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Modeling Decarbonisation and Adaptation Scenarios: Role in Political and Economic Decision Making

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EXECUTIVE SUMMARY

Regulators and businesses around the globe are gradually realizing the importance of the measures for climate change adaptation and mitigation. Therefore, decision-makers, i.e. national regulators, regional authorities, and corporate leaders, need an appropriate toolkit to ensure that adequate decisions are made based on quantitative evaluations of various decarbonisation and adaptation scenarios. Contemporary model complexes allow not only calculating climate change scenarios and their impact on human welfare and health, economy development as a whole and its individual sectors, but also the scope (and cost) of decarbonisation scenarios for countries, regions and sectors.

By virtue of the very formulation of the problem, which takes into account not only macroeconomic, demographic, and technological, but also climatic factors, the development of model complexes capable of calculating such scenarios requires the application of an interdisciplinary approach, from knowledge of climatology to a deep understanding of specific sectors of the economy. At the moment, the EU, the USA, the Asia-Pacific countries, and Russia carry out work on such model complexes with varying degrees of complexity and detail. Currently, the toolkit developed in the European Union seems to be the most advanced. Therefore, this research not only answers the questions of who and why need such scenarios and describes the basic approaches to modelling, but also examines in detail the European set of models and its main outcomes.

In our opinion, it will be useful for the Russian Federation too to take into account such foreign experience in developing evaluations of the economic consequences of climate change and decarbonisation. This research provides a brief overview of the existing Russian models that can be used to create a similar integrated modelling system in the country.

INTRODUCTION

Why is modelling decarbonisation and adaptation scenarios in demand now?

Model complexes allow building long-term scenarios for the development of the world and certain regions and countries, evaluating the impact of the introduced policies and regulations on all stakeholders, economy and public welfare in general.

To counter the threat of climate change at the global level, extraordinary measures have been taken in recent years to reduce greenhouse gas emissions. Adopted internationally in 2015, the Paris Agreement[1] aims to keep the average global temperature rise below 1.5 ˚C to improve adaptability to the consequences of climate change, transition to low-carbon development, and achieve carbon neutrality (i.e., zero atmospheric anthropogenic CO_2 emissions) by 2050. As of May 2021, 189 countries (including Russia) have joined. All member countries are voluntarily committed to reducing net atmospheric emissions of CO_2 and other greenhouse gases by 2030[2]. So far, more than 60 countries have stated their goals to achieve carbon neutrality by 2050[3] [4].

Many Paris Agreement signatories have either already launched CO_2 emissions trading systems[5] (or some other forms of carbon pricing and taxing) or are set to do so in the near future. Many are introducing bans on the use of combustion engines[6], setting targets for the proportion of renewable energy sources[7] in their national energy balance, or setting targets for the proportion of low-carbon fuels[8]. As is clear, various decarbonisation initiatives are gradually taking shape throughout the world and this process already affects all of Russia's main foreign trade partners.

In 2019, the European Union (EU) announced a comprehensive strategy for a sustainable European economy, the European Green Deal[9]. Its centrepiece is to achieve climate neutrality (i.e., net zero emissions of all greenhouse gases (GHG)) by 2050. There was also set the ambitious intermediate goal of a 55% reduction in GHG emissions by 2030 compared to 1990, implying a 38-40% share of renewable energy sources in the energy balance and their 65% share in electricity production. At the same time, it is expected to reduce the consumption of energy

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[1] Paris Agreement, UN, 2015 (retrieved https://unfccc.int/sites/default/files/english_paris_agreement.pdf)

[2] UN official site (https://www.un.org/en/climatechange/paris-agreement)

[3] ONDC registry (interim) / Official website of the UNFCCC. (https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx)

[4] Submission portal. INDC / Official website of the UNFCCC. (https://www4.unfccc.int/sites/submissions/INDC/Submission%20Pages/submissions.aspx)

[5] IEA (2020), Implementing Effective Emissions Trading Systems, IEA, Paris https://www.iea.org/reports/implementing-effective-emissions-trading-systems

[6] Wappelhorst S., The end of the road? An overview of combustion engine car phase-out announcements across Europe, May 2020, International Council On Clean Transportation

[7] IEA/IRENA Renewables Policies Database

[8] IEA Policies database

[9] Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions The European Green Deal COM/2019/640 final

by 39-40%, coal by 70% and oil and gas by 30% and 25%, respectively, by 2030 compared to 2015.

The EU is now consistently creating comprehensive regulations that will force market participants and national governments to meet these highly ambitious goals.

Assessing the feasibility and possible consequences of such regulation requires the creation of hybrid model suites that combine climate modelling, energy modelling, and modelling of the economy and investment in the development of certain technologies and areas.

These model complexes allow building various long-term scenarios for the development of individual countries, regions, and the world. They also allow us to assess the impact of the introduced policies and regulatory methods on all stakeholders, the economy, and public welfare as a whole. In addition, the construction of scenarios allows assessing the relevance of the distribution of investment flows.

Who needs these scenarios?

Many stakeholders need the Model complexes provide quantitative estimates of energy demand, emissions of greenhouse gases, energy prices, society welfare, GDP level, required investment in infrastructure, government support, as well as evaluation of the degree of influence of regulatory measures

Toolkit, ensuring the evaluation of various decarbonisation and adaptation scenarios. The main stakeholders are the following[10] [11]:

- **Regulators and executive authorities at the national level.** It is important for them to understand how to organise regulation within the country, and which of the support measures or restrictions will help achieve the goals set in the field of climate and sustainable development.
- **Regulators at the international level.** This group of stakeholders solves problems related to negotiations at the international level. For example, for Russia, there is an increasing need for such a tool to justify a negotiating position with the EU regarding the introduction of a cross-border carbon tax. At the same time, even without such a model complex, the regulator needs to understand what the other side uses.
- **Financial sector.** Financial flows in the fuel and energy sector will be redistributed depending on the perspectives of a particular business. Large investors are already beginning to abandon investments in the coal and oil and gas industry. For example, the Norwegian Sovereign Wealth Fund and the World Bank are refocusing on green energy and other assets that are less vulnerable in decarbonisation scenarios.

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[10] Hare B., Brecha R., Schaeffer M., Integrated Assessment Models: what are they and how do they arrive at their conclusions?, Climate Analytics, 2018

[11] UN official site (https://unfccc.int/topics/mitigation/workstreams/response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models)

- **Business community.** Its members needs to understand what awaits them in the short and long term to build their business strategies. At the same time, businesses need reliable, clear, and comprehensible signals from regulators and executive authorities.
- **NPOs and climate activists**. For this category of stakeholders, it is important to have transparent and accessible information about the activities of businesses and government regulators in order to focus attention on what has not yet been done on their part.
- **The population.** This category of stakeholders is the most numerous and the most scattered. The population needs clear signals and accessible information about what other stakeholders are doing and how it will be useful and important for society. It needs to know what benefits it will receive, since such large-scale changes will necessarily lead to additional taxes or other financial burden.

For all these groups of stakeholders, model suites are important because they provide quantitative estimates in their development scenarios: energy demand, greenhouse gas emissions, energy prices, social welfare, GDP level, and required investments in infrastructure and governmental support, as well as assessments of the degree of influence of regulatory measures.

What are model complexes and decarbonisation and adaptation scenarios for?

The population

In the last 30 years, two groups of models have been formed for different stakeholders.

The first group evaluates climate impacts and how humanity can adapt to them (adaptation scenarios), and the second group looks at how to reduce climate change (mitigation/decarbonisation scenarios).

Model complexes are used to answer "what if?" and “how?" questions. These questions can be general. For example: what if the world takes no action to mitigate climate change? Or how can the world achieve the goals of the Paris Agreement in the 1.5 or 2 ˚C scenarios?

The questions posed to models can also be specific, e.g. “What if countries set a universal price of $ 100 per tonne of CO2 emissions by 2030?”, or “What if certain technologies, such as nuclear power or carbon capture and storage (CCS), are not available?”

Links built into model complexes allow exploring cascading effects, co-benefits, and unintended consequences by tracking how choices in one area affect the rest of the modelled world.[12]

In the last 30 years, two groups of models have been formed for different stakeholders, because it has become necessary for all of them to take into account the climate factor in their activities. The first group evaluates the degree of climate impacts and how humanity can adapt to them (adaptation scenarios), and the

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[12] https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change

second group looks at how to reduce climate change (mitigation/decarbonisation scenarios).

At the same time, each group of stakeholders is concerned with their own issues (Table 1).

Table 1 Key stakeholders and examples of questions, to which model complexes can answer to meet their needs.

Stakeholder	**Examples of questions, to which model complexes can answer**
Regulators and executive authorities at the national level	How and at what speed to decarbonise the economy to the benefit of the country? How to choose the most effective climate change adaptation measures?
Regulators at the international level	How can the world achieve the goals of the Paris Agreement in the 1.5 or 2 °C scenarios?
Financial sector	What happens if funding for carbon-intensive projects is completely limited?
Business community	How to decarbonise a company profitably? How to adapt real assets to climate change?
NPOs and climate activists	What if the world takes no action to mitigate climate change?
Population	How will decarbonisation and adaptation measures affect the income of the population? How will climate change affect health and living conditions?

Source: SKOLKOVO Energy Centre, Moscow School of Management SKOLKOVO

APPROACHES FOR MODELLING DECARBONISATION AND ADAPTATION SCENARIOS

Models and model complexes associated with the development of decarbonisation and adaptation scenarios answer two fundamental questions:

- How can one try to prevent climate change? How and at what speed to decarbonise the economy to the benefit of the country, region or company? What risks can wrong approaches to decarbonisation pose? (mitigation scenarios)
- What if nothing is done? How will climate change affect people, energy, and the economy in this case? What risks and benefits does it pose? How will we have to adapt to it? (adaptation scenarios).

The approaches to modelling various systems and sectors of the economy are quite universal, however, due to the fact that in Russia 78.9% of GHG emissions are accounted for by the energy sector[12], this section, when it comes to analysing approaches to modelling, is more focused on the study of model toolkits aimed at the fuel and energy complex (FEC).

Models can be divided into two broad categories: top-down and bottom-up.

Models typically can be divided into two broad categories: **top-down** and **bottom-up**[13]. Top-down models are typically adopted by economists and public administrations. These models focus on connecting the energy system to other macro-economic sectors. They are usually characterised by a simplified representation of the components and complexity of the energy system and are therefore not appropriate to identify sector-specific policies. Their application field is the evaluation of the impacts of energy and climate policies on socio-economic indicators as growth, public welfare, employment etc. Top-down approaches can also take into account interdependencies between sectors or countries.

The bottom-up approach is to develop engineering models with detailed descriptions of the technological aspects of the energy system and how it may develop in the future, which allows to determine sectoral policy. Demand for energy services is typically provided exogenously, and the models analyse how the given energy demand should be fulfilled in a cost-optimal fashion.[14] These detailed models from a technological-economic point of view allow the user to compare the impact of various technologies on the energy system and to evaluate various

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[12] Official site YU. A. IZRAEL INSTITUTE OF GLOBAL CLIMATE AND ECOLOGY http://www.igce.ru/2020/04/национальный-кадастр-антропогенных/

[13] Boehringer, Christoph & Rutherford, Thomas. (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up. Journal of Economic Dynamics and Control. 33. 1648-1661. 10.1016/j.jedc.2008.12.007.

[14] Per Ivar Helgesen, Top-down and Bottom-up: Combining energy system models and macroeconomic general equilibrium models Project: Regional Effects of Energy Policy (RegPol) CenSES working paper 1/2013

alternatives for lowering GHG emissions to reach the climate goals.

However, the bottom-up approach does not take into account the connections between the energy system and the macro-economic sectors, thus neglecting the impacts on these sectors.

Bottom-up models poorly take into account the economic component of technologies, which means that it is merely on their basis that the wrong policies and measures can be adopted.

The two approaches differ considerably in their identification of the relevant system and may therefore produce different guidance for policy-makers. The production functions in top-down models will usually have smooth substitution – a small price change leads to small changes in the mix of inputs or outputs. The bottom-up models will often react in a more binary way – a small price change can lead to no effect at all, or it can produce large shifts in the mix of inputs or outputs.[15] Algehed, Wirsenius et al. (2009) have studied differences between some top-down and bottom-up approaches and their usefulness to policy makers and regulators.[16]

There are also different approaches to linking models, which will be discussed below in the "Linking Models" section.

Macroeconomic top-down models

Top-down models can generally be divided into these four main types:[17]

- input-output models;
- computable general equilibrium models;
- econometric models;
- system dynamic models.

