. Energy modellers can study extremes both by incorporating them directly within models and by using complementary off-model analyses” (McCollum et al., 2020). Thus, uncertainty is an intrinsic attribute of macro-systems such as those evaluated by means of energy systems models (cities, regions, countries…). In this sense, uncertainty will have an effect on decisions and strategic planning. There are several types of uncertainties that affect decision-making processes. Some uncertainties can be quantitatively addressed and some others not, which relates to the rationale of ‘(un)known (un)knowns’ in Courtney et al. (1997): there are known knowns (things we know we know), known unknowns (things we know that we do not know, and that typically are addressed with varying parameters to reduce risks of error, testing robustness of results, etc.), and unknown unknowns (things we do not know we do not know). While known unknowns could be faced through sensitivity analysis on relevant systemic variables, unknown unknowns open the door to qualitative strategic thinking based on out-of-the-box scenarios (what happens if a pandemic arrives, what happens if oil price reaches 200 USD a barrel, etc.). As we conclude below, these questions highlight the importance of a modelling approach that takes into account existing uncertainty and that non-equilibrium outcomes are the common situations with changing and heterogeneous patterns.

7. Conclusions, final warnings, and recommendations

Once the health crisis is over, it will be necessary to invest more in public health and communication technologies with environmental and social sustainability criteria, not just monetary. Besides, although it is required to reactivate the economy and recover the lost or at-risk jobs, it is essential to redefine the productive schemes at all levels. This includes the commitment to a circular economy, reducing the pressure on resources through innovative eco-design solutions, dematerialisation, and creating second-life solutions away from precariousness and the underground economy. Besides, the mobility model must be changed, and a sustainable work-life balance scheme should be promoted via teleworking, whenever possible, not only to avoid the exponential expansion of contagions but also to reduce pollution. Fourth, the EU's leadership has to extend beyond its borders, undertaking actions to prevent carbon leakage, and engage in global actions and alliances disseminating experiences and learnings.

Finally, some policies are likely to generate much better economic and distributive outcomes than others. Energy-socio-economic-environmental modelling, which allows evaluating alternative and non-ordinary scenarios, is crucial to provide information to policymakers to make informed decisions. We emphasize the need for consistency with integrated modelling approaches that consider uncertainty, non-optimising behaviours, heterogeneous agents, non-equilibrium outcomes across sectors, rigidities, institutional frictions, etc. Specifically, we highlight the need to develop advanced modelling frameworks that integrate dynamic econometric multiregional models and inter-sectoral models of the EU economy, and multi-household micro-simulation models (representative of the population of the EU), as well as developing national energy systems models oriented to production technologies (electricity/fuels). Further research is needed to explore the possibility of hybridising integrated models and methodologies from other fields, like behavioural economics, political science, and social engineering. In this sense, there are analytical aspects that will require more outstanding modelling efforts, such as the social dimension (via S-LCA, agent-based models, diffusion models, physical models, neural networks, etc.), the adaptation of uncertainty analysis to the most relevant parameters, and aspects related to sustainability and energy and resource security. In summary, in order to tackle the significant challenges posed by the energy transition, applied research requires a multidisciplinary approach with the participation of energy modellers, data scientists, specialists in advanced governance and tax innovation, social researchers, philosophers, etc. Many of the techniques and lessons we learn today will guide future crises.

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Appendix. Some multidisciplinary models to address the energy transition challenges in the context of post-COVID-19 green recovery funds.

