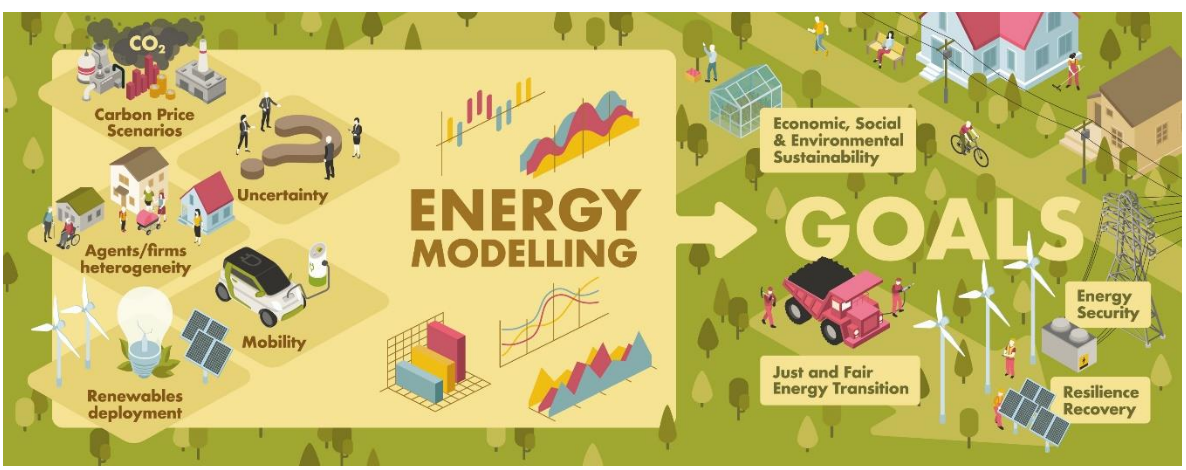
Energy-socio-economic-environmental modelling for the EU energy and post-COVID-19 transitions

Cazcarro, Ignacio[1,6]; García-Gusano, Diego[2]; Iribarren, Diego[3]; Linares, Pedro [4]; Romero, José Carlos [4]; Arocena, Pablo[5]; Arto, Iñaki[6]; Banacloche, Santacruz[7]; Lechón, Yolanda[7]; Miguel, Luis Javier[8]; Zafrilla, Jorge[9]; López, Luis-Antonio[9]; Langarita, Raquel [10]; Cadarso, María-Ángeles[9*]

[1] ARAID (Aragonese Agency for Research and Development), Agrifood Institute of Aragon (IA2). Department of Economic Analysis. Faculty of Economics and Business Studies, University of Zaragoza, Zaragoza (Spain)
[2] TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea Building 700, 48160 Derio, Bizkaia (Spain)
[3] Systems Analysis Unit, IMDEA Energy, 28935 Móstoles (Spain)
[4] Instituto de Investigación Tecnológica, Universidad Pontificia Comillas. Madrid (Spain)
[5] Institute for Advanced Research in Business and Economics (INARBE), Universidad Pública de Navarra (UPNA), Campus de Arrosadia, 31006 Pamplona/Iruña (Spain)
[6] Basque Centre for Climate Change (BC3), Scientific Campus of the University of the Basque Country, 48940 Leioa (Spain)
[7] CIEMAT. Unidad de Análisis de Sistemas Energéticos, Avda. Complutense 40, 28040 Madrid (Spain)
[8] Research Group on Energy, Economics and System Dynamics (GEEDS), University of Valladolid, Paseo Del Cauce 59, 47011 Valladolid (Spain)
[9] Global Energy and Environmental Economics Analysis Research Group (GEAR), University of Castilla-La Mancha, Department of Economics and Finance, Plaza de la Universidad 1, 02071 Albacete (Spain)
[10] University of Zaragoza. Department of Economic Analysis. Faculty of Economics and Business Studies, Zaragoza (Spain)
* Corresponding author: angeles.cadarso@uclm.es

https://doi.org/10.1016/j.scitotenv.2021.150329



Highlights

- Multidisciplinary modelling is required to conduct a resilient energy transition
- Policies' aim should not be limited to short-term maintenance of jobs and growth
- Decarbonization and sustainability must be the drivers for policy action
- Energy transition needs to assess potential impacts on social aspects
- Energy modelling is called for including new features and extreme scenarios