Input-output models follow the monetary flows between different sectors of the economy and include both intermediate and end-use deliveries from each sector. From these interrelations one can estimate the monetary effects of economic shocks or structural changes in the economy. These models are not dynamic in prices and assume that prices are decided exogenously.

Computable general equilibrium (CGE) models are based on microeconomic theory and calculate how both prices and activities in all sectors change in order to reach a general equilibrium in the economy. Like the first group, these models

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[15] Top-down and Bottom-up: Combining energy system models and macroeconomic general equilibrium models Project: Regional Effects of Energy Policy (RegPol) CenSES working paper 1/2013 Per Ivar Helgesen

[16] Algehed, J., S. Wirsenius, and J. Jönsson (2009). Modelling energy efficiency and carbon dioxide emissions in energy-intensive industry under stringent CO2 policies: comparison of top-down and bottom-up approaches and evaluation of usefulness to policy makers. ECEEE 2009 Summer Study. La Colle sur Loup, France: 11.

[17] Herbst, A., Reitze, F., F.A. Toro, and E. Jochem (2012). Bridging macroeconomic and bottom up energy models - the case of efficiency in industry. ECEEE 2012 Industrial Summer Study. Arnhem, the Netherlands, The European Council for an Energy Efficient Economy.

also build on the input-output data from national accounts to reflect sectoral interdependencies.

Econometric models deal with time series analysis and estimate statistical relations between economic variables over time in order to calculate projections from the resulting model.

System dynamic models have predefined rules for the behaviour of different actors in the model and are able to make complex non-linear simulations on this basis.

Conventional top-down analyses typically estimate aggregate relationships between relative costs and market shares of energy and other inputs to the economy, and link these to sectoral and total output in a broader equilibrium framework. The principal exogenous parameters are elasticities of substitution, which indicate the substitutability between any pair of aggregate inputs (capital, labour, energy, materials) and between energy forms (coal, oil, gas, etc.). Often, top-down models also have a parameter called "autonomous energy efficiency improvement", which indicates the rate at which price-independent technological evolution improves energy productivity. To the extent that these parameters are estimated from real market behaviour, top-down models reflect the actual preferences of consumers and businesses, as well as the market heterogeneity of real-world financial cost conditions. As top-down models are based on aggregate sectors, they represent technologies in less detail than bottom-up models.

Engineering bottom-up models

We can divide these models into these four main types:[18,19]

- optimisation models;
- simulation models;
- accounting models;
- multi-agent models.

Optimisation models optimise the choice of technology alternatives with regard to total system costs per system to find the least costly path to reach a specific goal over the entire projected period. Such models are also categorised as partial equilibrium models since they balance demand and supply in the covered sectors.

Simulation models constitute a very broad and heterogeneous group. Their modelling aspects depart from the pure optimisation framework. They can include econometrically estimated relations. Large simulation models can include partial

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[18] Fleiter, T., E. Worrell, and W. Eichhammer (2011). "Barriers to energy efficiency in industrial bottom-up energy demand models-A review." Renewable & Sustainable Energy Reviews 15(6): 3099-3111.

[19] Herbst, A., Reitze, F., F.A. Toro, and E. Jochem (2012). Bridging macroeconomic and bottom up energy models - the case of efficiency in industry. ECEEE 2012 Industrial Summer Study. Arnhem, the Netherlands, the European Council for an Energy Efficient Economy.

optimisation (e.g., from a company perspective) and can consist of different modules covering more aspects.

Accounting models are less dynamic, and do not consider energy prices. These models mainly apply exogenous assumptions on the technical development.

Multi-agent models are a broader modelling class than the optimisation models since they include the simultaneous optimisation by more agents.[20]

The main limitation of the traditional bottom-up approach is the assumption that a simple estimate of capital and operating costs indicates the full social cost of technological change. New technologies carry higher financial risks, as does the longer payback associated with irreversible investments, such as energy efficiency investments. In addition, some low-cost, low-emission technologies cannot completely replace their competitors. Consequently, traditional bottom-up models may suggest wrong technological options and wrong regulatory solutions for policy makers. Another limitation of the conventional bottom-up approach is that its partial equilibrium method limits or partially limits its capability to evaluate the macroeconomic effects of policies, especially the commercial and structural implications of energy price and cost changes across the economy. Therefore, bottom-up models can prescribe inappropriate policies and technologies.

Disadvantages of top-down and bottom-up approaches

Top-down models are based on aggregate sectors and present technologies in less detail than bottom-up models

Since top-down models lack technological detail, they are restricted to simulations of financial policy instruments. The magnitude of the financial signal necessary to achieve a given emission reduction target indicates its implicit cost, including the intangible costs related to the risks of new technologies, the risks of long payback technologies, and preferences for the attributes of one technology over its competitor.[21] CGE/IO models might lack some abatement options if these are not present in historic data since these operate on substitutions – if there was very little electricity in transport, it's hard to substitute to it. However, there are ways to deal with this.

The conventional top-down approach also has severe methodological limitations. The elasticity and autonomous efficiency improvement parameters in top-down models are estimated from empirical data. Even if the confidence intervals of these estimated parameters are narrow, these values derived

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[20] Top-down and Bottom-up: Combining energy system models and macroeconomic general equilibrium models Project: Regional Effects of Energy Policy (RegPol) CenSES working paper 1/2013 Per Ivar Helgesen

[21] Algehed, J., S. Wirsenius, and J. Jönsson (2009). Modelling energy efficiency and carbon dioxide emissions in energy-intensive industry under stringent CO_2 policies: comparison of top-down and bottom-up approaches and evaluation of usefulness to policy makers. ECEEE 2009 Summer Study. La Colle sur Loup, France: 11.

from past experience may not remain valid in the future. Parameter values could change dramatically in the future as financial costs of technologies change due to economies of scale in production or accumulated experience, and as consumers become more accepting of emerging technologies as these are established in the market. Hence, their values may not show the full adaptation of firms and households to policies that significantly affect economic conditions. This can in turn lead to high cost estimates for policies to decrease energy-related emissions.

Disadvantages of bottom-up and top-down models have spurred the development of a hybrid approach that combines technology and economics.

Another limitation of the top-down approach is that the constraints of policy formation often push policy makers toward towards market-based policies (as opposed to standards, bans, labelling, as these are much more difficult to implement). Yet with their aggregated depiction of technologies, top-down models are limited in simulating the effects of technology-specific policies.

Hence, conventional bottom-up models describe technologies in detail, but do not realistically portray microeconomic decision-making by businesses and consumers when selecting technologies and fail to depict potential macro-economic equilibrium feedbacks. Conventional top-down models, in contrast, address these deficiencies by representing macroeconomic feedbacks in an equilibrium framework and by estimating parameters of technological change from observations of aggregate market responsiveness to cost changes. However, since they lack technological detail, top-down models cannot be used to assess how future market responses and autonomous trends might differ from the past as technology-specific regulations, research and development, and new expectations interact with market incentives over long time periods. Because of these methodological differences, top-down and bottom-up models can predict divergent costs, and consequently suggest different policies, for meeting climate goals.

This methodological divide has stimulated exploration of hybrid approaches that integrate the technological explicitness of bottom-up models with the micro-economic realism and macro-economic feedbacks of top-down models. Efforts toward integrated modelling usually involve either incorporation of technological detail into a top-down framework, incorporation of behavioural realism, and/or macro-feedbacks into a bottom-up framework.

Linking the models

Models are linked through iterations with feedback of information between the models. The first example of linked energy-economy models was reported by Hoffman and

Jorgenson in 1977.[22] They linked the Brookhaven Energy System Optimisation Model (BESOM) with a general equilibrium model, and later with an input-output model. Over the following decades, several studies linked economic and systems engineering models, but all the links were informal, i.e., the information transfer between the models was directly controlled by the user. This brings us to the problem of categorizing different linking types.

Some terms that are commonly used to describe the linkage of models are hard linking and soft linking. Another approach to linking models defines a one-way linkage and a two-way linkage. With one-way linkage, the parameters of one model become exogenous for another one. With two-way linkage, models exchange data. This can occur more than once.[23]

We will use soft linking and hard linking terms,[24] where soft linking is information transfer controlled by the user. The user evaluates results from the models and decides if and how the inputs of each model should be modified to bring the two sets of results more in line with each other, i.e., how to make the models converge.

Hard linking is formal links where information is transferred without any user judgment – usually by computer programs. In areas where the models overlap, an algorithm may be used to negotiate results. Usually, one model is given control over certain results, and another model is set up to equilibrium models reproduce the same results.

One step further from hard linking would be to integrate the models. This distinction is harder to define. Integrated models are run together, instead of exchanging information between separate model runs.

The advantages of soft linking can be summarised as practicality, transparency, and learning. Likewise, the advantages of hard linking can be characterised as productivity, uniqueness, and control. Soft linking seems the most practical starting point for linking models based on different approaches. Initial investments in computer programming are kept low, and the modelers can fairly quickly obtain results for evaluation and learning. But for reasons of productivity, hard linking is the preferred end product, but this reduces flexibility, and this flexibility is completely reduced with the increasing model complexity. As the volume of model runs increases, and more model users become involved, more resources are needed to retain the quality of soft linked models than of hard linked

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[22] Hoffman, K.C. and D.W. Jorgenson (1977). "Economic and Technological Models for Evaluation of Energy-Policy." Bell Journal of Economics 8(2): 444-466.

[23] DELZEIT R, at all, Linking Global CGE models with Sectoral Models to Generate Baseline Scenarios: Approaches, Challenges, and Opportunities, Journal of Global Economic Analysis, Volume 5 (2020), No. 1, pp. 162-195.

[24] Wene, C.O. (1996). "Energy-economy analysis: Linking the macroeconomic and systems engineering approaches." Energy 21(9): 809-824.

models. In other words, a soft linked model often cannot work without its main operator, i.e., it cannot simply be passed to another person, unlike a hard linked model. However, hard linked models will not be well suited for modelling in crisis and force majeure conditions, since in any case they will require operator intervention to adjust the input data and limiting parameters.

However, hard linking produces one unique result for each set of assumptions and data. Both assumptions and data may be well documented. The quality of the results is controlled by reviewing these assumptions and data. Soft linking often produces noise in the form of differences between the results of the models for energy flows, prices and technologies within the common region. Noise control is complicated because most of the useful sets of common measuring points turn out to be non-exclusive. Due to soft linking noise, uncertainty analysis becomes very difficult. In spite of stringent procedures, each case of soft linking contains an element of human judgement. This also holds for hard-linking but in hard-linking, the exchange of information is automatized, but the choice of which parameters will be exchange is also human judgement. This also applies to hard linking. Although the exchange of information is automated with hard linking, the choice of parameters that the models will exchange is also a human choice.

Models can be linked not only in pairs, but also create a toolkit for interdisciplinary modelling. In particular, the EU uses an integrated set of models to assess in detail the impacts of climate policies on economic sectors (energy and transport, land use, air quality and employment).

The exchange of information between various models allows for extensive and consistent evaluation. For example, detailed information about technologies from energy models can be used in economy-wide models to assess the implications for competitiveness and employment[25].

Integrated evaluation models

Integrated evaluation models combine different strands of knowledge in one structure. The typical goal is to analyse environmental problems, across different academic disciplines. The activity aims to generate useful information for policy making rather than to advance knowledge for knowledge's sake, hence the term "assessment". Below are some of the models that study CO_2 emissions.

- Integrated Global System Modelling (IGSM) by MIT Joint Programme on the Science and Policy of Global Change (including the EPPA model)[26]

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[25] Weitzel, M., Vandyck, T., Keramidas, K. et al. Model-based assessments for long-term climate strategies. Nat. Clim. Chang. 9, 345–347 (2019). https://doi.org/10.1038/s41558-019-0453-5

[26] Description and Evaluation of the MIT Earth System Model (MESM) Sokolov et al., AGU Journal of Advances in Modelling Earth Systems , 10(8), 1759-1789 (2018)

- Global Change Analysis Model (GCAM) by Joint Global Change Research Institute under Maryland University (JGCRI)[27]
- MESSAGE-GLOBIOM model at IIASA[28] [29] [30]
- The Model for Evaluating Regional and Global Effects of GHG reduction policies (MERGE) developed at Stanford University[31]
- The GEM-E3 general equilibrium model has been extended to better represent the electricity sector. To this end, electricity producing technologies are treated as separate production sectors while their investment decisions remain discrete. The advantage of this approach is that it is fully consistent with the general equilibrium framework while it leads to a full identification of the technologies.[32]
- Engineering and economic models are another example of hybrid models that combine macroeconomic principles with technological details. Using the POLES-JRC model, an approach to integrate the energy sector with macroeconomic assessment and climate policy assessment was created.[33]

Developing models is always about inevitable trade-offs between accuracy and feasibility. Deliberately chosen model limitations will vary greatly depending on the questions the model is answering.

