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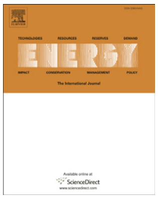

Carrying out a multi-model integrated assessment of European energy transition pathways: Challenges and benefits

F. Gardumi [a], [*], I. Keppo [b], [c], M. Howells [d], [e], S. Pye [b], G. Avgerinopoulos [a], V. Lekavičius [f], A. Galinis [f], L. Martišauskas [f], U. Fahl [g], P. Korkmaz [g], D. Schmid [g], R. Cunha Montenegro [g], S. Syri [c], A. Hast [1], U. Mörtberg [a], O. Balyk [h], K. Karlsson [i], X. Pang [a], G. Mozgeris [j], R. Trubins [k], D. Jakšić [l], I.M. Turalija [l], M. Mikulić [m]

[a] *Royal Institute of Technology, Sweden*
[b] *University College London, United Kingdom*
[c] *Aalto University, Finland*
[d] *University of Loughborough, United Kingdom*
[e] *Imperial College London, United Kingdom*
[f] *Lithuanian Energy Institute, Lithuania*
[g] *University of Stuttgart, Germany*
[h] *University College Cork, Ireland*
[i] *Svenska Miljöinstitutet, Sweden*
[j] *Vytautas Magnus University, Lithuania*
[k] *Swedish University of Agricultural Sciences, Sweden*
[l] *Energy Institute Hrvoje Požar, Croatia*
[m] *Hrvatska elektroprivreda, Croatia*

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ABSTRACT

With the publication of the European Green Deal, the European Union has committed to reaching carbon neutrality by 2050. The envisaged reductions of direct greenhouse gases emissions are seen as technically feasible, but if a wrong path is pursued, significant unintended impacts across borders, sectors, societies and ecosystems may follow. Without the insights gained from an impact assessment framework reaching beyond the techno-economic perspective, the pursuit of direct emission reductions may lead to counterproductive outcomes in the long run. We discuss the opportunities and challenges related to the creation and use of an integrated assessment framework built to inform the European Commission on the path to decarbonisation. The framework is peculiar in that it goes beyond existing ones in its scope, depth and cross-scale coverage, by use of numerous specialised models and case studies. We find challenges of consistency that can be overcome by linking modelling tools iteratively in some cases, harmonising modelling assumptions in others, comparing model outputs in others. We find the highest added value of the framework in additional insights it provides on the technical feasibility of decarbonisation pathways, on vulnerability aspects and on unintended environmental and health impacts on national and sub-national scale.

1. Introduction

With the publication of the European Green Deal, the European Union ratcheted its ambition on climate change and committed to carbon-neutrality by 2050 [1]. Though supported by many Member States, the transformational change mandated by the Green Deal also raised concerns from some. For instance, Members of the European Parliament (MEPs) from Poland reacted to the announcement by stating the need for the European Commission to work with member states [2]. MEPs from Italy highlighted the need to look at the social and economic impact of achieving climate neutrality and MEPs from France echoed the Italian proposal for a more humane social and ecological transition. Such concerns stem

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[*] Corresponding author.
E-mail address: gardumi@kth.se (F. Gardumi).

[1] Independent Researcher.

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from specific social, economic and environmental pressures, and are often not captured explicitly by the analysis supporting emission mitigation plans.

Impact assessments are mandated for major strategies and policies in the EU, including those related to emissions and energy [3,4]. These are typically based on the results of a range of modelling tools [5,6], quantifying the transitions for a set of key indicators, such as investments required, changes in the energy supply chains, energy security implications, resource use, pollution and air quality, jobs and affordability. Typically, however, such assessments miss key aspects of the transition in their analysis, both with respect to the *scope* of the issues covered, and in terms of the *depth* and *scale* of the analysis. The scope of most EU-wide assessments is restricted to a techno-economic dimension,[1] and missing a wider analysis of environmental, economic and social impacts [7–9]. In the cases in which the scope is extended, the assessments tend to lack the depth (or specificity) that can be captured generally only through case studies [10]. The case studies, in turn, provide depth, but do not capture the cascading effects and social implications of decarbonisation policies through geographical scales, from EU, to local [11]. There is a risk that these gaps limit the support models can provide to policy makers [12] and, as a consequence, affect the EU energy and decarbonisation policy agenda. This, in turn, may slow down EU's action for a just transition [13], or cause unintended and irreversible effects on resource systems [14].

To address the above gaps, a Consortium of modelling teams including the authors of this paper carried out an interdisciplinary modelling exercise, assessing through a set of transition scenarios a wide range of environmental, social and economic impacts to a low-carbon EU society. The exercise utilised an integrated assessment framework that:

- Is wide, using a broad set of tools together covering a wide range of potential impacts of decarbonisation on the EU level;
- Adds depth through context- and sector-specific case studies that are linked to the wider EU analysis on key issues;
- Covers a range of geographical scales, from global to local, to capture the cascading effects between them.

The framework is illustrated in Fig. 1. It is centred around standard techno-economic assessment tools, providing a view of the evolution of the energy supply and demand technology mix in the EU. The central energy system model is linked with several other tools that add detail on the impacts of decarbonisation over three main dimensions: economy, society and environment. For each of these three dimensions, assessments at different geographical scales, from global to local, are carried out, mainly through sector and geography specific case studies.

Individual parts of the modelling exercise and the methodologies underpinning each modelling tool are published in literature [15–23]. However, bringing all the modelling analyses together offers insights that go beyond those that individual models can give, as well as consistency challenges. These additional insights and challenges can contain key information for the research agenda of European modelling in support of decarbonisation pathways. Yet, they can be overlooked if the integrated assessment framework as a whole is not analysed.

In this paper, we aim to demonstrate the challenges, importance, and benefits of creating and using a framework simultaneously aiming to increase scope, depth and scale, to fully assess the implications of the transition to a low-carbon society.

The rest of the paper is organised as follows. Section 2 describes our approach to the analysis of the modelling framework. Section 3 presents key conclusions on the challenges and benefits of the framework and it discusses key insights that can be drawn from it. Section 4 draws the conclusions.

2. Methods

In this section we detail key steps of the process of extracting insights from the integrated assessment framework. One is the design of the decarbonisation pathways to be assessed through the framework; one is the analysis of the modelling results from the framework. We do not, in this paper, focus on each part of the integrated assessment individually (as most are described in the published literature [15–23] or in project reports [24–27]), but rather on the assessment as a whole.

2.1. Definition of narratives and key assumptions

The key differentiating characteristics of the decarbonisation pathways were defined during several stakeholder workshops, involving the modelling teams and a set of external experts. The process and methods for creating the pathway narratives was informed by morphological analysis [28].

In a first phase, the workshop participants discussed and filled in, in groups, tables where, for each one of several *dimensions* (Economy, Policy, Society, Global setting, Environment, Technology) they indicated how the future of the EU may play out (otherwise said, they indicated possible future *states*). The dimensions were pre-defined. The states for the different dimensions were determined by the participants according to their personal or institutional knowledge. The only constraint we gave for the *states* is that they should be purely explorative: they should represent possible changes in each sector and should not be chosen based on how positive or negative, or likely or unlikely, they are. The states indicated by all groups for each dimension were collected, an extract of the raw outcome of the group work is presented in Table 1. The number of states is not the same across all dimensions because the groups felt more confident about some dimensions than others. Note that the states of each dimension should be, at this stage, understood as a collection (down the column) independent of the states in other dimensions. In other words, there is no horizontal link yet across dimensions.

In a second phase, initiated during the workshop with the external experts and finalised by the modelling teams, *internally coherent* combinations of states are created, by choosing one state per dimension. In some cases, the opposite of one state is chosen, to span a broader range of outcomes (e.g. ‘passive society’ instead of ‘active society’). In most cases, the formulation of the states is slightly refined compared to the raw inputs collected during the workshops.

The output of this phase is a number of combinations, each representing manageable syntheses of assumed changes across sectors. We select some of these combinations, to cover a range of alternative developments (see Table 2).

In the following, and final, part of the exercise we create a storyline of changes across sectors in the EU for each of the chosen combinations and call it a pathway. The storyline consists of an overall title and a non-technical narration with only key numbers outlined.