Abstract

Relevant energy questions have arisen because of the COVID-19 pandemic. The pandemic shock leads to emissions' reductions consistent with the rates of decrease required to achieve the Paris Agreement goals. Those unforeseen drastic reductions in emissions are 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. Focusing on the EU, this discussion article argues how recovery plans are an opportunity to deepen the way towards a low-carbon economy, improving at the same time employment, health, and equity and the role of modelling tools. 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 precious 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 and incorporate uncertainty analysis. All these instruments will evaluate 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 the Governments of the Member States (MS) have announced and developed many 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, delivered in July 2021 (EC, 2021e). 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 a 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, 2021f), outlining how they will invest the funds, and how they will contribute to a sustainable, equitable, green and digital transition. The reforms and investments

[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).

included in the plans should be 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 most extensive 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 policy-makers 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 policy-makers in managing an efficient, secure, and fair energy transition. It is organized 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 analyze 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 decarbonization. The energy transition as an engine of recovery can lead to large investments in clean energy technologies. According to the priorities of the GRPs, mobilization of funds will mainly focus

[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, 2021g).

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 neutralize 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 prioritize 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?

[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, penalizing 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 decarbonization (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 digitization. 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 electrolyzers, 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 decarbonize 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, incentivizing 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 optimizers, 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/optimization, 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 optimizing 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 optimization 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].

[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 analyze, 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 analyzing 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, dematerialization, 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 policy-makers to make informed decisions. We emphasize the need for consistency with integrated modelling approaches that consider uncertainty, non-optimizing 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 hybridizing 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.

Funding information

All the authors belong and thank the support to the MENTES network on Energy Modelling for a Sustainable Energy Transition, by the Spanish Ministry of Science, Innovation and Universities (project/grant RED2018-102794-T).

I.A. and I.C. thank the support of the Spanish Ministry of Science, Innovation and Universities (MALCON, RTI2018-099858-A-I00), the Spanish State Research Agency through María de Maeztu Excellence Unit accreditation 2018-2022 (Ref. MDM-2017-0714) and Basque Government BERC Programme. L.J.M., I.A. and I.C. gratefully acknowledge the project LOCOMOTION H2020-LC-CLA-2018-2 (No 821105) and L.J.M. MODESLOW, funded under the Spanish National Research, Development and Innovation Programme (Ministry of Economy and Competitiveness of Spain, ref. ECO2017-85110-R). I.C. and R.L thank the Spanish Ministry of Science, Innovation and Universities (PID2019-106822RB-I00). M.A.C., L.A.L. and J.Z. thank the support of the University of Castilla-La Mancha and the European Fund for Regional Development (FEDER) (Ref. 020-GRIN-29137). P.L. gratefully acknowledges the support of project RTI2018-093692-B-I00 by the Spanish Ministry of Science and Innovation (MCI), the National Research Agency (AEI) and the European Fund for Regional Development (FEDER). Y.L. and S.B. gratefully acknowledge the support of project MUSTEC, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 764626.

References

Antal, M., van den Bergh, J.C.J.M., 2014. Re-spending rebound: A macro-level assessment for OECD countries and emerging economies. Energy Policy 68, 585-590. https://doi.org/10.1016/j.enpol.2013.11.016

Banacloche, S., Gamarra, A.R., Téllez, F., Lechón, Y., 2020. Market Uptake of Solar Thermal Electricity through Cooperation Deliverable 9.1: Sustainability assessment of future CSP cooperation projects in Europe.