Obviously, it is impossible for any policy-oriented energy economy model of industry to be completely accurate in its representation of current conditions and in its assessment of future dynamics under different technology and policy paths. Instead, it must be accepted that in the design of models, significant compromises between accuracy and practical feasibility are unavoidable, and that the deliberately chosen model limitations will vary considerably depending on which questions the model is intended to answer.

To enhance model usefulness, the process of model formation should be related to and guided by criteria that judge the ability

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[27] Global Change Assessment Model (GCAM). U.S. Environmental Protection Agency, Washington, D.C.

[28] Krey V, Havlik P, Fricko O, Zilliacus J, Gidden M, Strubegger M, Kartasasmita G, Ermolieva T, Forsell N, Gusti M, Johnson N, Kindermann G, Kolp P, McCollum DL, Pachauri S, Rao S, Rogelj J, Valin H, Obersteiner M, Riahi K (2016) MESSAGE-GLOBIOM 1.0 Documentation. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria http://data.ene.iiasa.ac.at/message-globiom/.

[29] Fricko O, Havlik P, Rogelj J, Klimont Z, Gusti M, Johnson N, Kolp P, Strubegger M, Valin H, Amann M, Ermolieva T, Forsell N, Herrero M, Heyes C, Kindermann G, Krey V, McCollum DL, Obersteiner M, Pachauri S, Rao S, Schmid E, Schoepp W, Riahi K (2017) The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change, Volume 42, Pages 251- 26, DOI:10.1016/j.gloenvcha.2016.06.004.

[30] Huppmann D, Gidden M, Fricko O, Kolp P, Orthofer C, Pimmer M, Kushin N, Vinca A, Mastrucci A, Riahi K, Krey V (2019) The MESSAGEix Integrated Assessment Model and the ix modelling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environmental Modelling & Software, Volume 112, Pages 143-156, DOI:0.1016/j.envsoft.2018.11.012

[31] Alan Manne, Robert Mendelsohn, Richard Richels, MERGE: A model for evaluating regional and global effects of GHG reduction policies, Energy Policy, Volume 23, Issue 1, 1995, Pages 17-34, ISSN 0301-4215, https://doi.org/10.1016/0301-4215(95)90763-W.

[32] https://ec.europa.eu/jrc/en/gem-e3

[33] Keramidas, K., Kitous, A., Despres, J., Schmitz, A. POLES-JRC model documentation 2017. https://doi.org/10.2760/814959

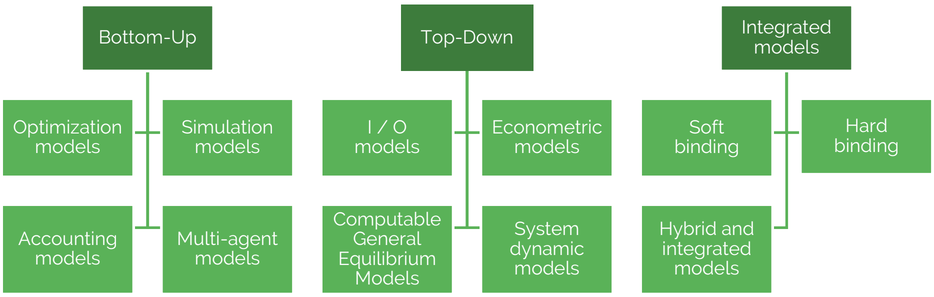
of a model to be more useful to policy makers seeking to induce technological change. Policy makers, as well as decision makers in industry, need models that can realistically evaluate the combined effect of policies that range from economy-wide to technology-specific, including command-and-control instruments (e.g., performance standards, stipulated technology) and price-based instruments (e.g., taxes, subsidies). Murphy, et al. (2007) suggested the below three key criteria for the evaluation of the usefulness of a model for policy makers.[34]

1. Explicitly represent the technologies that compete to provide services in the analysed industry sector as well as throughout the entire economy.
2. Simulate the way in which consumers, firms, and producers choose between these technologies in a way that closely reflects the real world.
3. Capture equilibrium feedback between energy-technology decisions and the overall structure and performance of the economy.

The conventional bottom-up and top-down approaches are inherently limited in providing sufficient and adequate information to decision makers regarding effective policy instruments for CO_2 abatement in industry. That is why methods and models that combine traditional bottom-up and top-down approaches have become in demand.

The models can be classified in the first approximation as shown in Figure 1.

Figure 1 Classification of approaches to energy and climate modelling



Source: compiled by SKOLKOVO Energy Centre based on model descriptions

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[34] Murphy, R., Rivers, N., Jaccard, M. 2007. Hybrid modelling of industrial energy consumption and greenhouse gas emissions with an application to Canada. Energy Economics 29(4): 826-846.

APPROACHES FOR MODELLING AND TOOLS USED IN THE EU FOR ANALYSING THE EU DECARBONISATION AND MITIGATION POLICY

In the EU, there are two modelling toolboxes: impact and adaptation modelling and mitigation modelling.

Energy and climate change impact models in the EU belong to different types of models considered. In the EU, there are two modelling toolkits: impact and adaptation modelling (PESETA project) and mitigation modelling (decarbonisation). They include sets of models that are integrated with each other.[35]

The main models included in the complex to form adaptation and decarbonisation scenarios were created about 20-30 years ago (Table 2). During this time, they were constantly refined and developed. Today, to build scenarios for adaptation and decarbonisation, the European Commission (EC) uses more than 15 models of various types from simple empirical statistical to complex integrated computable general equilibrium ones.

Table 2 - Date of creation of the models from the European model complex

Model	Year of creation
PRIMES	1990
WOFOST	1994
POLES	1990
LISFLOOD	2001
Fire Weather Index (FWI) system	1992
CAPRI	1999
GLOBIOM -G4M	late 2000
GAINS	
GEM-E3 (+application GEM-E3 CAGE)	1989-1992

Source: PRIMES MODEL 2013-2014 Detailed model description E3MLab/ICCS at National Technical University of Athens, An overview on the CAPRI model Common Agricultural Policy Regionalised Impact Model W.Britz, University Bonn, EC official website https://cordis.europa.eu/article/id/3211-evaluation-of-the-joule-programme, IASA official website https://iiasa.ac.at/web/home/research/GLOBIOM/GLOBIOM.html, POLES-JRC model documentation 2017 EUR 28728 EN Keramidas, K., Kitous, A., Després, J., Schmitz, A, A. Wit, et all 25 years of the WOFOST cropping systems model, Agricultural Systems, Volume 168, 2019, Pages 154-167, LISFLOOD-FP User manual Code release 5.9.6 Paul Bates, Mark Trigg, Jeff Neal and Amy Dabrowa School of Geographical Sciences, University of Bristol, University Road, Bristol, BS8 1SS, UK. 25 November 2013

Adaptation scenarios are built within the framework of the PESETA IV project, while to build decarbonisation scenarios a set of integrated models are used.

In this paper, the authors consider the most comprehensive tool for building development scenarios, which is available in the EU, created by the Joint Research Centre (JRC).

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[35] https://ec.europa.eu/clima/policies/strategies/analysis/models_en

About the Joint Research Centre

The Joint Research Centre (JRC)[36], under the auspices of the European Commission, provides European and national authorities with scientific and research support to make political decisions and solve contemporary problems that society faces today. The research and innovation centre is largely funded from the EU budget.

The JRC is headquartered in Brussels and unites 6 research centres located in Gil (Belgium), Ispra (Italy), Karlsruhe (Germany), Petten (Netherlands) and Seville (Spain).

The Centre was established in 1957, after the signing the Treaty establishing the European Economic Community and the Treaty establishing the European Atomic Energy Community (EURATOM). It was originally established as the Joint Centre for Nuclear Research. Already in 1958, the construction of the Italian nuclear research centre in Ispra was launched. It's worth noting that the principle of distributed research, i.e. the possibility of geographic and organisational diversification of the research centre, has been fixed in writing already during the creation of the centre. The table below shows that the main models used by JRC to build decarbonisation and adaptation scenarios belong to different organisations or has been developed jointly (Table 3).

Table 3 - Examples of models used by the JRC and their affiliation

Model	Owner	Location
PRIMES	E3MLab/ICCS института NTUA	Greece
PROMETHEUS	E3MLab/ICCS института NTUA	Greece
POLES	Enerdata, European Commission's JRC IPTS и University of Grenoble-CNRS	France, Spain
CAPRI	Eurocare GmbH, JRC и другие	Germany, Spain
GLOBIOM -G4M	IIASA	Austria
GAINS	IIASA	Austria
GEM-E3 (+application GEM-E3 CAGE)	E3MLab/ICCS of NTUA, JRC-IPTS и другие	Greece, Spain

Source: Official website of the EC (https://ec.europa.eu/clima/policies/strategies/analysis/models_en)

Until the 1970s, the Centre focused on nuclear research, in particular, on the development of prototypes of new nuclear reactors. However, against the background of a growing technological gap, mainly between the EU and the United States, in the 1970s, the Centre began to diversify its activity. This decade laid the ground for renewable energy and hydrogen technology programme, as well as for environmental monitoring and remote sensing that could be used to study pollution and monitor agriculture and natural resources.

In the 1980s, even more attention was paid to the safety of nuclear power plants after the accidents at Three Mile Island and Chernobyl. In the 1990s, the focus was expanded to health and consumer protection. For example, in 1993, the European Commission established the European Office for Wine, Alcohol and Spirit Drinks (BEVABS) under the JRC. Using magnetic resonance, scientists examined how the wine was made and whether sugar was added to it. Research in the field of climate and ecology was expanded. In 2000, the JRC facilitated the discovery of the first plutonium compounds to demonstrate superconductivity.

Thanks to the Centre's competencies in data analysis, modelling and information quality, in the 2000s, it began supporting the European

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[36] EC official site (https://ec.europa.eu/jrc/en)

Commission in statistics, macroeconomic modelling, financial econometrics and sensitivity analysis, multicriteria social evaluation and knowledge assessment.

The Centre cooperates with more than a thousand organisations around the world whose scientists have access to many of the JRC's facilities through various collaboration agreements.[37]

The Joint Research Centre (JRC) supports the EU policy with independent scientific research. The Centre, in essence, develops tools and makes them available to regulators and politicians. The JRC is part of the European Commission's Directorate-General, which is headed by the Commissioner for Innovation, Research, Culture, Education and Youth.[38] The Centre is governed by a Board of Governors, which assists and advises the Director General and the European Commission on the strategy and role of the JRC, its scientific, technical and financial governance. The Board members also represent JRC's interests in their respective countries.

The JRC's non-nuclear research activities are funded within the EU Research and Innovation Framework Programme Horizon 2020[39], while nuclear research activities are funded by the EURATOM Research and Training Programme. The JRC's annual budget is €330 million.

The model complex developed by the JRC is an integrated model that allows evaluating climate change scenarios and its impact on energy, transport, industry, agriculture, forestry, land use, atmospheric dispersion, health, ecosystems (acidification, eutrophication), macroeconomics with many sectors, employment and social security in the EU.

PESETA IV - adaptation scenarios and climate change impacts

The JRC PESETA IV project aims to better understand the biophysical and economic consequences of climate change. It does this by using projections of climate change for Europe from several climate models along with a set of climate change impact models. The project covers several sectors that are relevant to society and the natural environment, such as coastal floods, river floods, droughts, agriculture, energy supply, transport, water resources, habitat loss, forest ecosystems, wildfires, labour productivity and human mortality. Most estimates are based on the assumption that future climate change will occur in the present, which will affect today's economy and population. The economic consequences of the predicted impacts are estimated.

Methodologies

The negative impact of climate change is extremely diverse and multifaceted, and forces biophysical impact models, which result in economic consequences.

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[37] Highlights of the JRC 50 years in science, EU, JRC 2007

[38] https://ec.europa.eu/jrc/en/about/organisation

[39] Horizon 2020 is the largest EU research and innovation programme with funding of €80 billion for 7 years (from 2014 to 2020) - in addition to private investment.