The resulting narratives and related pathways are named *Coalitions for a Low-carbon path* (CL), *Local Solutions* (LS) and *Paris Agreement* (PA). CL represents a supply-focused transition, with

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[2] This was highlighted by Foulds and Christensen as a critical issue in the current EU research on pathways to a low-carbon transition and linked to the nature of EU research funding [7].

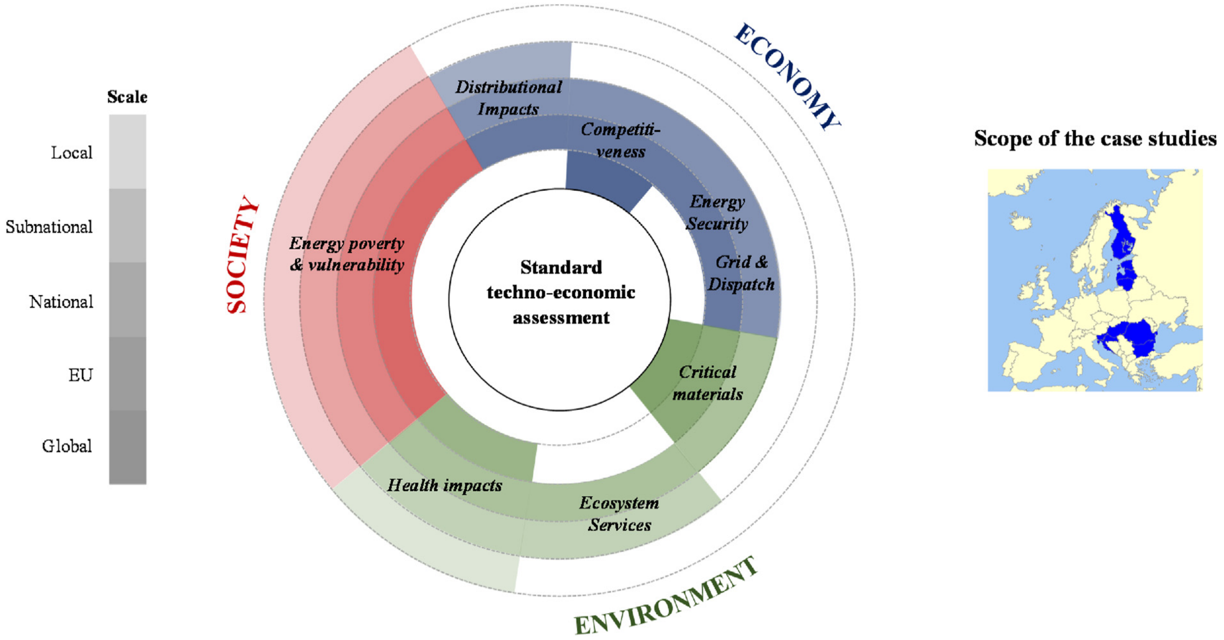

Fig. 1. Modelling framework and coverage. The economic, societal and environmental dimensions are shown in different colours. The scales are represented with different shades: the darker shade in the innermost circle represents the global scale, while the lighter shade in the outermost circle represents the local scale. The geographical scope of the case studies is shown in the map to the right.

Table 1
Sample raw outputs of the pathway definition workshops.

Economy	Policy	Society	Global setting	Environment	Technology
Increased regional disparities	Low cooperation	Active society (change of consumers' perception face climate change)	Weaker climate ambitions globally	Low water availability and scarce resources	Slower development of technologies like storage and higher reliance on fossil fuels
More divergent GDP growth	More bi-lateral cooperation (e.g. on emission targets)			Self-sufficient cities	Investments in decentralised technologies
Competitiveness of EU industries limited due to limited global climate action	Fragmented policy making			Land scarcity	Local solutions for the residential sector
Competitiveness of EU industries affected by increased global climate action					Strong technological breakthroughs

Table 2
Key elements of the pathways, divided by dimension (economy, policy, society, global setting, environment and technology).

	State		
Dimension	Coalitions for a Low-carbon path	Local Solutions	Paris Agreement
Economy	*Growth at different speeds*		*Competitiveness of the EU potentially affected by rapid shift to low-carbon economy*
Policy	*Stronger decision making/policy parallels within clusters of Member States*	*Pace of local solutions leaves policy making lagging behind in the near to medium term*	*The EU takes the lead in fulfilling its obligations under the Paris Agreement*
Society	*Passive society in the transition*	*Change of EU citizens' perception towards climate change and resulting behavioural shifts*	
Global setting	*Global push to climate change mitigation driven by some regions/countries*		*Global R&D push to climate change mitigation*
Environment	*EU's general recognition of the impacts of climate change*	*Citizens' recognition of the impacts of climate change.*	*General strong recognition of the impacts of climate change*
Technology	*Large penetration of centralised renewable energy supply options*	*Accelerated renovation of residential buildings and uptake of low-carbon technologies in households and road transport*	*Large penetration of low-carbon energy technologies both in centralised supply and at end-use level*

passive consumers reacting to policies as they emerge. Policies are not universal across the EU, but vary by groups of countries (or 'coalitions'), according to their socio-economic and geographic characteristics. In LS consumers take a leading role in the transition, leading to a rapid, non-policy driven take up of mitigation options such as low carbon energy appliances, energy efficiency measures and transportation technologies. Finally, in PA the EU undertakes a widely supported, ambitious decarbonisation effort, leading to a

95% reduction of CO_2 emissions by 2050. These narratives are used to guide the collection of numerical assumptions for each of the modelling tools of the assessment framework. The choice of numerical assumptions that are coherent with the narratives and coherent across modelling tools is where some of the greatest challenges lie. We discuss approaches and challenges in the next sections. The full narrative descriptions for the three pathways can be found in the supplementary material.

2.2. Setup of the modelling framework

The assessment of the decarbonisation pathways across the various scales, depths and geographies is supported by a modelling framework consisting of numerous tools. The extent, relevance and robustness of the insights that can be drawn from the analysis depends on the internal coherence of this framework, and on the assumptions underlying the individual models. While we push forward a multi-model and multi-scale analysis to highlight its benefits and value added, we are also aware of the challenges it presents in terms of consistency. We describe here how the modelling framework is created and what outputs it provides.

2.2.1. Synthesis of the modelling framework

Fig. 2 gives an overview of the assessment framework, the model linkages and the geographical and sectoral differences between them. It divides the modelling tools by the area of focus (techno-economic, society and environment) and by consistency with the pathway narratives. I.e. the narratives have been defined at the geographical scale of the EU and member state level, without subnational detail. The tools carrying out techno-economic modelling at the EU scale and with national resolution thus match the scale and resolution of the narratives and the assumptions of the latter can directly be turned into numerical inputs for these techno-economic tools. The tools that expand the breadth of the analysis to the social and environmental impacts also cover the EU scale, but with a different, generally higher, spatial and technological resolution. These models take inputs from the outputs of the techno-economic tools, but, due to the higher resolution, may require additional assumptions to disaggregate the inputs. The case studies focus on smaller geographical scales (sub-regions of the EU) and generally have higher spatial and technological resolution. Therefore, they have different scale and different resolution compared to the one of the pathway narratives and the central techno-economic assessment tools. They require inputs that are not available in the EU-wide pathway definitions and cannot be attained from the outputs of the techno-economic tools. Therefore, for these tools only a looser and more qualitative consistency check with the pathway narratives can be made.

The two tools at the centre of the EU-wide techno-economic assessment are the pan-European TIMES model [23,29], and the global Computable General Equilibrium model NEWAGE [30]. The TIMES model optimises the operation and investments of the full EU wide energy system up to year 2050, covering all 27 member states - and the United Kingdom, Norway and Switzerland - as distinct entities. NEWAGE is a global model, dividing the world into 18 regions of which nine are within Europe [31]. The two models are soft-linked iteratively to assess technological and economic implications of decarbonisation in the pathways. GDP projections, GVA for industrial sectors and sectoral growth for other sectors are outputs of NEWAGE fed to TIMES, and electricity production capacities by energy carrier, electricity imports and exports and CO_2 emissions and prices are outputs of TIMES fed to NEWAGE [23]. The convergence criterion for the iteration is the change in value of GDP. The iteration reaches convergence after 3 to 5 iterations, depending on the case analysed. The results of the combination of the pan-European TIMES model and the NEWAGE macroeconomic model are used as inputs for the analysis of health impacts, as detailed in Schmid et al. [20] and in the description below.