Barbier, E.B., 2010a. How is the Global Green New Deal going? Nature 464, 832-833. https://doi.org/10.1038/464832a

Barbier, E.B., 2010b. A Global Green New Deal: Rethinking the Economic Recovery. UN Environment Programme.

Bauhardt, C., 2014. Solutions to the crisis? The Green New Deal, Degrowth, and the Solidarity Economy: Alternatives to the capitalist growth economy from an ecofeminist economics perspective. Ecol. Econ. 102, 60-68. https://doi.org/10.1016/j.ecolecon.2014.03.015

Cambridge Econometrics, 2019. E3ME Manual: Version 6.0.

Campiglio, E., 2014. Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy.

CAT, 2020. A government roadmap for addressing the climate and post COVID-19 economic crises.

Courtney, H., Kirkland, J., Viguerie, P., 1997. Strategy under uncertainty. Harvard Bus. Rev. Nov-Dec.

Cowen, T., 2021. The Best Way to Judge Any Green Energy Policy. Bloom. Opin.

EC, 2020. European Economic Forecast – Spring 2020. Statistical annex. https://doi.org/10.1787/empl_outlook-2015-10-en

EC, 2021a. Statistics Eurostat. GDP.

EC, 2021b. Statistics Eurostat. Employment.

EC, 2021c. Statistics Eurostat. Deficit.

EC, 2021d. Eurostat. CO_2 emissions from energy use clearly decreased in the EU in 2020. Products Eurostat News.

EC, 2021e. 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. Communication from the European Commission. COM(2021) 550 final. Brussels, 14.7.2021.

EC, 2021f. The Recovery and Resilience Facility.

EC, 2021g. The EU's 2021-2027 long-term budget & NextGenerationEU.

Escribano, G., Lázaro, L., Bersalli, G., Lilliestam, J., 2020. Geopolitics and energy security of CSP deployment for domestic use and intra-European trade in the time of COVID-19. Deliverable 9.2 MUSTEC project.

EU, 2020. Standard Eurobarometer: Public Opinion in the European Union.

European Commission, 2018. Communication from the Commission to the European Parliament, the European Council, the Council, the European Central Bank, the European Economic and Social Committee and the Committee of the Regions Action Plan: Financing Sustainable Growth.

Forster, P.M., Forster, H.I., Evans, M.J., Gidden, M.J., Jones, C.D., Keller, C.A., Lamboll, R.D., Quéré, C. Le, Rogelj, J., Rosen, D., Schleussner, C.-F., Richardson, T.B., Smith, C.J., Turnock, S.T., 2020. Current and future global climate impacts resulting from COVID-19. Nat. Clim. Chang. https://doi.org/10.1038/s41558-020-0883-0

Galvin, R., Healy, N., 2020. The Green New Deal Is More Relevant Than Ever. Sci. Am. Obs. | Opin.

Greening, L.A., Green, D.L., Difiglio, C., 2000. Energy efficiency and consumption—The rebound effect—A survey. Energy Policy 28, 389–401.

Guan, D., Wang, D., Hallegatte, S., Huo, J., Li, S., Liang, X., Xu, B., Lu, X., Wang, S., Hubacek, K., Gong, P., 2020. Global economic footprint of the COVID-19 pandemic. Res. Sq. (Preprint). https://doi.org/10.21203/rs.3.rs-25857/v1

Guerriero, C., Haines, A., Pagano, M., 2020. Health and sustainability in post-pandemic economic policies. Nat. Sustain. 3, 494-496. https://doi.org/10.1038/s41893-020-0563-0

IEA-ETSAP, 2020. The IEA-ETSAP methodology (the TIMES energy system model).

IEA, 2021. Global Energy Review: CO2 Emissions in 2020.

IEA, 2020a. European Union 2020. Energy Policy Review.

IEA, 2020b. World Energy Investment 2020.

Jevons, W.S., s. f. The Coal Question; An Inquiry concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-mines, Second edi. ed. MacMillan and Co, London.