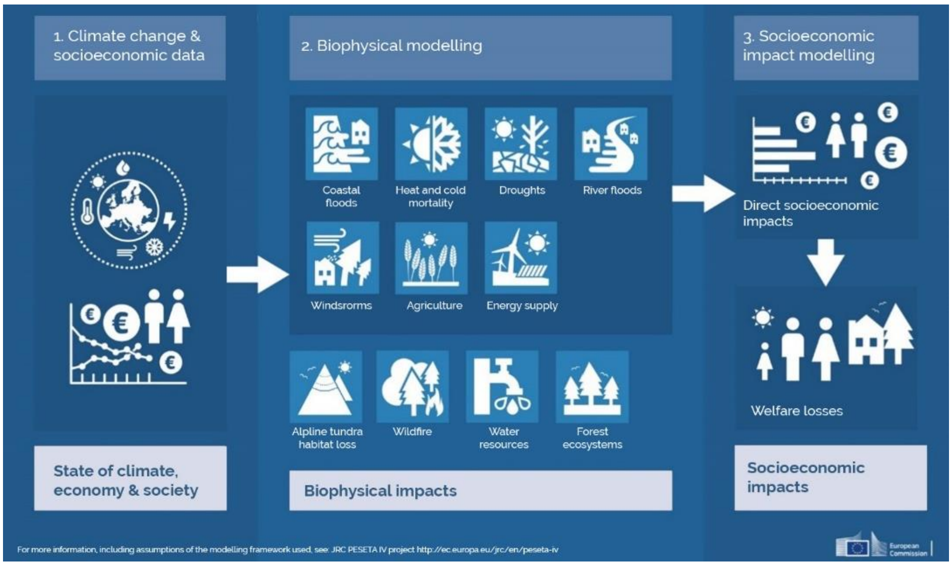
To find a solution to this problem, careful modelling of the impacts of climate change and a scenario approach are necessary. So, in the PESETA project, the bottom-up approach is applied, and three main methodological steps can be distinguished.

PESETA IV evaluates the benefits (avoided negative impacts) of reducing greenhouse gas emissions and the potential of adaptation measures at the EU sectoral level. This is done by assessing the sectoral climate change impacts (damages) in the future when mitigation and adaptation policy actions take place, compared to a situation where no policy actions are taken. For the scenario without climate policy actions, impacts are assessed at global warming of 3 °C and no adaptation. The benefits of mitigation policy, from achieving the Paris Agreement warming goals, are evaluated by estimating impacts with 1.5 °C and 2 °C global warming. Various sector-specific adaptation mechanisms are considered for some sectors.

The approach comprises the following three stages (Figure 2)

1. First, scenarios of climate change and socio-economic development are selected.
2. At the second stage, the models, which are used to quantify how the projected changes in climate variables affects agriculture, energy supply, river floods, coastal floods, the effects on human mortality due to heat and cold waves, droughts, forest ecosystems, alpine tundra habitat loss, wildfires, water resources, and windstorms, are run.
3. At the third stage, industrial and harmful impacts are consistently evaluated in a broader economic context. Some of the biophysical impacts are analysed in terms of direct human impacts and economic losses; in particular, for agriculture, energy supply, river floods, coastal floods, heat and cold waves, droughts, and windstorms. Finally, the direct human and economic impacts are integrated into an overall economic model in order to estimate corresponding welfare losses.

Figure 2 – Overview of PESETA IV methodology



Source: European Commission, the JRC PESETA IV project

Climate modelling in PESETA IV

The climate models used in PESETA IV simulate physical climate processes on a grid that covers the whole of Europe. The climate models used are known as "regional climate models", which means they produce climate projections at a relatively small scale (0.11 degree, ~ 12.5 km). In other words, these models have the most detailed scale of all currently available scales for pan-European studies.

Simulations of the climate will differ between climate models, even when the forces that drive climate change, such as greenhouse gas emissions, are the same. This is known as climate modelling uncertainty. To account for this uncertainty, PESETA IV uses an ensemble of 11 regional climate models that took part in a large, on-going climate model inter-comparison project called Coordinated Regional-climate Downscaling Experiment over Europe (EURO-CORDEX)[40].

Climate change impact modelling showed a clear division between north and south of the EU.

The three warming levels used in PESETA III (1.5 ˚C, 2 ˚C, and 3 ˚C) were estimated from two greenhouse gas emissions scenarios (RCP4.5 and RCP8.5) for each of the 11 regional climate models, to account for the effects of different warming rates on average global temperature, as the year when any given warming level is reached (e.g., 2 ˚C) will differ between both climate models and emissions scenarios (Table 4). Figure 3 shows the change in annual temperatures and precipitation across Europe between the present (1981-2010) and the three warming scenarios.

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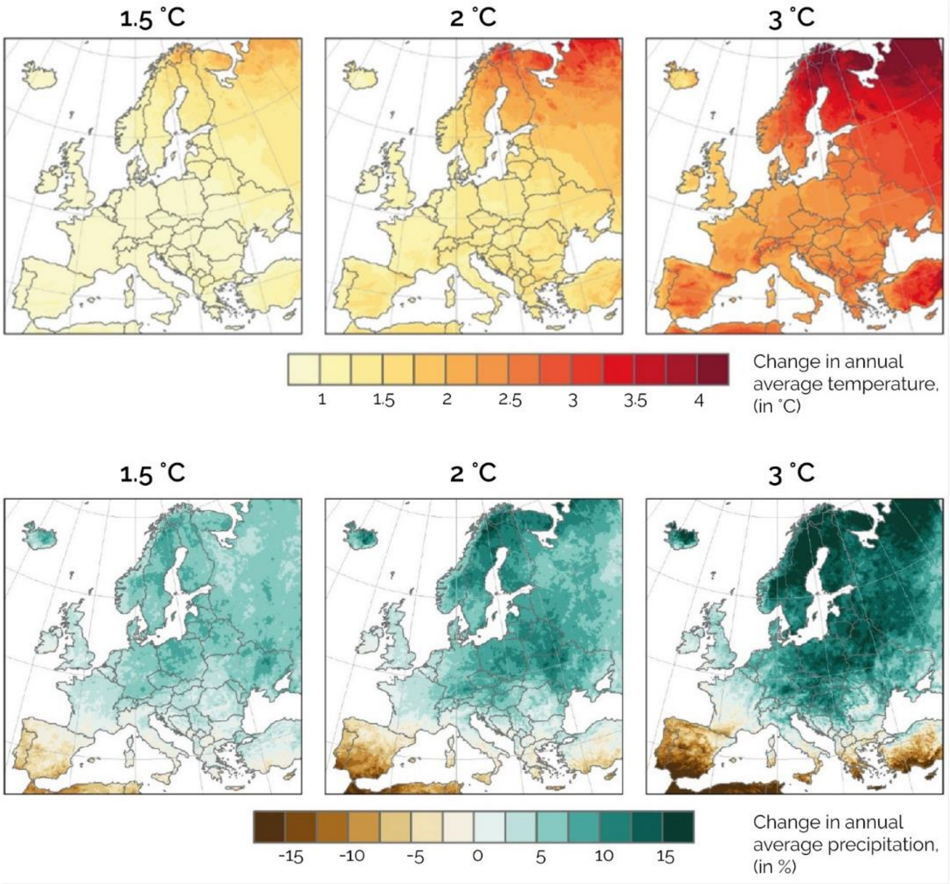
[40] http://euro-cordex.net

Table 4 – Priority subset of 5 climate models used in PESETA III, and the year of reaching 2 °C

	The full name of the climate model	2 °C
H1	CNRM-CERFACS-CNRM-CM5_r1i1p1_CLMcom-CCLM4-8-17	2044
H2	ICHEC-EC-EARTH_r12i1p1_CLMcom-CCLM4-8-17	2041
H3	IPSL-IPSL-CM5A-MR_r1i1p1_IPSL-INERIS-WRF331F	2035
H4	MOHC-HadGEM2-ES_r1i1p1_SMHI-RCA4	2030
H5	MPI-M-MPI-ESM-LR_r1i1p1_SMHI-RCA4	2044

Source: European Commission, the JRC PESETA III project

Figure 3 – Changes from the present (1981-2010) in annual temperatures (top panels) and precipitation (bottom) for the three global warming scenarios used in PESETA IV (1.5 °C, 2 °C, and 3 °C warmer than pre-industrial).



Source: European Commission, the JRC PESETA IV project

Overview of impact models

PESETA IV uses state-of-the-art impact models to quantify the effects of climate change on several sectors across Europe (Table 5). Some of the models are used across multiple sectors because the projections from one impact model can be used as input to another model, e.g., the hydrological model projections are used to estimate the impact of climate change on river flooding, drought, water availability, and energy (for hydropower).

Table 5 – The impact sectors investigated by PESETA III and the impact models used

Impact category	Biophysical impact assessment model	Modelling the socio-economic impact
Water resources	LISFLOOD	Impact on population affected by water scarcity Static and dynamic models
Coastal floods	Flood inundation mapping	Empirical flood damage function Static and dynamic flood models
River floods	LISFLOOD and inundation mapping	Empirical flood damage function
Drought	LISFLOOD	Empirical drought damage function Static and dynamic models
Agriculture	CARPI and WOFOST	Agricultural economics modelling using the regional impact model of the Common Agricultural Policy (CAPRI)
Energy	POLES	Modelling of energy production costs
Wildfires	Fire Weather Index (FWI) system	
Habitat loss	Climate zoning	
Heat and cold extremes	Empirical statistical model	Human impact and empirical mortality rates
Windstorms	Empirical statistical model	Empirical wind and human mortality damage function
Forest ecosystems	Empirical statistical model	
Economic integration		Integrated economic modelling for climate assessment using the General Equilibrium Model (CaGE)

Source: European Commission, the JRC PESETA IV project

Socio-economic scenarios

PESETA IV primarily aims to assess impacts as if future climate change were to occur in the present, affecting today's economy and population. Therefore, most of the sectors assume that current levels of population and gross domestic product (GDP) do not change in the future. This is known as a "static" analysis.

However, in some cases, it is interesting to also understand the sensitivity of impacts to future socioeconomic change. To this end, impacts under different assumptions of future socioeconomic change are also estimated for 2050 and 2100, for coastal and river flooding, drought, windstorms, health, and market adjusted assessment of crop production. For these sectors, high-resolution population projections were derived from the ECFIN 2015 Ageing Report to account for population dynamics. Comparison of these "dynamic" impacts with the "static" impacts allows disentangling the effects of climate and socioeconomic changes on future climate risk.

Appendix 1 provides a more detailed description of the models for EU studies.

Peseta IV results

Limiting global warming to below 2 °C will significantly reduce the impact of climate change in Europe.

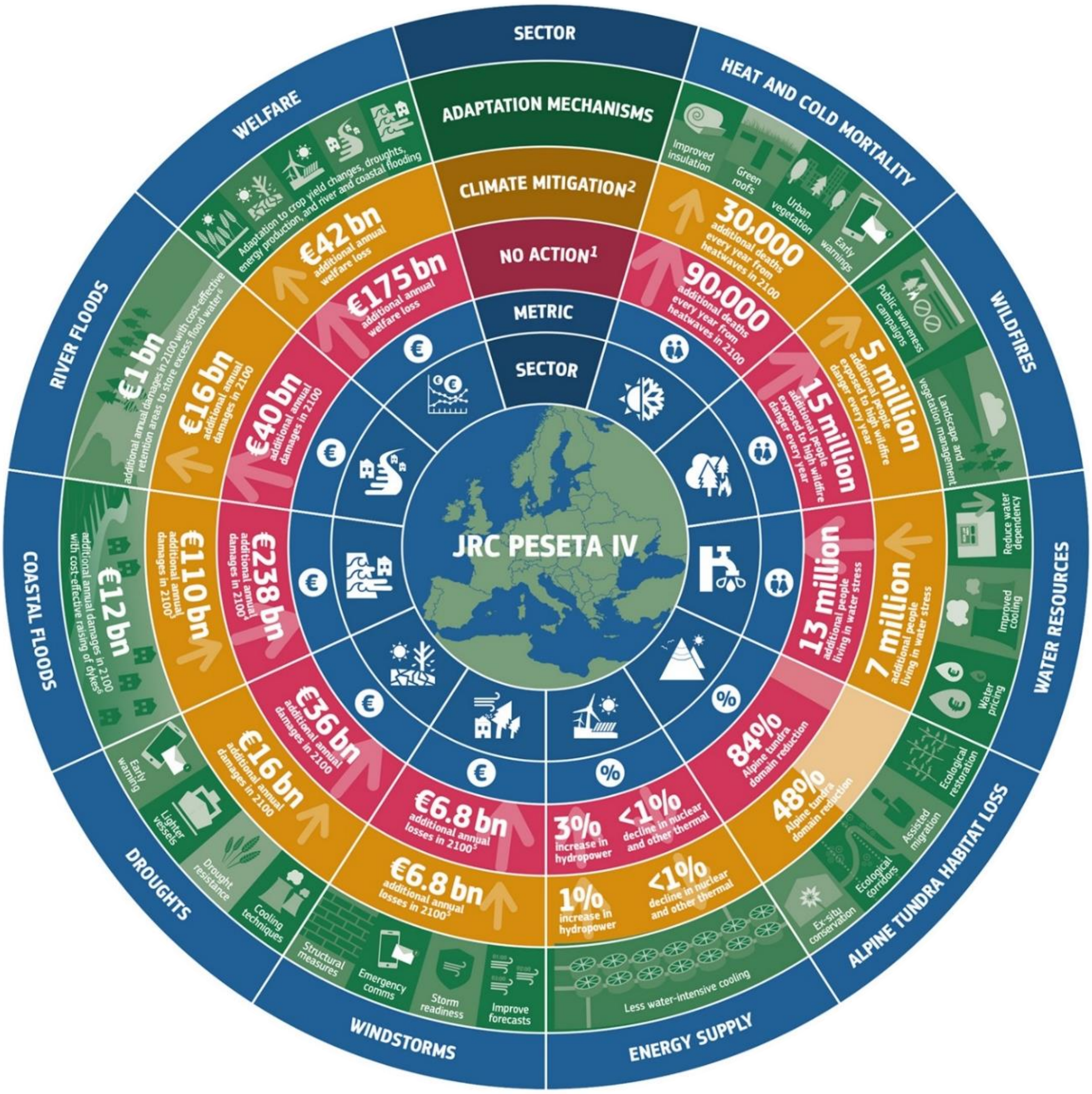
Climate mitigation can considerably lower the impacts of future climate change in Europe. But not all the impacts will be avoided by mitigation. Adaptation can further reduce climate change impacts in a cost-efficient way.