For techno-economic assessments at the regional and national scale, MESSAGE [32], OSeMOSYS [33] and PLEXOS [34] are used. The first two are used in a case study looking at the development of the electricity system in the North-East European region in national decarbonisation pathways based on the CL pathway (details in the supplementary material) [16,22]. They refine models already employed in Lithuania to support the government in the elaboration of the national energy policy [35]. The models have national resolution and cover the Baltics and Finland. Their key characteristic is that they include the contribution of different power plants

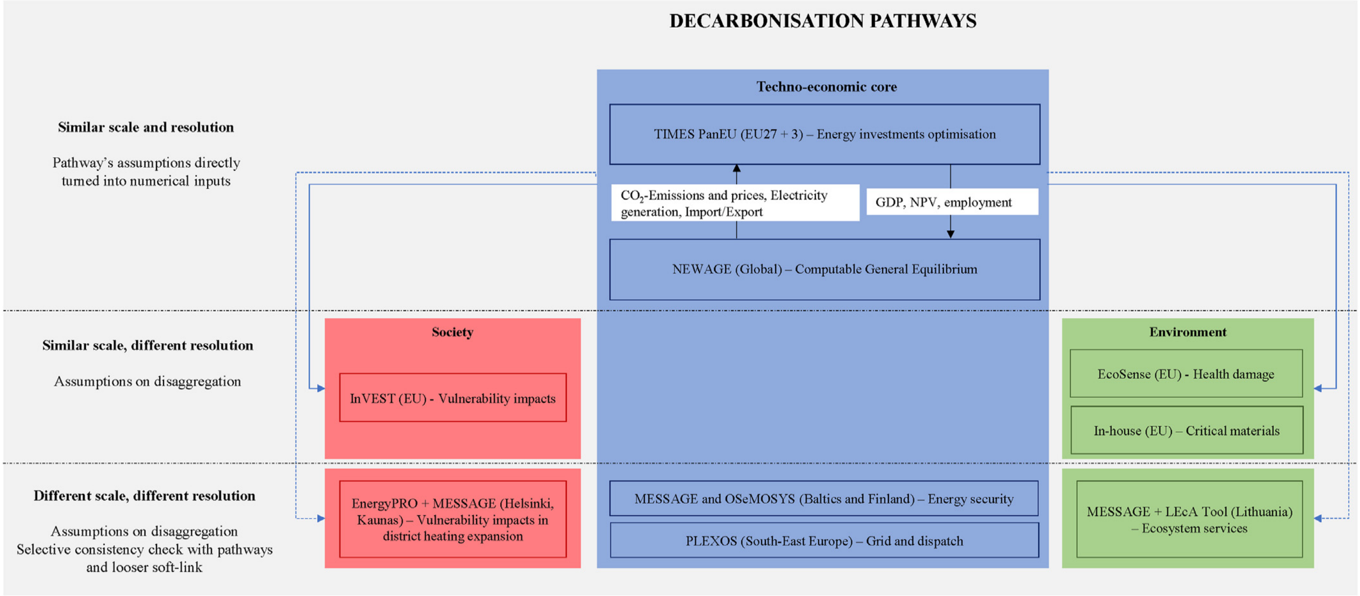

Fig. 2. Synthesis of the integrated assessment framework.

and interconnections to reserve capacity supply in the energy security study and a probabilistic representation of disruptions on the network. This differentiates them from the pan-European TIMES energy model. PLEXOS is used in a case study looking at capacity expansion in five countries in South-Eastern Europe (Bulgaria, Croatia, Hungary, Romania and Slovenia). It analyses the feasibility of dispatch in these countries in a selected year (2030) with hourly resolution, taking as input the electricity generation capacities calculated by the TIMES pan-European model for the CL pathway. The two tools are used in synergy: the existing and future technological options for electricity supply and their techno-economic characteristics are fully harmonised.

For the analysis of social impacts on the EU scale, the InVEST tool is used [24]. The tool maps out indicators of vulnerability with NUTS1 (coarser, national and sub-national level [36]) and NUTS2 (finer, provincial level [36]) resolution. The indicators capture regions already susceptible to energy poverty, based on both consensual and quantitative metrics, with high employment in energy intensive and extractive industries, and with general vulnerability due to lower incomes and longer term unemployment [24]. The link with the pan-European model here is that selected metrics at country level from the energy system analysis (such as residential energy costs, industry sector costs and investments, coal production and use) are mapped against vulnerability metrics for the three pathways. Insights are extracted from this comparison, without any aggregation or disaggregation of outputs of the pan-European model.

The analysis of social impacts on a local scale consists of a case study on District Heating systems in Kaunas (Lithuania) and Helsinki region (Finland) [17,27]. The choice of the tools for this part of the analysis falls again on tools already present and largely employed locally. For Helsinki, the tool is energyPRO, a systems optimisation tool that optimises the operation of energy systems over one year with high temporal resolution [37]. For Kaunas, the tool is MESSAGE. The use of energyPRO and the scope and temporal resolution of the model for Helsinki present interesting modelling challenges. This model and the TIMES pan-European model cannot be linked as they are: for the District Heating case, a number of parameters mostly absent in the TIMES model needs to be considered, such as the current structure of the District Heating system in Helsinki, the age of the current plants and how fast the system can realistically change in the short-to medium-term. Also the national and city level policies and plans regarding District Heating systems need to be added. All these aspects cannot be taken into account in the pan-European model, since it lacks the spatial detail needed for that. In fact, the District Heating development pathways analysed in the study fit well with the overall assumptions of all three EU and national level pathways, highlighting the different context of national and city level analysis. Yet, the pan-European model suggests least-cost system development pathways that may also affect the District Heating systems on a city scale, e.g. through energy prices and energy system structures beyond the district heating systems of the specific cities. A way to account for both system-wide and city-level changes needs to be found. Hast et al. [27] choose not to link the models directly, but to use the results of the pan-European model to guide the investments at city-scale in the medium-to long-term. In the short-term, the energyPRO model is constrained to take into account only the capacity expansion plans by municipalities and utilities, while the pan-European model is not. In 2030, the District Heating infrastructure is altered so that the changes and trends in the fuel mix are similar to those in the pan-European model's results. In 2050 the District Heating infrastructure is altered so that the fuel mix matches the least-cost one suggested by the pan-European model. In order to draw insights on the usefulness of this soft linking approach, Hast et al. [27] compare it with one where energyPRO is not linked with TIMES and used in isolation.

Finally, within the environmental dimension, aspects related to critical materials, health impacts and ecosystem services are analysed. The scope is similar to the latest integrated impact assessments run for the EU and beyond [3,10], but the modelling teams delve deeper into each type of impact through different case studies. The EcoSense tool is used for the analysis of health impacts in the whole EU (plus Norway, Switzerland and United Kingdom) under the three pathways and it is linked with the TIMES-NEWAGE core, after iteration between the latter two [20]. The national-scale emissions resulting from TIMES are used as input to EcoSense, processed through dispersion algorithms and overlapped with maps of population density and exposure to obtain health impacts with a spatial resolution of $0.25^\circ \times 0.5^\circ$ (latitude x longitude). The unit damage costs computed by EcoSense for different pollutants are fed back into the TIMES pan-European model for externalities to be optimised together with other costs. The analysis of ecosystem services focuses on Lithuania [18], under a national decarbonisation pathway loosely based on the CL pathway, and uses MESSAGE and the LEcA Tool [38]: with MESSAGE, a long-term optimisation of the energy system of Lithuania is carried out; LEcA Tool takes as input the resulting use of biomass for energy supply and evaluates its impact on the mentioned ecosystem services with a geospatial approach. On the side of critical materials, Li et al. assess the cumulative use of critical materials in the three pathways for the whole EU. They combine investments in new capacity of energy technologies resulting from the TIMES pan-European model with material demand per unit capacity of each technology as retrieved from literature [39].