Khazzoom, J.D., 1980. Economic Implications of Mandated Efficiency Standards for Household Appliances. Energy J. 1, 21–40. https://doi.org/10.5547/issn0195-6574-ej-vol1-no4-2

Kratena, K., Streicher, G., Salotti, S., Sommer, M., Valderas Jaramillo, J., 2017. FIDELIO 2: Overview and theoretical foundations of the second version of the Fully Interregional Dynamic Econometric Long-term Input- Output model for the EU-27. https://doi.org/10.2760/313390

Kratena, K., Streicher, G., Temurshoev, U., Amores, A.F., Arto, I., Mongelli, I., Neuwahl, F., Rueda-Cantuche, J.M., Andreoni, V., 2013. FIDELIO 1: Fully Interregional Dynamic Econometric Long-term Input-Output Model for the EU27, JRC Scientific and Policy Reports. https://doi.org/10.2791/17619

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F., Peters, G.P., 2020. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. Nat. Clim. Chang. 10, 647-653. https://doi.org/10.1038/s41558-020-0797-x

Linares, P., 2020. Natural Gas News Can We Use The Covid-19 Crisis To Move Towards A More Sustainable Economy? Oxford Inst. Energy Stud. A Q. J. debating energy issues policies.

Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the TIMES Model PART I.

Maxwell, D., Owen, P., McAndrew, L., Muehmel, K., Neubauer, A., 2011. Addressing the Rebound Effect, a report for the European Commission DG Environment. 26 April 2011.

McCollum, D.L., Gambhir, A., Rogelj, J., Wilson, C., 2020. Energy modellers should explore extremes more systematically in scenarios. Nat. Energy 5, 104-107. https://doi.org/10.1038/s41560-020-0555-3

McKibbin, W.J., Fernando, R., 2020. The Global Macroeconomic Impacts of COVID-19: Seven Scenarios. SSRN Electron. J. 1-43. https://doi.org/10.2139/ssrn.3547729

Micale, V., Macquarie, R., 2020. How the coronavirus recovery effort can support a European Green Deal. Clim. Home News.

Mintz-Woo, K., Dennig, F., Liu, H., Schinko, T., 2020. Carbon pricing and COVID-19. Clim. Policy (in press). https://doi.org/10.1080/14693062.2020.1831432

MTE, 2020. National Integrated Energy and Climate Plan (PNIEC) 2021-2030, Gobierno de España.

Navas-Anguita, Z., García-Gusano, D., Iribarren, D., 2020. Long-term production technology mix of alternative fuels for road transport: A focus on Spain. Energy Convers. Manag. 226, 113498. https://doi.org/10.1016/j.enconman.2020.113498.

Obergassel, W., Hermwille, L., Oberthür, S., 2020. Harnessing international climate governance to drive a sustainable recovery from the COVID-19 pandemic. Clim. Policy (in press). https://doi.org/10.1080/14693062.2020.1835603

OECD, 2020. OECD Policy Responses to Coronavirus (Covid-19): Evaluating the initial impact of COVID-19 containment measures on economic activity.

OJEU (Official Journal of the European Union), 2020. REGULATION (EU) 2020/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088.

OJEU (Official Journal of the European Union), 2018. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance).

Oxford_Economics, 2020. World Economic Prospects (March, April, May/June) 2020.

Patel, R., Goodman, J., 2020. The Long New Deal. J. Peasant Stud. 47, 431-463. https://doi.org/10.1080/03066150.2020.1741551

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. 33, 74-86. https://doi.org/https://doi.org/10.1016/j.rser.2014.02.003

Pianta, S., Brutschin, E., van Ruijven, B., Bosetti, V., 2021. Faster or slower decarbonization? Policy-maker and stakeholder expectations on the effect of the COVID-19 pandemic on the global energy transition. Energy Res. Soc. Sci. 76, 102025. https://doi.org/10.1016/j.erss.2021.102025

Pollitt, H., Lewney, R., Kiss-Dobronyi, B., Lin, X., 2020. A post-Keynesian approach to modelling the economic effects of Covid-19 and possible recovery plans.