Model/ tool	Features	Potentialities/Questions	Publication/Project
DENIO model	Hybrid between an econometric input-output model and a computable general equilibrium model. Integration of rigidities and institutional frictions that make fiscal policies and investments have a different impact in the short term and in the long term. High detail in the energy sectors (and link to bottom-up ones), and high detail of households and estimates using and merging (through Statistical Matching) micro-data from the Household Budget Survey and the Living Conditions Survey.	The cited features make it highly useful for linking micro and macroeconomics in terms of, e.g., distribution questions. Capable of evaluating the economic impact of different plans and strategies designed by the Government of Spain such as the Integrated National Energy and Climate Plan (PNIEC 2021-2030), the Long-Term decarbonisation Strategy (ELP 2050) or the "Long-term Strategy" for specific sectors. Also used by the European Commission to analyse the economic impact of the Clean Air Package.	Inspired by Kratena et al. (2013, 2017). González-Eguino et al. (2020), MITECO (2020a, 2020b, 2020c), Arto et al. (2015, 2019), MITMA (2020). A similar one in the Basque Country: DERIO (Dynamic Econometric Regional Input-Output model)
PICASO energy systems optimisation model	Thorough technology breakdown of (alternative) fuel production technologies. Integration of life-cycle sustainability indicators.	To assist energy decision- and policy-makers in developing roadmaps focused on prospective technology production mixes of alternative fuels for road transport, with time horizon 2050.	Related to the national project PICASO (ENE2015-74607-JIN AEI/FEDER/UE) Navas-Anguita et al. (2020)
EDISON* tools	Supply-Use Tables (SUTs), input-output tables (IOTs), social accounting matrices (SAMs), input-output & computable general equilibrium models for energy policy analysis. Capable of capturing flexible forms in production and consumption, with all sectors in the economy, and detail in specific industries/products such as electricity.	The cited features make it highly useful for evaluating footprints (notably GHG emissions), questions on drivers of change and scenario analysis on the energy transition, decarbonisation, etc. in Spain and in the world. Currently questions on electricity self-production and self-consumption using disaggregated SUTs are specifically addressed.	Cazcarro et al. (2014, 2015, 2020), Doumax-Tagliavini & Sarasa (2018), Duarte et al. (2010, 2017, 2018), Langarita et al. (2019, 2020), Schumacher et al. (2020)
ENERKAD	Energy assessment tool for urban scenarios that performs energy and environmental simulations. Through energy simulation, ENERKAD calculates the annual and hourly energy demand and consumption at building, district or city level, allowing the analysis and comparison of current and future scenarios based on the	It has an easy-to-use interface based on QGIS, facilitating the visualisation of the results obtained, helping to make decisions to reduce energy consumption and CO_2 emissions and promoting sustainability. It is based on the so-called Building Stock Models (BSM) and allows calculating on an hourly basis the energy demand, energy consumption and environmental emissions associated with such	ENERKAD

	application of different strategies.	consumption for each building in a city, using data from the cadastre and basic cartography. This data is combined with information such as building envelope characteristics, consumption patterns and climate information for the area, among others, to characterize the model as a whole.	
LEAP-OSeMOSYS	Modelling tool based on an accounting framework (energy balances) and parametric simulation of energy flows. Its foundation is based on the idea of scenario analysis.	LEAP allows the analysis of energy consumption, production and resource extraction in all sectors of the economy, as well as emissions. Its versatility allows analyses to be carried out on any scale (from local and regional to national and supranational). Depending on the behavioural rules chosen, behaviour based on sectoral or technological activity can be introduced, as well as deterministic relationship rules on how entities consume/produce energy. Coupling with OSeMOSYS or NEMO allows for optimisation (cost minimization subject to constraints).	LEAP-OSeMOSYS
SIAM_EX	Sustainability Impact Assessment Model for Extremadura (SIAM_EX) is an extended (social, economic and environmental) multiregional input-output model with detail at regional level from the EUREGIO Database.	The model allows a complete assessment of socio-economic impacts by productive sectors, ranging from the generation of added value (wages and benefits), to the identification of wage income generated by income quintiles or by population density, as well as to indicators of employment generated by gender, age, occupation or education attained.	PEIEC 2030 – Integrated Plan of Energy and Climate for Extremadura (Spain) 2030
FISA	Framework for Integrated Sustainability Assessment (FISA) is based on a combination of a multiregional input-output analysis (MRIO) and a social risk database entitled "Social Hotspots Database" (SHDB)	The combined framework allows for the simultaneously capture of the socioeconomic and environmental impacts as well as the social risks involved within the supply chain of projects.	Rodríguez-Serrano et al. (2017a, 2017b)
TIMES-Spain	Energy optimisation model of the TIMES family representing the Spanish energy system. TIMES (The Integrated MARKAL-EFOM System) (IEA-ETSAP, 2020) is a generator of optimisation models to estimate long-term and multi-period energy dynamics developed by the IEA in the frame of the ETSAP	TIMES optimisation models aim to provide energy services at the lowest cost by simultaneously making investment and operating decisions in equipment, primary energy supply and energy trading. The investment decisions made by the models are based on the analysis of the characteristics of alternative generation technologies, on the economic analysis of energy supply, and on environmental criteria.	The TIMES-Spain energy model has been developed by CIEMAT within the framework of several European projects (NEEDS project https://cordis.europa.eu/project/id/502687; RES2020 project https://ec.europa.eu/energy/intelligent/projects/en/projects/res2020 REACCESS project https://cordis.europa.eu/project/id/212011) Information of the model can be found in García-Gusano (2014) and Labriet et al. (2010)

	Technology Collaboration Programme.		

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