2.2.2. *Analysis of the model results*

In this section we briefly analyse the key results from the various published parts of the assessment, before synthesising the benefits and challenges that the use of the framework brings with it.

2.2.2.1. Techno-economic domain. Korkmaz et al. [15] modelled the three energy system and macroeconomic pathways at EU scale. For all pathways, increases in renewable energy supply, increased electrification of economies and reduction of energy consumption emerge as central. Greatest reductions in CO_2 emissions come from transportation and industry (Fig. 3a) and electricity generation is almost entirely decarbonised by 2050 (Fig. 3b).

GDP grows in all the pathways analysed, with the lowest growth observed in the PA pathway. This is not only driven by actions in the EU, but also those of the rest of the world, reducing the demand for European exports such as non-ferrous metals, chemicals, motor vehicles and machinery (Fig. 3c). Since the largest economies and emitters (USA, China, the EU and OECD) have their own emission caps in all three pathways, the results indicate only a low risk of carbon leakage, despite the reduction in exports.

The decarbonisation of the energy system is a central component of most of the discussions at the EU level, but on the member state level other topics can reach similar importance. Energy security, and the dependence on a single source of primary energy supply, is a key concern in North-Eastern and Eastern Europe, where the shift towards renewable sources can contribute to increasing security of supply. Energy security, however, is not only a matter of supply as disruptions in the energy system can be caused by various reasons. Therefore, disruptions of various nature should be considered in planning. Martišauskas et al. investigated whether the expected development of the electricity system in the North-East European region under decarbonisation constraints changes based on how energy security is seen, using MESSAGE and OSeMOSYS [16]. They highlight challenges not captured by the EU

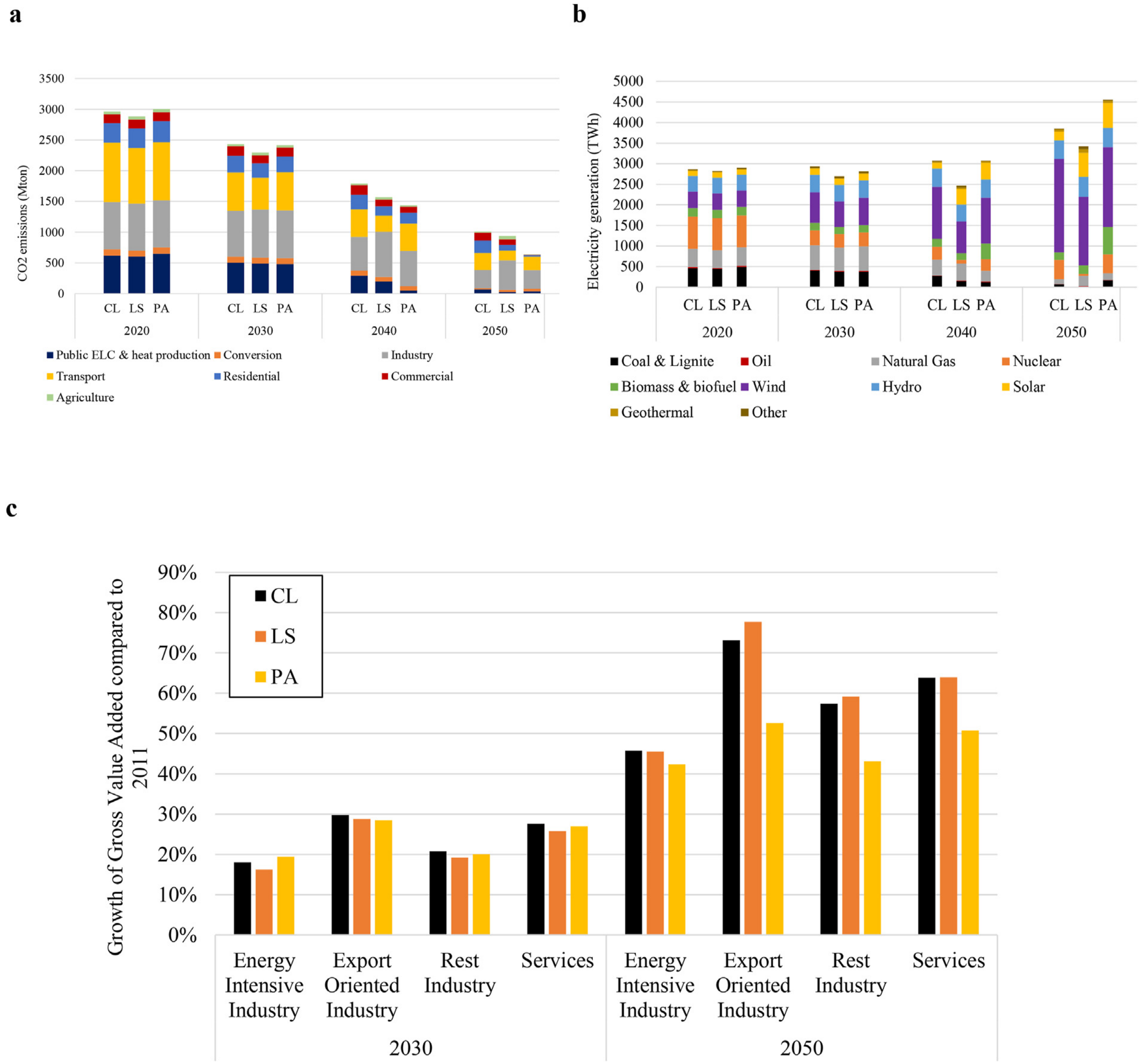

Fig. 3. Insights from the techno-economic models, on EU 27 + 3 scale, for the CL, LS and PA pathways: a) sectoral contributions to decrease of CO_2 emissions; b) Electricity generation by source; c) Growth of Gross Value Added for main sectors compared to 2011.

models, by showing the central role international interconnections could have in ensuring the provision of reserves, necessary by regulation and to backup variable renewables. According to the purely techno-economic optimisation criteria underpinning current large integrated system analyses (where reserve capacity is usually not detailed), interconnections would be used entirely for market purposes. When the need for reserves is taken into account, part of the interconnector capacity is not available for international exchange of electricity. We synthesise this result for Finland, in Fig. 4, extrapolating it from the analysis carried out in Ref. [16].

Turalija et al. [26] investigated the feasibility of the long-term power supply capacity mix indicated by the pan-European analysis, in terms of hourly operation of the grid and dispatch, using PLEXOS. This was relevant as the analysed pathways all accounted for large penetration of variable renewables across the EU and the temporal granularity of the TIMES model is somewhat coarse for modelling systems with a high share of renewables. The case study focused on five countries in South-Eastern Europe (Bulgaria, Croatia, Hungary, Romania, Slovenia), one of the areas endowed with higher variable renewable potential in the EU. The case study analysed two decarbonisation pathways for the region, in line with the CL pathway analysed at EU level: one with lower and one with higher renewable generation targets. It confirmed on a more granular level the feasibility of the CL pathway. The results do, however, also highlight trade-offs: higher renewable targets lead to higher total generation in the region and to lower wholesale electricity market prices (with associated lower profitability). These conclusions highlight the importance of adding a perspective on national system operation and market outcomes to the EU-wide system optimisation approach taken by the TIMES model. The latter includes capital costs in the system optimisation, whereas the grid and dispatch model only includes marginal costs. Higher renewable targets may have a price-depressing impact also at EU scale.