Prina, M.G., Manzolini, G., Moser, D., Nastasi, B., Sparber, W., 2020. Classification and challenges of bottom-up energy system models - A review. Renew. Sustain. Energy Rev. 129, 109917. https://doi.org/10.1016/j.rser.2020.109917

Salter, E., 2020. Coronavirus Recovery Needs a Green New Deal. Tribune.

Schumacher, I., Cazcarro, I., Duarte, R., Sarasa, C., Serrano, A., Xepapadeas, A., Freire-González, J., Vivanco, D.V., Peña-Lévano, L.M., Escalante, C.L., López-Feldman, A., Chávez, C., Vélez, M.A., Bejarano, H., Chimeli, A.B., Féres, J., Robalino, J., Sal, A., 2020. Perspectives on the Economics of the Environment in the Shadow of Coronavirus. Environ. Resour. Econ. 76, 447-517. https://doi.org/10.1007/s10640-020-00493-2

Shan, Y., Ou, J., Wang, D., Zeng, Z., Zhang, S., Guan, D., Hubacek, K., 2021. Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. Nat. Clim. Chang. 11, 200-206. https://doi.org/10.1038/s41558-020-00977-5

Solé, J., Samsó, R., García-Ladona, E., García-Olivares, A., Ballabrera-Poy, J., Madurell, T., Turiel, A., Osychenko, O., Álvarez, D., Bardi, U., Baumann, M., Buchmann, K., Capellán-Pérez, Černý, M., Carpintero, De Blas, I., De Castro, C., De Lathouwer, J.D., Duce, C., Eggler, L., Enríquez, J.M., Falsini, S., Feng, K., Ferreras, N., Frechoso, F., Hubacek, K., Jones, A., Kaclíková, R., Kerschner, C., Kimmich, C., Lobejón, L.F., Lomas, P.L., Martelloni, G., Mediavilla, M., Miguel, L.J., Natalini, D., Nieto, J., Nikolaev, A., Parrado, G., Papagianni, S., Perissi, I., Ploiner, C., Radulov, L., Rodrigo, P., Sun, L., Theofilidi, M., 2020. Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model. Renew. Sustain. Energy Rev. 132, 37-49. https://doi.org/10.1016/j.rser.2020.110105

Sorrell, S., Dimitropoulos, J., 2008. The rebound effect: Microeconomic definitions, limitations and extensions. Ecol. Econ. 65, 636-649. https://doi.org/https://doi.org/10.1016/j.ecolecon.2007.08.013

Sorrell, S., Dimitropoulos, J., Sommerville, M., 2009. Empirical estimates of the direct rebound effect: A review. Energy Policy 37, 1356-1371. https://doi.org/https://doi.org/10.1016/j.enpol.2008.11.026

Tukker, A., Dietzenbacher, E., 2013. Global multiregional input-output frameworks: an introduction and outlook. Econ. Syst. Res. 25, 1-19. https://doi.org/10.1080/09535314.2012.761179

UNEP, 2009. Rethinking the Economic Recovery: A Global Green New Deal. Environment.

UNEP/SETAC Life Cycle Initiative, 2011. Towards a Life Cycle Sustainability Assessment. Making informed choices on products.

Werth, A., Gravino, P., Prevedello, G., 2021. Impact analysis of COVID-19 responses on energy grid dynamics in Europe. Appl. Energy 281, 116045. https://doi.org/https://doi.org/10.1016/j.apenergy.2020.116045

Wiedmann, T., Barrett, J., 2013. Policy-relevant applications of environmentally extended MRIO databases - experiences from the UK. Econ. Syst. Res. 25, 143-156. https://doi.org/10.1080/09535314.2012.761596

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 decarbonization Strategy (ELP 2050) or the "Long-term Strategy" for specific sectors. Also used by the European Commission to analyze 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 optimization 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, decarbonization, 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 visualization 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 optimization (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 optimization model of the TIMES family representing the Spanish energy system. TIMES (The Integrated MARKAL-EFOM System) (IEA-ETSAP, 2020) is a generator of optimization models to estimate long-term and multi-period energy dynamics developed by the IEA in the frame of the ETSAP	TIMES optimization 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.		