Thus, the economic losses in the global warming scenario for 3 °C (the red part of the below circle) will be about €500 billion. At the same time, 28 million people will be further affected by water stress and forest fires, and climate change will lead to the additional deaths of 90,000 people from heatwaves by 2100. 84% of the Alpine tundra will be lost.

In the climate mitigation scenario, economic losses will be lower (the yellow part of the circle), amounting to about €190 billion. At the same time, 12 million people will be further affected by water stress and forest fires, and climate change will lead to the additional deaths of 30,000 people from heatwaves by 2100. 48% of the Alpine tundra will be lost.

In the adaptation scenario, the economic losses will be lower (the green part of the circle) and will amount to about €13 billion. At the same time, the annual investment from now to 2100 for the installation and maintenance of reservoirs will amount to €3.3 billion per year. The strengthening of protection along the coastline of populated and economically important coastal areas will avoid €220 billions of flood losses annually in the EU and the UK by the end of this century, at an annual cost of less than €2 billion per year from now to 2100 (Figure 4).

Figure 4 – PESETA IV results in brief



NO ACTION 3˚C
CLIMATE MITIGATION 1.5˚C
ADAPTATION MECHANISMS

Source: European Commission, the JRC PESETA IV study

Adapting to climate change will allow minimising unavoidable impacts in a cost-effective manner.

The JRC PESETA IV study shows that ecosystems, people, and economies in the EU will face major impacts from climate change if we do not urgently mitigate greenhouse gas emissions or adapt to climate change. The burden of climate change shows a clear north-south divide, with southern regions in Europe much more impacted, through the effects of extreme heat, water scarcity, drought, forest fires, and agriculture losses.

Limiting global warming to well below 2 ˚C would considerably reduce climate change impacts in Europe. Adaptation to climate change would further minimise unavoidable impacts in a cost-effective manner, with considerable co-benefits from nature-based solutions.

Model complex for analysing decarbonisation and mitigation policies in the EU

Decarbonisation scenarios provided a global context for the development of the EU's long-term strategy

Besides PESETA model complex for analysing climate change impacts and adaptation scenarios, the EU has developed a toolkit for quantifying decarbonisation and mitigation scenarios, which helps the European Commission to analyse possible regulatory options.

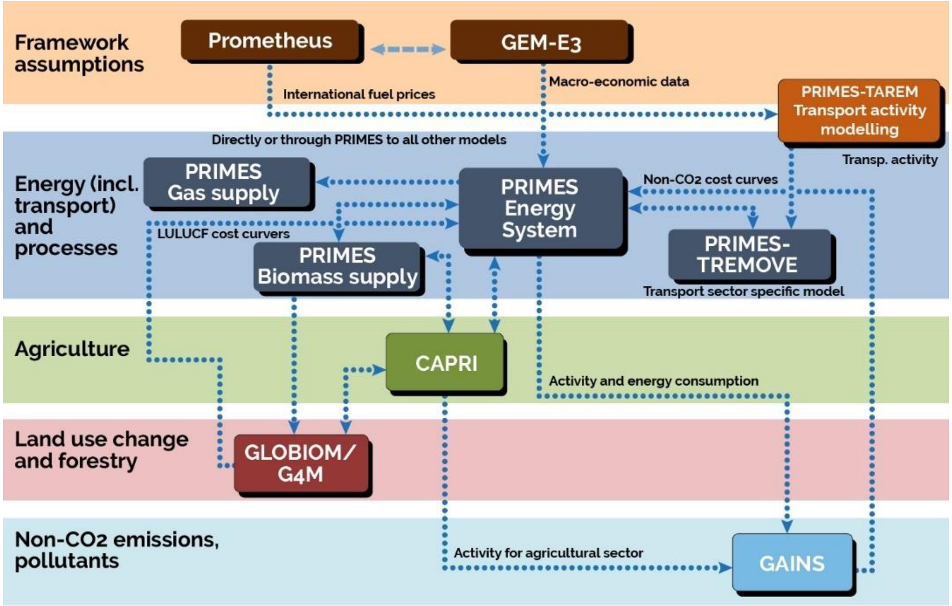
A key part of the decarbonisation scenario modelling is the regular production of updated EU and member state GHG emission reference scenarios under current trends and policies, in consultation with member state experts. Policy scenario results provide analytical information to support the analysis of environmental, economic, and social impacts, e.g., cost-effectiveness analysis and other complex analyses involving multiple objectives.

Model complex structure

The models cover all GHG emissions and removals (Figure 5).

- Emissions: CO_2 emissions from energy and processes (PRIMES), CH_4, N_2O, fluorinated greenhouse gases (GAINS), CO_2 emissions from LULUCF (GLOBIOM-G4M), air pollution SO_2, NO_x, $PM_{2.5}$-PM_{10}, ground level ozone, VOC, NH_3 (GAINS)
- Emissions reduction and removal: structural changes and technologies in the energy system and industrial processes (PRIMES), technological non-CO_2 emission reduction measures (GAINS), changes in land use (GLOBIOM-G4M-CAPRI)
- Geography: all individual EU member states, EU candidate countries, and, where relevant, Norway, Switzerland, and Bosnia and Herzegovina
- Impacts: energy, transport, industry, agriculture, forestry, land use, atmospheric dispersion, health, ecosystems (acidification, eutrophication), macro-economy with multiple sectors, employment, and social welfare

Figure 5 – Modelling tools for EU energy sector analysis



Source: European Commission

Some results of modelled scenarios for analysing decarbonisation and mitigation in the EU

Stimulating renewables energy efficiency, hydrogen and new approaches to mobility is not enough to achieve the EU net-zero emission targets by 2050

The IMAGE, POLES and GLOBIOM models were used to produce global scenarios compatible with 2 °C and 1.5 °C, with several variants (e.g. low biomass use). The EU mitigation reached in 2050 in these scenarios set the frame or confirmed that the mitigation considered in the EU scenarios (of -80% or -100%) was compatible with the global objectives of 2 °C/1.5 °C. It could be said that these scenarios provided the global context to the EU's long-term strategy[41] [42].

The EU, responsible for 10% of global greenhouse gas emissions, is a global leader in the transition towards a net-zero-greenhouse gas emissions economy. Almost in 2009, the EU set a goal to reduce emissions by at least 85-90% by 2050[43].

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[41] Keramidas, K., Tchung-Ming, S., Diaz Vazquez, A., Weitzel, M., Vandyck, T., DesprÃ©s, J., Schmitz, A., Rey Los Santos, L., Wojtowicz, K., Schade, B., Saveyn, B. and Soria Ramirez, A., Global Energy and Climate Outlook 2018: Sectoral mitigation options towards a low-emissions economy, EUR 29462 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97462-5, doi:10.2760/67475, JRC113446.

[42] Esmeijer K.,Elzen M., Gernaat D., Vuuren D., Doelman J., Keramidas K., Tchung-Ming S., Després J., Schmitz A., Forsell N., Havlik P., and Frank S., 2 °C AND 1.5 °C SCENARIOS AND POSSIBILITIES OF LIMITING THE USE OF BECCS AND BIO-ENERGY, Netherlands Environmental Assessment Agency The Hague, 2018

[43] Brussels, 28.11.2018 COM(2018) 773 final COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy

EU 2018 case: how decarbonisation scenarios in the EU were created

In 2009, the EU set a goal to reduce emissions by 80-95% by 2050. For this, a combined policy was developed that included:

- reformed EU emissions trading system (ETS),
- national greenhouse gas emission reduction targets,
- legislation established to maintain EU land and forests sink,
- targets to improve the EU's energy efficiency and to increase renewable energy by 2030, and
- legislation to improve the efficiency of cars.

However, model calculations showed that this policy would reduce greenhouse gas (GHG) emissions by only 60% by 2050.

To achieve those goals, eight additional pathways, all in line with the Paris Agreement, were developed. They were based on five scenarios that considered different technologies and actions that would contribute to the transition to a zero greenhouse gas economy. In this context, electrification grows with varying degrees, including from renewable energy sources, hydrogen and electric fuel (power-to-X), as well as energy efficiency of end users and the role of the circular economy.

These five scenarios achieve just above 80% greenhouse gas emission reductions, excluding land use and forestry, by 2050 compared to 1990. Including the decrease in land usage and forestry, which absorb more CO2 than they emit, these scenarios achieve around 85% net greenhouse emissions reductions by 2050 compared to 1990.

The first six scenarios generally ensured the achievement of the set goal of 80-95%, however, already at this stage, the EC began looking for ways to achieve zero emissions, and these scenarios did not ensure GHG neutrality by 2050.This is due to the fact that some GHG emissions will remain especially in the agricultural sector.

Therefore, it became obvious that it was necessary to study additional measures to reduce GHG emissions. For example, using biomass while increasing natural sinks in combination with carbon capture and storage technologies. The seventh and eighth scenarios examined these measures in detail to evaluate how to achieve neutrality of GHG emissions by 2050 and net negative emissions in the future.

The seventh scenario promoted all zero-carbon energy as well as energy efficiency, and relied on carbon-neutral technologies in the form of bioenergy combined with carbon capture and storage to balance the remaining emissions.

The eighth scenario was based on the seventh one, but also evaluated the impact of a circular economy and the potential positive role of changing consumer choice in favour of less carbon intensity. It also explored how to enhance land-use runoff to see how much it reduces the need for negative emission technologies.

Thus, the modelling of the scenarios made it possible to refine the decarbonisation measures in such a way that they were able to reduce emissions by 80-100%. Remember that in the original version they provided only 60% of the reduction in GHG emissions by 2050 compared to 1990

Evaluation of modelling results of goal achievement showed that the mere promotion of renewable energy sources (including biofuels), energy efficiency, circular economy, hydrogen and alternative fuels, or new approaches to mobility, is not sufficient for a net-zero greenhouse gas emissions economy by 2050. Under such technology scenarios, emissions are reduced by only 80% by 2050 compared to 1990. While combining all these options can reduce net emissions by around 90% (including the land use and forestry decrease), some greenhouse gas emissions will always, remain notably in the agriculture sector. Reaching net-zero greenhouse gas emissions will require maximising the potential of technological and circular economy options, the large scale deployment of natural land based carbon sinks (including in the agricultural and forestry sectors), and shifts in mobility patterns. The road to a net-zero greenhouse gas economy could be based on the joint action of the below seven main strategic building blocks.

Further investment in industrial upgrading, energy conversion, circular economy, clean mobility, green and blue infrastructure and bioeconomy will create new high-quality "Green Jobs".

Block 1. Maximise the benefits from energy efficiency including zero emission buildings.