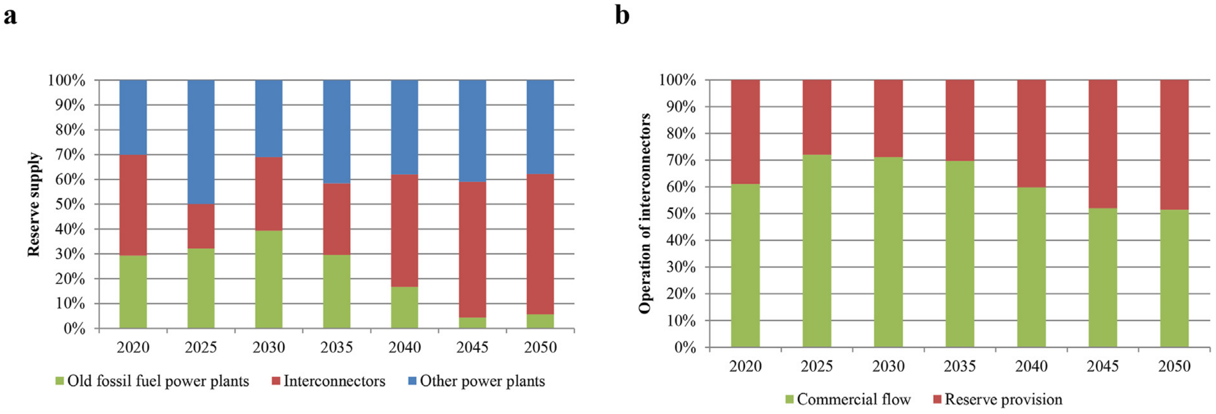

Fig. 4. Insights on energy security in Finland. a) % share of reserve supply by interconnections, old fossil fuel steam turbines and Combined Heat and Power plants and other power plants; b) Share of reserve provision and commercial flow in operation of interconnectors.

2.2.2.2. Societal domain. The energy transition is not only a techno-economic problem, but also raises a number of issues related to societal impacts, e.g. vulnerability of consumers and energy poverty [13]. Pye et al. undertook an EU wide analysis with the InVEST tool, to explore regional vulnerabilities to the low carbon transition [24]. These aspects were not highlighted in previous impact assessments [3,7,8,11].

They found that, using measures of affordability and lived experience (Fig. 5a), energy vulnerability in households is highest in Eastern and Southern Europe. Factors giving rise to this include inadequate heating systems for the colder periods of the year, as well as poor building fabric and other energy system inefficiencies especially in Eastern Europe. The scenario metrics suggest that many of the vulnerable regions may also incur higher energy costs, but also large investments related to the transition. This investment highlights the opportunities for resolving some of the underlying structural problems inherent in driving energy vulnerability (poor building stock, insufficient heating provision).

Like household energy vulnerability, also employment vulnerabilities related to extractive sectors, such as coal, are concentrated (Fig. 5b), with Poland and Germany being particularly notable. As all pathways show a rapid decline in both coal production and use, just transition planning, including training and new opportunities for the workers in these industries, is vital for the affected regions and needs to be put in place over the next decade. Similarly, certain regions have high shares of employees in energy-intensive industries, which could be affected by increased energy costs, due to global competitive pressures. Such regions exist e.g. in Eastern

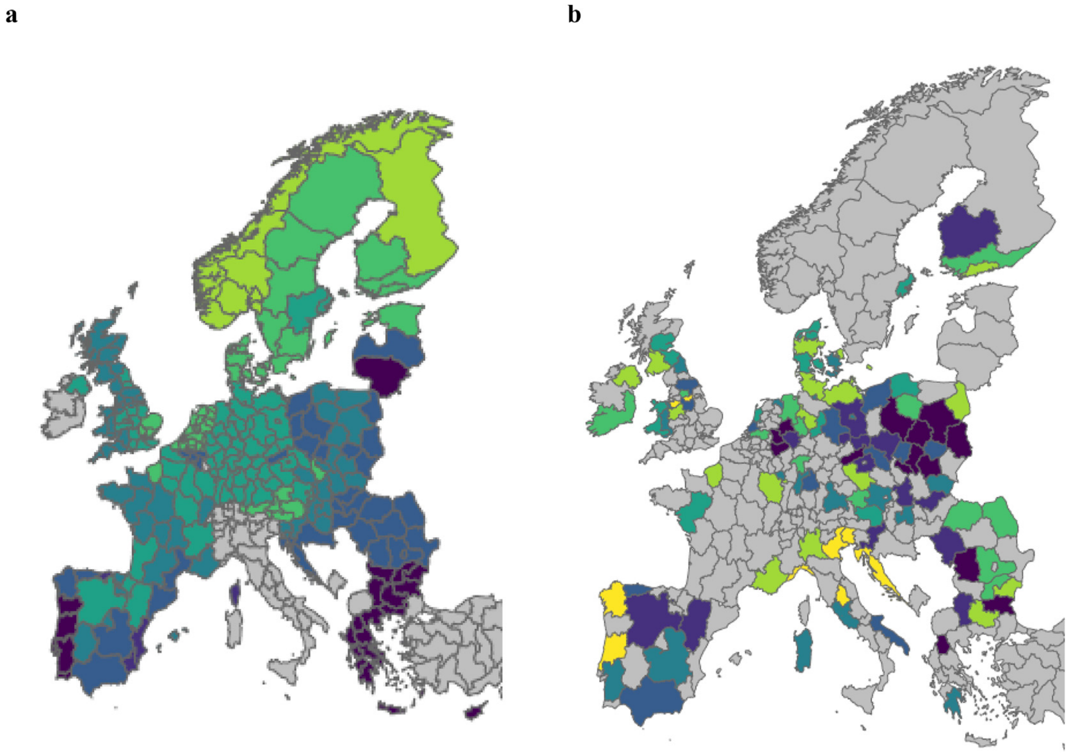

Fig. 5. Energy vulnerability across the EU. a) Adequate warmth consensual indicator: darker shades indicate a higher proportion of households struggling to adequately heat their homes; b) Coal (and peat) mining employees: darker shades indicate a higher proportion of employees in coal mining.

Europe, BENELUX, and parts of Scandinavia, and the affected sectors include metals, non-metallic minerals, paper and pulp, and to a lesser extent, chemicals. As for the residential sector, the pathways show energy cost increases for these industries, driven by investments in low carbon technologies and cleaner fuels.

Hast et al. [27] looked at vulnerability on a local scale. The case study modelled the decarbonisation plans for District Heating systems in Kaunas (Lithuania) and Helsinki region (Finland). They observed what links exist between energy poverty, affordability and specific technological changes locally in Lithuania, and compared this result to Finland. They compared results from two modelling approaches (described in section 2.2.1), one where a soft-link with TIMES is established and one where it is not. Either case leads to the same type of insight: an increase in the District Heating energy supply cost is observed in 2050. However, utilising two different approaches delivers further insights on the importance of considering different scales of analysis. By comparing the TIMES-level approach and the city-level approach, they noticed that results are different, concerning costs and fuel use in particular. A higher District Heating cost increase is seen in the TIMES-level approach than in the city-level approach. Yet, in the TIMES-level approach fossil fuels are completely phased out by 2050 while also natural gas is used in District Heating production in the city-level approach. This suggests that the decarbonisation of District Heating supply is achieved with lower costs when city-specific situations and characteristics are taken into account more closely and burning of fossil fuels is allowed. Hast et al. also simulated the potential impacts of selected District Heating price changes on energy poverty levels in the aforementioned urban areas [27]. For comparability, they applied in this part of the analysis the same price increase of 25% to the two urban areas. The impact of rising energy prices in Kaunas confirms the trend seen at a national and broader level, i.e. the increased exposure of households to the risks of non-affordable supply. Delving into the local scale unveiled however the importance of local plans for the development of specific technologies in determining these effects. In Kaunas, where energy poverty is higher among households that use district heating than among those that do not, the rising district heating prices will hit many of the already vulnerable customers. Up to 46% of the households using District Heating could end up spending more than 10% of their income on energy, one of the indicators the authors chose for considering a household energy poor. Much milder effects are seen in Helsinki, where the level of energy poverty among households connected to District Heating is lower than the national average. Therefore, any action that increases District Heating energy cost in Kaunas would be socially sensitive, whereas it would be less so in Helsinki.

2.2.2.3. Environmental domain. A low carbon energy transition may increase the use of critical materials. However, by analysing the results of the TIMES pan-European model for the three pathways, Li et al. [39] showed that the specific technologies driving this increased use and the related materials depend on the specific technology pathway. Their analysis found that the highest increase in demand for critical materials could be driven by electrification of transport (the main driver of critical material demand increase) and especially materials like cobalt, neodymium and dysprosium could present the highest supply risk. As a comparison, Luderer et al. found in their global study materials needed for wind turbines and solar PV to form the largest bottleneck [10]. Technology detail and spatial disaggregation are important for determining which value chains may cause material depletion under which futures.