Appendix references

Arto, I., González-Eguino, M., Rodríguez-Zuñiga, A., Tomás, M., 2019. Impacto económico de la rehabilitación energética de viviendas en España en el periodo 2021-2030. Estudio (07) para la ERESEE 2020 "Estrategia a largo plazo para la Rehabilitación Energética en el Sector de la Edificación en España". Ministerio de Fomento, Subdirección General de Políticas Urbanas, Dirección General de Arquitectura, Vivienda y Suelo.

Arto, I., Kratena, K., Amores, A.F., Temurshoev, U., Streicher, G., 2015. Market-based instruments to reduce air emissions from household heating appliances. Analysis of scrappage policy scenarios. European Com- mission, Joint Research Centre, Institute for Prospective Technological Studies. ISBN 978-92-79-50850-9.

Cazcarro, I.; Duarte, R., Sánchez Chóliz, J., Sarasa, C. and Serrano, A. (2014): "Environmental footprints and scenario analysis for assessing the impacts of the agri-food industry on a regional economy. A case study in Spain". *Journal of Industrial Ecology*. DOI: 10.1111/jiec.12209

Cazcarro, I.; Duarte, R., Sánchez Chóliz, J., Sarasa, C. and Serrano, A. (2015): Modelling regional policy scenarios in the agri-food sector: A case study of a Spanish region. *Applied Economics*. DOI: 10.1080/00036846.2015.1102842.

Cazcarro, I.; Langarita, R., Sánchez Chóliz, J. and Sarasa, C. (2020). Exploring sustainable scenarios for renewable electricity: Analyzing higher electricity self-production and self-consumption using disaggregated supply and use tables. Versión previa presentada en ERSA Web Conference 2020. *Working paper*.

Doumax-Tagliavini, V.; Sarasa, C. (2018). "Looking towards policies supporting biofuels and technological change: Evidence from France". *Renewable & Sustainable Energy Reviews*, 94, 430-439. DOI: 10.1016/j.enpol.2018.03.065

Duarte Pac, R.; Mainar, A.; Sánchez-Chóliz, J. (2010). The impact of household consumption patterns on emissions in Spain, *Energy Economics*, 32(1), pages 176-185.

Duarte Pac, R.; Langarita Tejero, R.; Sánchez Chóliz, J. (2017). The electricity industry in Spain: a structural analysis using a disaggregated input-output model. *Energy*. 141, pp. 2640 - 2651. 2017. DOI: 10.1016/j.energy.2017.08.088.

Duarte Pac, R.; Sánchez Chóliz, J.; Sarasa, C. (2018). Consumer-side actions in a low-carbon economy: A dynamic CGE analysis for Spain. *Energy Policy*. 118, pp. 199 - 210. 2018. DOI: 10.1016/j.enpol.2018.03.065.

García-Gusano, D., 2014. A long-term analysis of the Spanish environmental policies using the life cycle assessment method and enegy optimization modeling.

González-Eguino, M., Arto, I., Rodríguez-Zúñiga, A., García-Muros, X., Sampedro, J., Kratena, K., Cazcarro, I., Sorman, A.H., Pizarro-Irízar, C., Sanz-Sánchez, M.J., 2020. Análisis de impacto del Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030 de España. Papeles de Economía Española, 163, 9-22.