Block 2. Maximise the deployment of renewables and the use of electricity to fully decarbonise Europe's energy supply.

Block 3. Use clean, safe, and connected mobility.

Block 4. Establish a competitive EU industry and circular economy as a key part of reducing greenhouse gas emissions.

Block 5. Develop an adequate smart network infrastructure and inter-connections.

Block 6. Reap the full benefits of the bio-economy and create essential carbon sinks.

Block 7. Tackle remaining CO_2 emissions with carbon capture and storage.

As for investment, modernising and decarbonising the EU's economy will stimulate significant additional investment. Today, around 2% of GDP is invested in our energy system and related infrastructure. This would have to increase to 2.8% (or around €520-575 billion annually) in order to achieve a net-zero greenhouse gas economy. This means considerable additional investments compared to the baseline, in the range of €175-290 billion per year. This is also in line with the IPCC special report that estimated that, between 2016 and 2035, investments are needed in the energy system representing about 2.5% of world GDP. However, certain options such as a rapid transformation towards a circular economy and behavioural changes have the potential to reduce the need for additional investment.

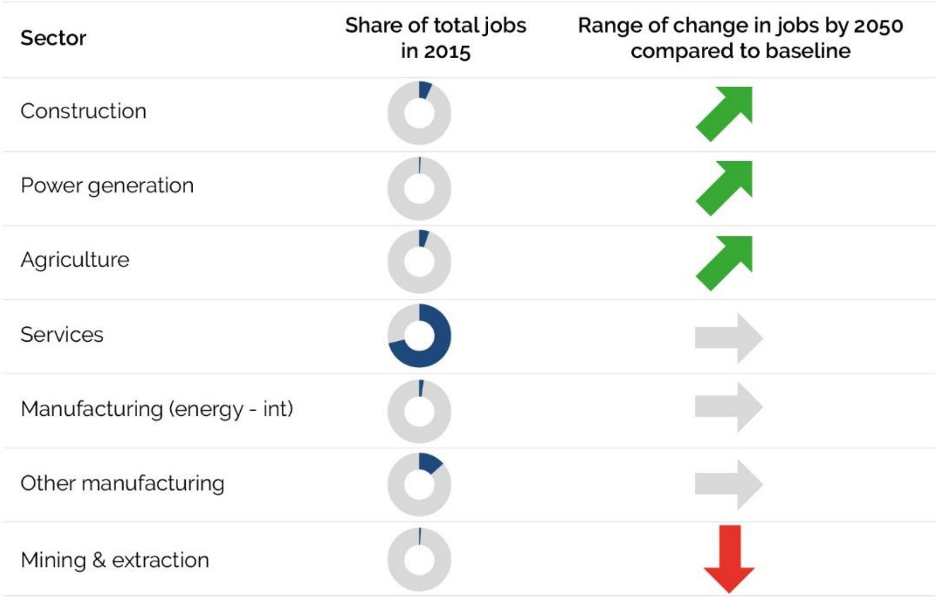
At the same time, significant health costs can be saved. Today, air pollution in the EU causes severe diseases and almost half a million pre-mature deaths annually with fossil fuels, industrial processes, agriculture, and waste being the main sources of pollution. These activities are also the main sources of greenhouse gases. Achieving a net-zero greenhouse gas emissions economy on top of existing air pollution measures will reduce pre-mature deaths caused by fine particulate matter by more than 40% and health damage by around €200 billion per annum.

Even without the net-zero greenhouse gas emissions transformation, Europe's economy and society will look significantly different in 2050 from the way it does today. Demographics indicate that our society will be ageing significantly, with potential implications on the sustainability of public finances. On the other hand, our population will be generally better equipped for working with information and communication technologies. Such trends will facilitate the transition. Overall economic impacts of the deep transformation are positive despite the significant additional investments required in all sectors of our economy. The EU economy is expected to more than double by 2050 compared to 1990 even as it fully decarbonises. A trajectory compatible with net-zero greenhouse gas emissions, together with a coherent enabling framework, is expected to have a moderate to positive impact on GDP with estimated benefits of up to 2% of GDP by 2050 compared to the baseline. Very importantly, these estimates do not include the benefits of the avoided damage of climate change and related adaptation costs.

Regions whose economies depend on activities that are expected to shrink or be forced to transform in the future, i.e. coal, oil and gas, mining industries, will be severely affected.

The transition will spur growth in new sectors. "Green jobs" already represent 4 million jobs in the EU. Further investment into the industrial modernisation, the energy transformation, the circular economy, clean mobility, green and blue infrastructure, and the bio-economy will create new, local, high quality employment opportunities. Actions and policies to implement the EU's 2020 climate and energy targets have already added between 1% and 1.5% to the EU labour force and this trend will continue. Whereas the number of jobs increases in construction, farming, and forestry, and renewable energy sectors, for a number of sectors the transition can be painful (Figure 6).

Figure 6 - Impact of decarbonisation on various sectors of the EU economy

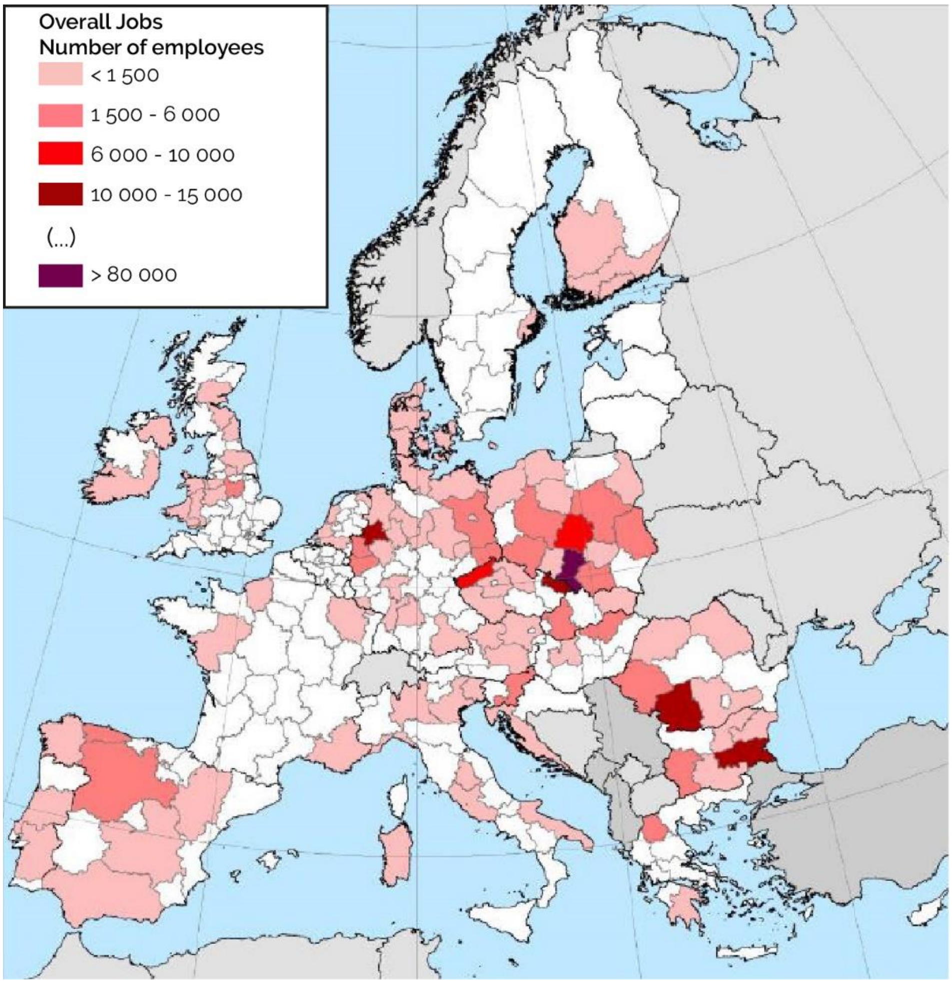


Sector	Share of total jobs in 2015	Range of change in jobs by 2050 compared to baseline
Construction	◔	↗
Power generation	◔	↗
Agriculture	◔	↗
Services	◕	→
Manufacturing (energy - int)	◔	→
Other manufacturing	◔	→
Mining & extraction	◔	↓

Source: In-depth analysis in support of COM(2018) 773

Particularly affected could be the regions whose economies depend on activities that either are expected to decline or will have to transform in the future. Areas such as coal mining and oil and gas exploration are likely to be affected. Energy intensive sectors such as steel, cement, and chemicals as well as car manufacturers will see a shift to new production processes with new skills required. Regions that depend economically on these sectors will be challenged, of which many are located in Central and Easter Europe, often in lower income member states (Figure 7).

Figure 7 - Total number of jobs in coal-fired power plants and coal mines in the EU

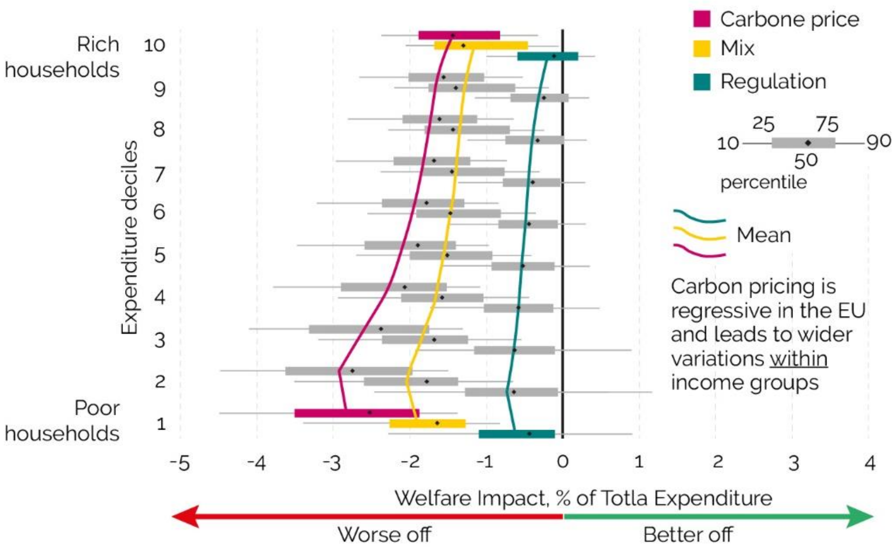


Source: Alaves Dias et al. (2018), EU coal regions: opportunities and challenges ahead, JRC112593

Other existing jobs will have to be transformed and adapted to the new economy. Managing this change requires taking into account a possibly shrinking and ageing labour force in the EU and the increasing substitution of labour due to technological changes including digitalisation and automation. Rural areas, for instance, will need to maintain a sufficiently skilled workforce to meet growing and changing demands in the agriculture and forestry sectors, while being confronted with a decreasing rural population. For small and medium enterprises, the transition is an opportunity, but also creates specific challenges such as access to skills and financing that need to be addressed.

The EU model complex allows exploring narrow questions, in particular, "What will have a greater impact on the population: regulation, a carbon tax, or a combination of the two?", or "What impact will a carbon tax have on different segments of the population depending on income?" Modelling shows that the carbon tax will have the greatest impact and will mostly affect low-income segments of the population. At the same time, the income from the carbon tax can be used to help this segment and, thus, to level the problem (figure 8).

Figure 8 - Effects of decarbonisation on various social groups (without compensation mechanisms)



Carbon pricing is regressive in the EU and leads to wider variations within income groups

Source: Temursho et al. (2020) Distributional impacts of reaching ambitious near-term climate targets across households with heterogeneous consumption patterns. JRC121765

BRIEF OVERVIEW OF MODELS IN RUSSIA

A fairly wide range of decarbonisation models is presented in Russia. There are models for various sectors of the economy, in particular: agriculture and forestry, transport sector, electricity and heat energy, processing industry, mining, oil refining, and construction.

Modelling of decarbonisation and adaptation scenarios has also been developing in Russia for several decades. This section provides a deliberately incomplete overview of models and model complexes existing in the country. Here one will find a short list of organisations that have participated in a series of modelling workshops organised jointly by the European Commission and the SKOLKOVO Energy Centre[44], as well as a description of the areas of application of these models is provided.

Decarbonisation models are represented in Russia in a fairly wide range and in various sectors of the economy, in particular, agriculture and forestry, transport, electricity and heat, industry, mining, oil refining, and construction.