For health impacts, Schmid et al. [20] assessed the impacts on life expectancy of the emission of pollutants, such as SO_2, NO_x, NH_3, Non-Methane Volatile Organic Compounds (NMVOC), $PM_{2.5}$ and PM_{10}, in the three decarbonisation pathways. They further monetised these impacts. Driven by the decarbonisation policies, the emission of pollutants, such as SO_2, NO_x, NH_3, Non-Methane Volatile Organic Compounds (NMVOC), $PM_{2.5}$ and PM_{10} decrease, as do the related impacts on human health. This is consistent with what has been found in previous assessments [3,10]. By monetising the impacts on life expectancy and including them in the cost-minimisation function of the TIMES energy system model, Schmid et al. identified decreases of the health costs between 76 and 84 billion € in 2050 compared to 2015 across the three pathways. This is less than what the Clean Planet for All analysis found (140–340 billion €), reflecting the high degree of uncertainty in assessments like this [40]. The pathways achieve a relative reduction in health impacts of about 35% which is in line with the 40% decrease in premature deaths stated in the Clean Planet for All assessment. A closer look at results for individual countries [41] shows, however, that the changes in health impacts are not evenly distributed; while there is a decrease for some countries (particularly in Central-Eastern Europe areas, e.g. Poland), the impacts may even increase for others (especially Southern Europe, e.g. Slovakia and Greece) (Fig. 6a). This 'transfer' of impacts derives from socio-economic differences between Member States such as assumed economic growth and associated industrial production, the potential to invest in different kinds of renewable energy sources and different country specific long-term greenhouse gases reduction targets. The interplay of these factors leads to increasing emissions of air pollutants in Southern Europe.

Finally, for ecosystem services Pang et al. [18,25] took again the case study of Lithuania, where biomass could have a significant role in the future energy supply matrix. They analysed the implications of intensive biomass harvesting for energy uses in Lithuania for five ecosystem services: provision of forest bioenergy feedstock, provision of industrial wood, carbon storage in the forest, recreation area and habitat supporting biodiversity. They compared two forest management strategies that could be used under decarbonisation trajectories for Lithuania in line with all the transition pathways analysed (CL, LS and PA): a Business as Usual strategy (BAU), representing a forest management strategy applied in Lithuania during the period 1998–2015; an Intensive forest management strategy (INT), where the harvesting probability is increased and hence the average harvest age decreased (but kept above legal limits). They found that the national decarbonisation targets are met with increased use of biomass for energy. The increase in the analysed pathways is mostly due to the use of woody biomass for electricity and heat generation, and from importing biofuels for transportation. The use of domestic woody biomass can bear long-term consequences, even when technically exploitable biomass potentials are not exceeded and the carbon sinks are maintained. Under the BAU strategy in the Lithuanian case study on ecosystem service impacts, the use of bioenergy increases by 2050 by more than 30% for both bioenergy and industrial wood. Following the INT strategy, these levels are reached already in 2020, and sustained thereafter. Results show that while carbon storage is only mildly affected by the management strategy, the habitat network size declines are much more closely linked to the choice of strategy. With the BAU strategy, the habitat network size drops by about 10% by 2020 and recovers by 2040, whereas the INT strategy leads to a decline of 40% by 2020 and does not recover by 2050. Such drops in habitat network size may be detrimental to forest biodiversity, since population sizes of sensitive species may become too low to recover at all (Fig. 6b and c).

3. Insights

The main insights of this work are two-fold. The first set of

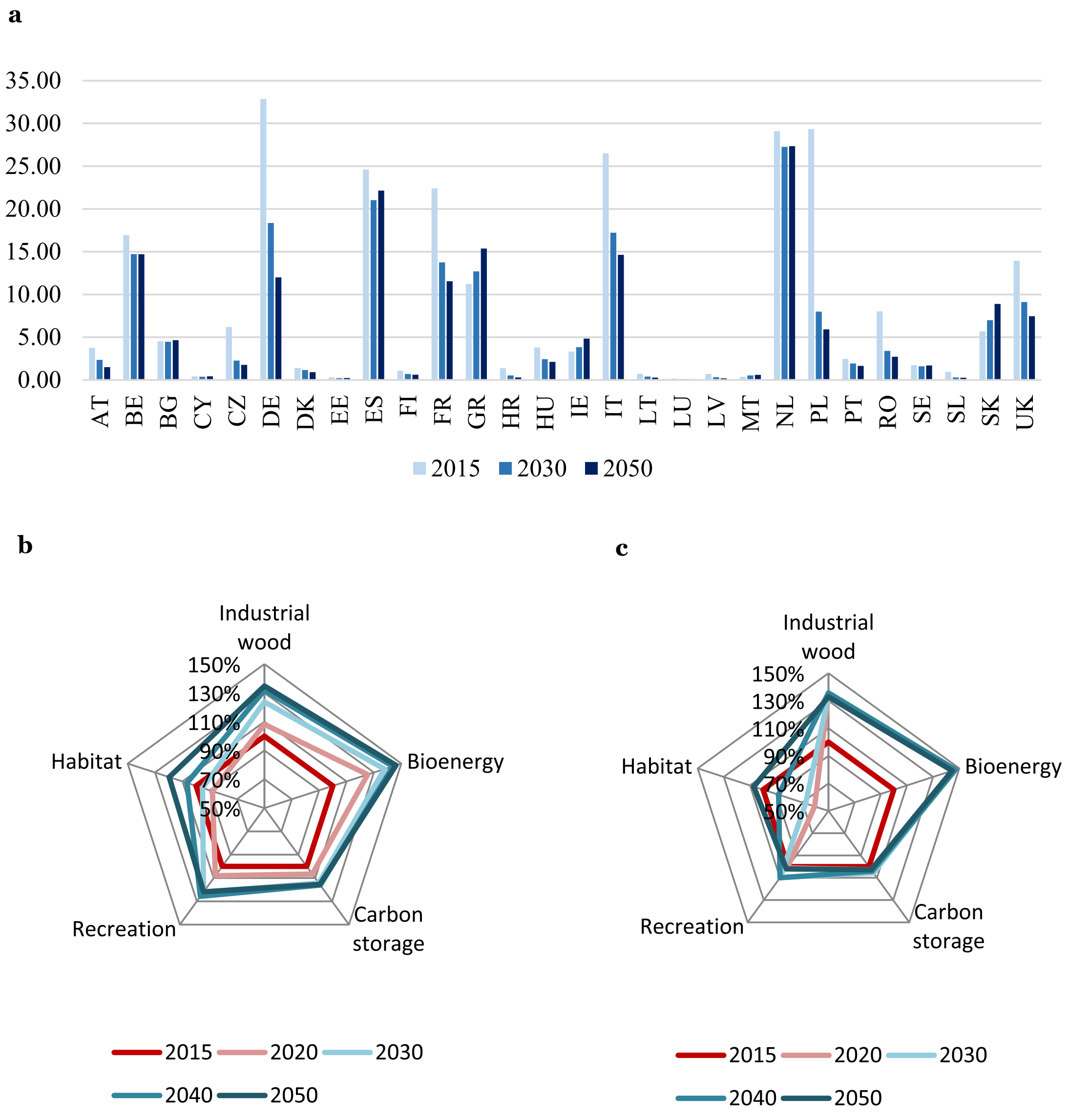

Fig. 6. Insights on the environmental and resources domain: a) Monetised health impacts per country in the PA pathway; b) Impacts on ecosystem services in Lithuania, for BAU forest management strategy; c) Impacts on ecosystem services in Lithuania, for INT forest management strategy.

insights is a collection of experiences on the challenges, benefits and limitations of connecting the numerous modelling tools (and case-study-specific models) in an integrated assessment framework. We discuss solutions we adopted to overcome potential inconsistencies of connecting models with different geographic scales and technological resolutions; we also discuss how the extraction of insights must consider as valid only those insights that come from coherent sets of assumptions. The second set of results showcases a selection of insights that are specific to the integrated framework and would be missed if the model results were analysed only separately.