Kratena, K., Streicher, G., Salotti, S., Sommer, M., Valderas Jaramillo, J.M., 2017. FIDELIO 2: Overview and theoretical foundations of the second version of the Fully Interregional Dynamic Econometric Long-term Input-Output model for the EU-27. European Commission, Joint Research Centre, Institute for Prospective Technological Studies. ISBN 978-92-79-66258-4.

Kratena, K., Streicher, G., Temurshoev, U., Amores, A.F., Arto, I., Mongelli, I., Neuwahl, F., Rueda-Cantuche, J.M., Andreoni, V., 2013. FIDELIO 1: Fully Interregional Dynamic Econometric Long-term Input-Output Model for the EU27. Luxembourg. European Commission. ISBN 978-92-79-30009-7.

Labriet, M., Cabal, H., Lechón, Y., Giannakidis, G., Kanudia, A., 2010. The implementation of the EU renewable directive in Spain. Strategies and challenges. Energy Policy 38. https://doi.org/10.1016/j.enpol.2009.12.015

Langarita, R.; Sánchez-Chóliz, J.; Sarasa, C.; Duarte, R.; Jiménez, S. (2017) "Electricity costs in irrigated agriculture: A case study for an irrigation scheme in Spain", *Renewable & Sustainable Energy Reviews*, 68(2), 1008-1019. DOI: 10.1016/j.rser.2016.05.075.

Langarita, R.; Duarte, R.; Hewings, G.; Sanchez-Choliz, J. (2019). Testing European goals for the Spanish electricity system using a disaggregated CGE model. *Energy*, 179, 1288 - 1301. ISSN 0360-5442. DOI: 10.1016/j.energy.2019.04.175.

Langarita, R., Cazcarro, I.; Sánchez Chóliz, J. and Sarasa, C. (2020). Modelling fiscal changes for the electricity sector using a computable general equilibrium model for Spain. 15th Conference on Sustainable Development of Energy, Water and Environment Systems – SDEWES. *Working paper*.

MITECO. 2020a. Plan Nacional integrado de Energía y Clima, PNIEC 2021-2030.

MITECO. 2020b. Impacto económico, de empleo, social y sobre la salud pública del Plan Nacional Integrado de Energía y Clima 2021-2030.

MITECO. 2020c. Estrategia de Descarbonización a Largo Plazo, 2050. Estrategia a largo plazo para una economía española moderna, competitiva y climáticamente neutra en 2050.

MITMA. ERESEE 2020, Actualización 2020 de la Estrategia a largo plazo para la Rehabilitación Energética en el Sector de la Edificación en España.

Navas-Anguita, Z., García-Gusano, D., Iribarren, D. Long-term production technology mix of alternative fuels for road transport: A focus on Spain. *Energy Conversion and Management*; 226 (2020) 113498. https://doi.org/10.1016/j.enconman.2020.113498.

Schumacher, I., Cazcarro, I., Duarte, R., Sarasa, C., Serrano, A., Xepapadeas, A., Freire-González, J., Vivanco, D.V., Peña-Lévano, L.M., Escalante, C.L., López-Feldman, A., Chávez, C., Vélez, M.A., Bejarano, H., Chimeli, A.B., Féres, J., Robalino, J., Sal, A., 2020. Perspectives on the Economics of the Environment in the Shadow of Coronavirus. Environ. Resour. Econ. 76, 447–517. https://doi.org/10.1007/s10640-020-00493-2.

Rodríguez-Serrano, I., Caldés, N., de la Rúa, C., & Lechón, Y. (2017a). Assessing the three sustainability pillars through the Framework for Integrated Sustainability Assessment (FISA): Case study of a Solar Thermal Electricity project in Mexico. Journal of Cleaner Production, 149, 1127-1143.

Rodríguez-Serrano, I., Caldés, N., de la Rúa, C., & Lechón, Y. (2017b). Assessing the three sustainability pillars through the Framework for Integrated Sustainability Assessment (FISA): Case study of a Solar Thermal Electricity project in Mexico. *Journal of Cleaner Production*, *149*, 1127-1143.