Scientific institutes and other organisations that are engaged in modelling decarbonisation scenarios include the Institute for Energy Research RAS[45], RANEPA[46] [47] [48], JSC NIIAT (Moscow)[49], Irkutsk National Research Technical University, the Centre of Strategical Developments[50], the Obukhov Institute of Atmospheric Physics[51], CENEF-XXI[52] [53] [54], ISESP RAS, NUST MISIS, HSE University, the Institute for National Economic Forecasts RAS[55], MPEI, and MADI[56].

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[44] https://energy.skolkovo.ru/en/senec/media/2198-news-senec-09042020/#:~:text=On%20April%206%2C%20a%20first,scenarios%20took%20place%20by%20videoconference.&text=The%20workshop%20had%20several%20sessions,in%20several%20key%20economic%20areas.

[45] SCANER Super Complex For Active Navigation in Energy Research The Energy Research Institute of the Russian Academy of Sciences (ERI RAS) Scientific Editor Academician A. A. Makarov, 2011

[46] GLOBIOM documentation P. Havlík, et all, International Institute for Applied Systems Analysis (IIASA) 4 June 2018

[47] 2019 Golub A., Lugovoy O., Potashnikov V.: Quantifying barriers to decarbonisation of the Russian economy: real options analysis of investment risks in low-carbon technologies // Climate policy, v. 6, 716-724 pp. https://doi.org/10.1080/14693062.2019.1570064

[48] 2020 Safonov, G., Potashnikov, V., Lugovoy, O., ...Dorina, A., Bolotov, A.: The low carbon development options for Russia// Climatic Change, 2020, 162(4), pp. 1929-1945 https://doi.org/10.1007/s10584-020-02780-9

[49] Donchenko, V.V. Introduction of low-emission zones in cities as an effective tool for implementing the concept of ensuring the environmental sustainability of transport systems / Donchenko, V.V., Sharov, M.I., Chizhova V.S. // Bulletin of the Moscow Automobile and Road Construction State Technical University (MADI). - 2020. - No. 1 (60). - pp. 106-112.

[50] Prospects for the development of the coal industry in Russia: export potential, financial situation, socio-economic effects, Centre for Social and Economic Research, 2020.

[51] Alexandrov, G. A., Brovkin, V. A., Kleinen, T., and Yu, Z.: The capacity of northern peatlands for long-term carbon sequestration, Biogeosciences, 17, 47–54, https://doi.org/10.5194/bg-17-47-2020, 2020.

[52] Bashmakov, I.A. Low-carbon Russia: 2020. CENEF. Moscow, 2009. Costs and Benefits of a Low-Carbon Economy and Social Transformation in Russia: Prospects Before and After 2050. Edited by Bashmakov, I.A., Moscow, CENEF, 2014;.

[53] Bashmakov, I. A., Low-carbon development strategy for the Russian economy. Voprosy Ekonomiki. 2020. № 7, pp. 1—24.

[54] Igor Bashmakov. Improving the Energy Efficiency of Russian Buildings. Problems of Economic Transition, vol. 58, No. 11–12, 2016, pp. 1096–1128;

[55] Shirov, A.A., Kolpakov, A. Yu. Economy of Russia and mechanisms of global climate regulation, Journal of the New Economic Association, No. 4 (32), pp. 87–110

[56] Trofimenko, Yury & Komkov, Vladimir & Trofimenko, Konstantin. (2020). Forecast of energy consumption and greenhouse gas emissions by road transport in Russia up to 2050. Transportation Research Procedia. 50. 698-707. 10.1016/j.trpro.2020.10.082.

Macroeconomic models are presented in smaller numbers due to their complexity and scale. Their holders are CENEF-XXI[57], the Institute for National Economic Forecasts RAS (the Effects of Climate Change on Russia's Economy), and the Institute for Energy Research RAS (the Impact of the Fuel and Energy Complex on the Economic Development of Russia)[58].

Adaptation models are not widely represented in the Russian scientific community. They are studied at Yu. A. Izrael Institute of Global Climate and Ecology[59], MPEI (for electric power), and RANEPA (for agriculture).

Climate modelling is also carried out by Russian teams of scientists, in particular, at INM RAS[60], Climate Centre and IAP RAS[61].

A large number of teams are engaged in the study of processes and phenomena that are the consequences of climate change, this topic is widely represented by the following institutions: at Marchuk Institute of Numerical Mathematics RAS, Obukhov Institute of Atmospheric Physics, Lomonosov MSU, Voeikov Main Geophysical Observatory, Hydrometcentre of Russia, State Hydrological Institute, Institute of Computational Mathematics and Mathematical Geophysics, P.P. Shirshov Institute of Oceanology RAS, V.I. Ilichev Pacific Oceanological Institute Far Eastern Branch Russian Academy of Sciences, Water Problems Institute of the Russian Academy of Sciences, Limnological Institute Siberian Branch of the Russian Academy of Sciences, All-Union (All-Russian) Research Institute of Agricultural Meteorology, A.N. Severtsov Institute of Ecology and Evolution, Institute of Monitoring of Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences (IMCES SB RAS), Sukachev Institute of Forest of the Siberian Branch of the RAS, V.V. Dokuchaev Soil Science Institute, Institute of Geography, Russian Academy of Sciences, Centre for Forest Ecology and Productivity of the Russian Academy of Sciences, Institute of Physicochemical and Biological Problems in Soil Science, Yu.A. Izrael Institute of Global Climate and Ecology, Institute of Applied Physics of the Russian Academy of Sciences, Zuev Institute of Atmospheric Optics of the Siberian Branch of the RAS, Institute of Economic Forecasting of the Russian

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[57] Bashmakov I.A. Will there be economic growth in Russia in the middle of the 21st century // Voprosy Ekonomiki 2011. No. 3. - pp. 20-39

[58] Lukatsky, A.M.Malakhov, V.A., Fedorova G.V. Information and Analytical System for Researching the Relationship between Energy and Economics, Preprint WP2 / 2003/01 Series WP2, Quantitative Analysis in Economics, State University Higher School of Economics Moscow 2003

[59] Bogdanovich, A. Yu. Synergy of the global climate goal of sustainable development and the national adaptation plan in Russia / Bogdanovich, A. Yu. , Lipka O. N. // Problems of ecological monitoring and modelling of ecosystems, 2020, Vol. 31, No. 3-4, pp. 7-32, DOI 10.21513/0207-2564-2020-3-07-32.

[60] Alekseev V.A., Volodin E.M., Galin V.Ya., Dymnikov V.P., Lykosov V.N. Modelling the modern climate using the atmospheric model of the INM RAS, Moscow, Preprint of the INM RAS, 1998, p. 180

[61] Mokhov, I. I. Russian climatic research 2003–2006 / Mokhov I. I. // Bulletin of the Russian Academy of Sciences. Atmospheric and Oceanic Physics, 2009, Vol. 45, No. 2, pp. 180-192.

Academy of Sciences (IEF RAS), and Karpov Scientific Research Institute of Physics and Chemistry.

Taking into account geographic location of the country, in Russia, the models related to the Arctic and permafrost zone are actively developed in the country. They cover a wide range of topics, from how much cargo can pass through the Northern Sea Route to ensuring public health. These themes are developed by the following organisations: the Centre of Strategical Developments, RANEPA, the Pacific Geographical Institute of the Far Eastern Branch of the Russian Academy of Sciences, the Melnikov Permafrost Institute the Siberian Branch of Russian Academy of Sciences, the ECI Tyumen Scientific Centre SB RAS, the Sergeyev Institute of Environmental Geoscience Russian Academy of Sciences (IEG RAS), the National Research Tomsk State University, and the Arctic and Antarctic Research Institute.

Russian models cover quite well the transport sector (especially road transport) and the need for fuel in this segment, energy, oil and gas sector.

Much attention is paid to the theme of natural carbon sinks (forests, soil, swamps, etc.) by the scientific community, in particular, the Institute for Water and Environmental Problems of the Siberian Branch of the Russian Academy of Sciences, MSU, the Yu. A. Izrael Institute of Global Climate and Ecology, Institute of Soil Science and Agrochemistry, Centre for Forest Ecology and Productivity of the Russian Academy of Sciences (CEPF RAS), Space Research Institute, Kazan Federal University, A.M. Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences, and Water Problems Institute RAS.

At this stage, the information provided by the participants of the EU-Russia modelling workshop offered the possibility to get the description of 30 models. Russian models cover quite well the transport sector (especially road transport) and the need for fuel in this segment, energy (including heat production), oil and gas sector. In general, other sectors of the economy are also covered, but require more detail, especially in the industrial sector, which is represented only by corporate stakeholders. At the same time, the analysis shows a lack of adaptation, macroeconomic and agricultural models (Table 6).

From a regional point of view, the models cover Russia and its regions well, but there are few global models. In terms of the timelines, most models use the period up to 2050. No modelling is conducted for beyond 2050.

Table 6 - Aggregate table of Russian models

Sector	Status
Agriculture and forestry	🟧
Energy	🟩
Transport	🟩
Industry	🟥
Construction	🟧
Social security	🟧

🟥 lack of models 🟧 models are present 🟩 large pool of models

Source: compiled from the materials of the participants of the EU-Russia modelling workshops

The disadvantage of the Russian models is that most of them are scattered and stand apart from each other, and, as it follows from the above sections, the models must work together for the tasks of decarbonising the economy or adapting it to climate change.

It is also important to have a suite of models that will allow us to compare models. The comparison of models is an extremely important parameter that increases the confidence in them for the scientific community and, in particular, decision makers. This practice is used, for example, by the IPCC in its assessment reports.

The value of comparison and verification of various models for the development of the entire system on the example of the set of models "Flattening the carbon curve"

In 2014, Centre for Energy Efficiency (CENEF) analysed models and forecasts of greenhouse gas emissions in Russia. In addition to the Russian models, the results of the IEA scenarios from the work "Energy Technology Perspectives 2012" were included. The analysis revealed 30 scenarios (mainly for the energy sector) that covered the entire field of possible solutions: from slow to dynamic economic growth, and from the application of only existing measures to control emissions to drastic measures.

A comparison of all the scenarios obtained showed that it is highly likely that greenhouse gas emissions in the energy sector in Russia will reach the absolute upper limit by 2060, which will be 11% lower than the emissions of 1990. At the same time, the wider the range of GHG control measures used, the lower the upper limit of GHG emissions in the energy sector will be. Another conclusion from the analysis of the "Flattening the carbon curve" scenarios shows that measures and policies on GHG emissions do not slow down economic growth.

When comparing model parameters, it is important to consider the following parameter types: exogenous, endogenous, internal system change, environmental system change, and system restriction.[62].

When modelling or comparing Russian models with foreign ones, it is important to take into account some peculiarities of Russia. The first feature is territorial and climatic. So, when modelling the absorption and emission of CO_2 in Russia, it is

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[62] According to the I. Bashmakov's presentation on the 6th EU-Russia modelling workshop, April 8, 2021

necessary to take into account the large volume of forests, swamps, as well as territories located in the permafrost zone - this fact will strongly affect the input data of the models, the level of expected emissions in a given global context of climate change, as well as the selection of mitigation measures.

When modelling or comparing Russian models with foreign ones, the following should be taken into account:

1. a large volume of forests, swamps, as well as territories located in the permafrost zone.
2. the structure of exports and imports in Russia.

The second feature is the structure of exports and imports. Russia exports hydrocarbons, and then at the expense of foreign exchange earnings not only imports consumer goods that are not produced in the country, but also goods and equipment necessary for the extraction of hydrocarbons, which at this stage could not be localized and produced in Russia.

The dependence of the budget on hydrocarbon exports raises an important question for modelling: how will the Russian economy go through the loss of export revenues and with what funds will the country import low-carbon technologies?

Further prospects for the development of modelling of decarbonisation and adaptation scenarios in Russia are still unclear. Russian regulators already understand the importance of studying this area (climate change), and, from our point of view, modelling of adaptation and mitigation scenarios should become part of these studies.

In February 2021, Russian President Vladimir Putin signed a decree launching the federal scientific and technical programme in the sphere of ecological development and climatic changes for 2021-2030, stipulating development of science-intensive technological solutions aimed at the provision of environmental security; the improvement of the environment; the climate study, mechanisms of adaptation to climate change consequences; and the provision of sustainable and balanced socio-economic development of the Russian Federation with a low level of greenhouse gas emissions by conducting research on sources and sinks of greenhouse gases and taking measures to reduce the negative impact of such gases on the environment.

In fact, according to this document, the priority scientific and technological directions are the development of mechanisms for adaptation to climate change (recall that, according to the primary information on model suites in Russia, received from the participants of the seminars, adaptation models are poorly developed) and the use of natural sinks of greenhouse gases. At the same time, the document does not mention the technologies, mechanisms, and scenarios of decarbonisation.