3.1. Challenges and opportunities in the process of linking models

The number of distinct tools constituting the integrated framework used for analysis in this study - and their specific foci (i.e. detailed case studies and specific issues outside of the reach of more aggregated tools) - distinguish the framework from others commonly used. Using several more focused models provides the flexibility to zoom into specific aspects of the energy system transition, increasing the relevance for local stakeholders and policymakers. The inclusion of locally designed and modelled case studies, reflecting the EU wide scenario developments, supports the same objective. Connecting several tools like TIMES, NEWAGE and EcoSense allows the breadth of scope to be increased. All of this, however, also leads to a need for collecting input data for assumptions across sectors, geographies and scales, for harmonising the assumptions across the models to the extent possible and for excluding insights emerging from potential inconsistencies across the models.

Starting from the EU-wide techno-economic analysis, the iterative linking between TIMES and NEWAGE increases the coherence of at least a set of variables, compared to mono-directional soft-links: the energy investments computed by the pan-European energy system model take into account an evolving economic context (affecting energy demands) and vice versa. The two models are also well aligned to the pathway narratives, which are designed to take into account global, EU-wide and overall national developments.

Together, these models provide a coherent assessment of the evolution of the energy supply and demand technology mix in the EU and several economic implications of this evolution. The iterative linking is computationally efficient and it overcomes some consistency issues that come with mono-directional links. It must be noted, however, that the two models cannot be fully coherent, since their geographical boundaries are different (global for NEWAGE, EU-wide for the TIMES pan-European model) and the decision making rationale is different.

The analysis of the impacts of the decarbonisation pathways on energy poverty and vulnerability of consumers (social impacts) and on emissions and health (environmental impacts) is carried out using and processing direct outputs of the above techno-economic core, at the same geographic scale (EU) but at higher resolution. The higher spatial resolution of the analysis requires careful consideration. The study on energy poverty and vulnerability of consumers assesses metrics at NUTS1 and NUTS2 resolution. However, it requires no disaggregation of the results of the techno-economic core, hence no additional set of assumptions for downscaling. National-level scenario metrics from the techno-economic core models, such as residential energy costs, coal production and industry and investments are used with subnational vulnerability metrics derived from the Household Budget Survey microdata [42]. This allows the assessment of potential changes in vulnerability under the various transition pathways with a certain level of consistency between the models, despite their different resolutions. The study on emissions and related health impacts directly uses national level emissions from the TIMES model to calculate changes in concentration levels on a spatial resolution of 0.25° × 0.5° (latitude x longitude), through dispersion algorithms. For simplicity, no changes in the spatial allocation of major emission sources are assumed for future years, i.e. the model implicitly assumes that future power plants are, for example, to be built at the same site as today's power plants. Apart from this assumption, no challenge arises due to the spatial resolution of TIMES (national) and the one of the emissions and health impact study.

The work carried out through sub-EU level case studies, at lower geographical scales and focused on specific sectors, adds significant detail and value to the analysis, but also two main challenges:

- The pathway narratives include assumptions on developments at European and national level, but these may either (a) not directly lead to a single set of corresponding assumptions for the sub-national level or (b) not explicitly cover all the assumptions needed for the case study. Therefore additional assumptions need to be made for interpreting the EU level assumptions and narratives for the case studies.
- For the case study analyses to be relevant for local researchers, stakeholders and decision makers, we suggest that they need to be carried out with existing research infrastructure and models. This implies that different models may be used than the ones used for the analysis at European scale, even when covering similar aspects (such as energy system investments and costs). Different models have different underlying methodologies and structure. For example, the District Heating optimisation model used for Helsinki region in Finland was developed in Finland using the framework energyPRO, whereas the one for Kaunas was developed in Lithuania using MESSAGE. energyPRO and MESSAGE are both bottom-up (technology-rich) energy system optimisation modelling tools; but in this case the former carried out an optimisation at higher time resolution, for only one year and assuming investments as sunk costs; the latter carried out a lower time resolution analysis for multiple years, including investments in the optimisation.

The first of these two main challenges from the case studies is addressed by identifying key elements of the EU level pathways and ensuring consistency with those in the case study, while allowing a looser alignment for less central assumptions. The key policy targets in the security, dispatch and ecosystems case studies were harmonised with the techno-economic core and the overall pathway narrative. In the security case study, the emission targets for the non-ETS sectors, the carbon prices and the renewable targets were aligned. In the grid and dispatch case study, the carbon prices were aligned. In the ecosystems services case study, the emission reduction targets for CO_2 and the targets for penetration of renewables were aligned. The emission targets were cross-checked in the District Heating study. They were complying with and overshooting the national targets. Fuel prices and technology assumptions for the technologies shared by the various models were harmonised, with additional assumptions added, if technology granularity was higher in the case study models. In the energy security and District Heating studies not all investments in infrastructure were harmonised, due to the EU wide model having too little detail on them for the purposes of the case studies.

The second challenge was unavoidable in the energy security and District Heating case studies. It imposed that only a subset of all modelling insights be considered of potentially general validity (i.e. for the rest of the EU). Picking again the case of energy security, the insights regarding the importance of interconnectors for reserve purposes under strong decarbonisation policies are considered of general validity. These rely on the high detail of the model in the representation of reserve services, interconnectors and technological options and on the alignment between the model's and pathway's assumptions on the national decarbonisation targets. However, the precise technology mixes as optimised by TIMES and MESSAGE are not comparable, due to non-alignment between some techno-economic assumptions for energy supply technologies. In the case of the District Heating case study, despite the structural differences between the Finnish energyPRO model and the Lithuanian MESSAGE model, an overall insight on the trend of District Heating cost increase can be extracted and considered robust across tools and scenarios. However, no conclusion can be drawn from e.g. the comparison of the cost increases in the Helsinki region and in Kaunas, because these are calculated using different methodologies.

3.2. Added value of the framework

The review and analysis of the model results presented in section 2 allows us to draw some conclusions on selected advantages of the integrated assessment framework in terms of insights provided.

The grid and dispatch case study provide insights on the feasibility of the capacity mix calculated with TIMES and the potential effects on electricity prices, making the TIMES results easier to communicate to and more relatable for national decision makers and utilities in the analysed countries. Such case study can be replicated in all the other regions of the EU, with a similar approach: one where the numerical assumptions are scrutinised and updated by local stakeholders and directly fed to a larger EU energy system optimisation model. While in our case no feedback loop from the case study models to TIMES was needed (the electricity supply mix is feasible in the analysed cases), there may be cases where it is. Therefore, the possibility for feedback loops needs to be taken into account in future studies. From the point of view of its utility in the integrated assessment, the energy security case study highlights particularly that technological detail on reserve provision can and should be somehow integrated into pan-European energy system optimisation models. This would allow the European Commission to obtain more reliable results on the actually available transmission capacities between countries.

On the societal side of the analysis, the vulnerability study adds two layers of information regarding the just transition. On one side, it points out potential losers across geographies and income classes. On the other side, it also highlights opportunities for investments that would resolve some of the underlying structural problems inherent in driving energy vulnerability. The important indication that emerges from this, highlighted by the combination of TIMES and InVEST results, is that policy needs to manage the short-term risks of increasing cost, which could impact negatively on affordability, while incentivising and supporting the large-scale investment that is necessary. Finally, in the case of the District Heating study, a comparison between a case where national outputs of energy supply investments from the TIMES pan-European model are projected to the national scale and one where plans by local companies are assumed was made. The comparison sheds light on potential gaps between EU-wide decarbonisation plans and local ones, where the local ones may be able to achieve the same outcomes (i.e. decarbonisation objectives) with a more efficient use of local infrastructure.

On the environmental side, the inclusion of unit damage costs from EcoSense adds an important detail to the techno-economic modelling core and significantly changes its rationale. The system costs are optimised considering also health damage costs, as real and not sunken costs. The energy supply mix that results is one that tells decision makers how to minimise, among other expenses, also public health expenses (although, notably, based on a number of uncertain assumptions). It also unveils dynamics that could be in contrast with the desired just transition, where some health impacts could be transferred between regions in the EU. The results of the health damage study and the vulnerability study can be overlapped (no additional set of assumptions would be needed for this) to identify potential losers under several aspects. This in turn can give the European Commission information that is useful to better understand and address the concerns by the Member States (examples cited in the introduction section). The post-processing of TIMES results to assess the use of critical materials under different decarbonisation pathways constitutes a fundamental expansion of the techno-economic analysis. It provides a reality check of the cost-optimal decarbonisation pathways versus the global availability of material resources, with details on the origin of the materials and the specific demand-supply bottlenecks that could arise. Identifying the future decarbonisation and investment paths that could give rise to bottlenecks may allow the European Union to take early corrective actions to avoid the bottlenecks. Finally, the analysis of ecosystem services in Lithuania shows one case where EU and national decarbonisation policies mandating technological shifts may have unintended consequences if not complemented by local regulations that move beyond the technological domain. The long-term decline in habitat network size shows that the current choice of forest management strategy will determine available resources in terms of ecosystem services not only in the near future, but also in 2050 and beyond. In the case of Lithuania, an intensive management strategy may lead to decline in bioenergy feedstock availability in the decades after 2050. This may map back to a regulatory gap between EU decarbonisation policies, national policies and local policies. The EU policies mandate renewable energy targets for Member States; the national policies mirror such mandates and, if not accounting for constraints in the ecosystems, may allow technical solutions that are detrimental for the local ecosystem in the long term.

3.3. Open challenges

While the modellers overcame several challenges deriving from the use of this framework and derived several benefits, some issues remain open. We mean to discuss them here to add to the research agenda in support of decarbonisation pathways in the EU.

We harmonised assumptions and created links between some models at a time, but not between all models at the same time. For example, the PLEXOS model for the grid and dispatch study was harmonised with the TIMES pan-European model before the latter was integrated with NEWAGE and EcoSense. The harmonisation should be repeated for full consistency, since the CO_2 prices and the electricity supply mix calculated by the TIMES model change before and after the integration with NEWAGE and EcoSense. Additionally, the dispatch model did not feed information back to the TIMES pan-European model, and the latter does not therefore consider the additional information about the operation of the plants in its definition of the optimal capacity mix - or competition between electricity and other energy carriers. Similar considerations can be done for all the other links between the TIMES model and case study models. Harmonising all the models would require numerous iterations, increasing in number the more models are linked. This in turn requires resources and time. This highlights a general trade-off: the higher number of tools and the presence of case studies does enrich the study, but it requires significantly higher effort to reach full harmonisation and iteration across the tools.

Linked to the above, such a large assessment framework is more difficult to update with new numerical assumptions than one constituted of fewer modelling tools and managed by fewer modelling teams. In our case, the models were developed by distinct institutions, with resources provided for each through EU funding, in quite a decentralised way. While this was done to increase the relevance of the analysis in national contexts and allow national stakeholders to give inputs through the case studies, it made the processing of modelling inputs and outputs more challenging. A strength of commonly used Integrated Assessment Models (IAMs) is that their management and the processes to update them are much more structured. One recommendation emerging from this is that structuring the collaborations between the modelling teams and standardising the data exchanges beyond the scope of individual EU-funded projects is critical, for the long-term use and maintenance of the assessment framework.

4. Conclusions

The structural changes needed of every sector of the economy in the EU and its Member States to meet deep decarbonisation targets such as those envisaged in the Green Deal have been deeply studied. Both the impact assessments mandated by the European Commission and the complementary research body — including published work of the authors of this paper — agree on key elements such as shift to renewables, electrification of economies and reduction of final energy consumption. They also agree on an overall limited impact of decarbonisation strategies on national economies.

However, published work suggests that the impacts of the deep decarbonisation pathways envisaged by the EU on societies, resources and ecosystems may be different across sectors, contexts and scales. For example, new investments in renewable infrastructure and fuel shifts may make energy access less affordable in specific regions within the Member States and for specific income classes. Unaffordability may be of special concern in regions already experiencing energy poverty. The extensive and intensive use of renewable resources may lead to depletion of resources considered renewable to date, such as critical materials and ecosystems.

In this paper we analysed the challenges and benefits of creating and using an integrated assessment framework with wide scope, depth of analysis and cross-scale coverage to analyse in better detail selected aspects of EU decarbonisation pathways. The framework is peculiar in that it is not constituted by one integrated tool, but by numerous soft-linked tools. It does not try to capture all scales of assessment, from the EU to local, through one model, but it makes use of several case studies, each focusing on different regions, sectors and scales. The case studies are supported by models that are specialised in the type of assessment required and that are usually owned, developed and shared locally. This allows the scope, depth and cross-scale detail to be extended and it provides the ground for higher engagement of national policymakers and representation of national and sub-national realities.

The use of such framework brings benefits in terms of the types of the insights it can deliver on the social, economic and environmental impacts of decarbonisation pathways in the EU. On the techno-economic side, it allows validation of EU-wide results regarding the technical feasibility of the transition on a national scale, increasing the relevance of the analysis for national decision makers. On the social side, it unveils how EU-wide and national decarbonisation mandates could affect in different (and potentially overlapping) ways citizens, workers and sectors across geographies. It also unveils opportunities for investments that may reduce energy poverty and contribute to decarbonisation targets at the same time. On the environmental side, it quantifies several hidden effects of decarbonisation on health, ecosystems, use of critical materials, providing indications for corrective actions as the EU undertakes one or the other decarbonisation pathway. The use of a case-study approach to investigate specific dynamics within the decarbonisation of economies in the EU adds the most value to the framework. It allows the re-use of models and tools around which there is local expertise and the active engagement of local decision makers and utilities in the design of the analysed pathways.

However, using a modelling framework that is constituted of numerous tools with so specific foci also poses challenges of consistency, concerning the modelling assumptions and the general validity of the results. We detail these challenges and suggest ways to overcome many of them, some by linking modelling tools iteratively, others by harmonising modelling assumptions, others by comparing modelling outcomes, others by inter-disciplinary work and communication between the modelling teams. The way these challenges are overcome determines the types of insights that can be extracted from the integrated assessment framework and their level of confidence. Analysing the internal coherence of the assessment framework allows communication of which ones of its insights are most robust. One important trade-off emerges, between the number of modelling tools included in the framework and the ease of harmonisation. As the number of tools increases, the number of iterations and the time needed to harmonise the assumptions across all of them increases exponentially. The modelling approach can be replicated in further assessments and extended to many more research teams in Europe, but to that end it needs further structuring: clear procedures and standards for comparison of the models, their inputs and their insights should be set up. Standards and procedures used within the integrated assessment modelling community could be used, making sure that they can be applied to compare models with different scopes, resolution and scale.

Author contributions

F. Gardumi: Conceptualization, Methodology, Investigation, Project administration, Supervision, Writing, Revision; I. Keppo: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing, Revision; M. Howells: Conceptualization, Methodology, Funding acquisition, Project administration, Supervision; S. Pye: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing; G. Avgerinopoulos: Methodology, Project administration, Supervision; V. Lekavičius: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing; A. Galinis: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing; L. Martišauskas: Formal analysis, Investigation, Data curation; U. Fahl: Conceptualization, Methodology, Funding acquisition, Supervision, Revision; P. Korkmaz: Methodology, Formal analysis, Investigation, Data curation; D. Schmid: Methodology, Formal analysis, Investigation, Data curation, Revision; R. Cunha Montenegro: Methodology, Formal analysis, Investigation, Data curation; S. Syri: Methodology, Formal analysis, Investigation, Data curation; A. Hast: Methodology, Formal analysis, Investigation, Data curation; U. Mörtberg: Methodology, Formal analysis, Investigation, Data curation, Writing; O. Balyk: Methodology, Formal analysis, Investigation; K. Karlsson: Methodology, Formal analysis, Investigation, Data curation; X. Pang: Methodology, Formal analysis, Investigation, Data curation; G. Mozgeris: Methodology, Formal analysis, Investigation, Data curation; R. Trubins: Methodology, Formal analysis, Investigation, Data curation; D. Jakšić: Methodology, Formal analysis, Investigation, Data curation; I. M. Turalija: Methodology, Formal analysis, Investigation, Data curation; M. Mikulić: Methodology, Formal analysis, Investigation, Data curation;

Declaration of competing interest

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

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Appendix A. Supplementary data

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