The document suggests the implementation and development of scientific and educational Centres and laboratories within scientific and educational organisations that carry out research in the field of Russian environmental development and climate change, and the technical support for such research and training in this field, including the involvement of private investors.

CONCLUSIONS AND RECOMMENDATIONS

Amid growing concern about climate change, the modelling of scenarios of decarbonisation and adaptation to climate change is already becoming integral to the formation of long-term strategies for politicians, regulators, companies, financial organisations and NPOs around the world. The solution to the problem of climate change is no longer just a declaration of good will on paper, but an actionable task comprised of concrete measures and steps, such as the introduction of emission pricing in the EU, which would have an impact on the economy at both the regional and global levels.

Modelling of adaptation and decarbonisation scenarios becomes critical for decision-makers, as it allows to justify one or another policy in the field of decarbonisation, adaptation and regulation of GHG emissions, answer questions of interest and help develop the necessary measures and steps to achieve the adopted goals. From a technical point of view, modern modelling tools are complex sets of interconnected various approaches to model construction (bottom-up, top-down, integrated models).

To build such models, or rather model suites, requires a multidisciplinary approach and the efforts of various research teams, including everyone from climatologists to industry specialists. Only through partnership and cooperation, not only within a single country, but also at the global level, will it be possible to create the most complete model suites that meet today's requirements. At the same time, for the creation of such model suites, it is not enough to have only a scientific foundation. It is extremely important to have state participation and encouragement. Moreover, not only is the financial aspect important, it is also important that the main stakeholders request this information and aim to set goals in the first place. For example, the EU already has a similar modelling system for the European Commission. This system can be divided into two large toolkits: a toolkit for building adaptation scenarios and a toolkit for developing decarbonisation scenarios. Note that adaptation and decarbonisation scenarios for the European Commission have been developed in a single scientific hub JRC. At the same time, the hub itself operates on the distributed research principle, i.e. research is carried out in many organisations, some of which are part of the JRC, and some are not, and simply provide their own modelling tools for building scenarios.

The analysis of Russian models and model complexes showed that academic institutions have developed quite deeply the modelling of decarbonisation scenarios in the fuel and energy complex, which accounts for more than 2/3 of GHG emissions in Russia, and in the transport sector. The agriculture and industrial sectors are covered to a lesser extent. For example, the modelling in industry is represented only by corporate stakeholders. Adaptation models are fragmented by country region and by sector.

For Russia, this issue is especially relevant, since the energy transition unfolding in the main markets for our export products, the new climate policy of the Biden administration and China, the EU Green Deal pose huge challenges to the historically established hydrocarbon and resource model of the Russian economy. We have to find new growth points, to integrate into new global value chains focused on low-carbon energy sources. At the same time, decarbonising our own economy and investing in adapting to inevitable climate change also require careful planning and coordination.

Given the scale and role of the fuel and energy complex and energy-intensive industries in the Russian economy, decarbonisation programmes must be built in cross-sectoral coordination and taking into account the interests and priorities of the largest megacities and regions of the country.

Developed model complexes and a dialogue built on their basis between the business, public authorities, and representatives of scientific community (climatologists, industry institutes, sociologists, political scientists) are the necessary conditions not to be late and to consolidate the place of the Russian economy in the new global technological order.

To date, the resources aimed at understanding the effects of the global energy transition and climate change, as well as their effects on the economy of the Russian Federation and forecasting future scenarios of low-carbon development of the Russian Federation, look significantly smaller than abroad. In addition, the formation of bottom-up strategies is practiced, when a national strategy in a particular area is built by using the corporate initiatives of industry companies. The Energy Strategy of the Russian Federation until 2035, adopted in June 2020, practically does not address either climate risks or the risks and opportunities of energy transition. The strategy of low-carbon development of the Russian Federation until 2050 is still being discussed, and its connection with the scientifically grounded models of various institutes of the Russian Academy of Sciences is not quite clear. With this approach, we run the risk of missing the time required to form a well-thought-out and balanced position, and being unprepared for negotiations with more prepared international partners.

In addition, both in the business community and among the population, incomplete or erroneous ideas about climate change, energy transition and their consequences for the Russian Federation are widespread.

In our opinion, it is necessary:

- Invest in complementing the national ensemble of models for modelling adaptation to climate change and developing a strategy for the development of the Russian Federation, which will create the basis for the development of climate change mitigation and adaptation scenarios in the context of the low-carbon world economy and expand the circle of research teams, working on this issue, by creating open source models.
- Create a platform for a comprehensive discussion of the findings, both between representatives of the scientific community and between the scientific community, business and government authorities.
- Launch educational programmes to popularise knowledge about climate, energy transition and possible directions of the climate strategy of the country and individual industries.

ANNEX 1. DESCRIPTIONS OF EU MODEL COMPLEXES

Model PRIMES

Objective:

PRIMES provides detailed projections of energy demand, supply, prices, and investments in the future, covering the entire energy system including emissions for each European country and for the Europe-wide trade of energy commodities.

Methodology:

The model is the combination of behavioural modelling following a micro-economic foundation with engineering and system aspects, covering all sectors and energy markets.

Target function:

Mathematically, PRIMES solves an EPEC (equilibrium problem with equilibrium constraints), which allows prices to be explicitly determined.

Timeline	Geography	Sectoral coverage	Input data	Output data
1990 to 2050 (5-year increments)	EU Member States, Norway, Switzerland, and Bosnia and Herzegovina	Industry Tertiary sector Commercial and household sectors Transport Heat and power generation Production of gas, oil products, biofuel	GDP and economic growth per sector World energy supply outlook, world prices of fossil fuels Taxes and subsidies Interest rates, risk premiums, etc. Environmental policies and constraints Technical and economic characteristics of future energy technologies Energy consumption habits, parameters of comfort, rational use of energy and savings, energy efficiency potential Parameters of supply curves for primary energy, potential of sites for new plants especially regarding power generation sites, renewables potential per source type, etc	Energy balances Demand projections by sector including end-use services, equipment, energy savings Balance for electricity and steam/heat, including generation by power plants, storage, system operation Production of fuels Investment in all sectors, supply and demand, technology developments, vintages Transport activity Energy costs, prices, investment expenses per sector and overall CO2 Emissions from energy combustion and industrial processes Emissions of atmospheric pollutants Policy Assessment Indicators

Model GAINS

Objective:

Aimed at assessing air pollutants and non-CO2 GHG emissions and their interactions. GAINS is used as part of the standard modelling framework for negotiations under the Convention on Long-range Transboundary Air Pollution and the European Union.

Methodology:

The emission estimation is based on a methodology similar to the simplified methodology of the EMEP/EEA air pollutant emission inventory guidebook. The optimisation model determines where emissions can be reduced most cost-effectively.

Target function:

This model can be operated in two ways.

1. In “scenario analysis” mode, it follows emission pathways from sources to impacts, providing estimates of regional costs and the environmental benefits of alternative emission control strategies.
2. In “optimisation” mode, it identifies where emissions can be reduced most cost-effectively.

Timeline	Geography	Sectoral coverage	Input data	Output data
1990 to 2050 (5-year increments)	Europe (for 48 countries) Asia, with separate implementations for China (31 provinces), India (15 States) Annex I countries of the UNFCCC Convention	By fuel type, energy and transport by sector and type, other processes, ammonia emissions, NMVOCs	Production and economic indicators that characterise economic activity Parameters that characterise emissions (specific indicators of emissions of pollutants (without cleaning) from the main processes (sectors) Parameters that characterise emission reduction technologies (e.g., type of dust and gas treatment plant and its efficiency) Policies at the national level	Emissions by sectors and sources

Model GLOBIOM - G4M

Objective:

The model represents various land use-based activities, including agriculture, forestry, and bioenergy sectors. It was initially developed for impact assessment of climate change mitigation policies in land-based sectors, including biofuels. Now it is also increasingly being implemented for agricultural and timber markets foresight, economic impact analyses of climate change and adaptation, and a wide range of sustainable development goals.

Methodology:

This global recursive dynamic partial equilibrium model is built following a bottom-up setting based on detailed grid-cell information, providing biophysical and technical cost information.

Target function:

Market equilibrium is solved by maximizing the sum of producer and consumer surplus subject to resource, technological, and political constraints.

Timeline	Geography	Sectoral coverage	Input data	Output data
2000 to 2050 (10-year increments)	The global model, 50 world regions with disaggregation	Agricultural, bioenergy, forestry sectors	Geo-spatial data on soil, climate, weather, topography, land cover/use, crop management Assumptions on GDP, population growth, calorie consumption per capita Crop improvement Biofuel target	Biomass by species Accounting for greenhouse gas emissions and effluents from agricultural and forestry activities

Model PROMETHEUS

Objective:

This is aimed at the generation of stochastic information for key energy, environment, and technology variables. These variables include

- long-term restructuring of energy systems,
- fossil fuel resources and computation of international fuel prices,
- measuring uncertainty pertaining to the evolution of the energy system,
- full coverage of all energy sectors globally, and
- individual modelling of the main global carbon emitters.

Methodology:

Equations in PROMETHEUS represent the model's endogenous variables as a function of other endogenous variables, exogenous variables, parameters, and residual terms. All endogenous variables are stochastic and display covariance, the origins of which are analytically traceable using the model itself. The output of PROMETHEUS consists of empirical joint distributions of all endogenous variables obtained by applying the Monte Carlo method.

Timeline	Geography	Input data	Output data
2008 to 2050 (1-year increments)	OECD-Europe The New Members States (NMS-12) of the European Union (Czech republic, Slovakia, Slovenia, Malta, Cyprus, Poland, Hungary, Latvia, Lithuania, Estonia, Bulgaria, Romania) North America Western Pacific, which includes Japan, Australia, New Zealand India China Former Soviet Union excluding the Baltic Republics The Middle East (from the Mediterranean to the Iranian border with Afghanistan and Pakistan) North Africa (Egypt, Libya, Tunisia, Algeria, Morocco) Emerging economies (Latin America, South-Eastern Asia) Rest of the world (the least developed countries)	Population, work force GDP, economic growth per region Economic indicators (industrial value added, household income) World fossil fuel reserves and resources (for conventional and unconventional oil and gas resources) Taxes and subsidies for energy products Technology standards Energy efficiency and CO2 emission regulations Technical and economic characteristics of energy, transport and power generation technologies Supply curves and fuel availability constraints (e.g., renewables potential, domestic reserves, resources for fossil fuels, import limitations, potential of sites for nuclear, hydro power plants) Targets for emissions, renewables and energy efficiency	Detailed energy supply and demand balances for each region Energy demand by sector (industry, residential, transport) and by product/energy form Transport activity, fuels, passenger vehicles Detailed power generation mix by technology Production of fossil fuels (conventional and unconventional) Energy prices per fuel resulting from market equilibrium CO2 Emissions from fossil fuel combustion by sector Policy Assessment Indicators (e.g., carbon intensity ratio, RES shares, energy efficiency indices, energy system costs, etc.)

Model GEM-E3

Objective:

This is a general equilibrium model of international-national interactions between economy, energy, and the environment. It is a comprehensive model of the economy, the production sectors, consumption, price formation of commodities, labour and capital, investment, and dynamic growth. For the PESETA IV project, a simpler version of the model (CAGE) was used.

Methodology:

It is a general equilibrium model. The model is formulated as a simultaneous system of equations with an equal number of variables. The system is solved for each year in a recursive dynamic fashion.

Target function:

Maximising utility by consumers and profit by producers.

Timeline	Geography	Sectoral coverage	Input data	Output data
2014 to 2050 (5-year increments)	Different model versions exist for different applications with different geographic coverage	All production sectors (agriculture, coal, gas, oil, ferrous and non-ferrous metals, chemical products, paper products, electricity supply (coal, oil, gas, CCS coal, CCS gas, biomass, nuclear, PV, hydroelectric, wind), transport (air, land, water), transport equipment, other equipment, electric products, consumer goods, building, market services, non-market services)	GTAP database and Eurostat with economic data Typically, energy model outputs such as energy balances Population projections Labour market projections from ILO	Dynamic projections in volume, value and deflators of national accounts by country Full Input-Output tables for each country/region identified in the model Employment by economic activity and skill, unemployment rate by country Greenhouse gasses, atmospheric emissions, pollution abatement, capital, purchase of pollution permits, damages Consumption matrix by product, investment matrix by ownership branch Public finance, tax incidence, revenues by country Full bilateral trade matrices

Model CAPRI

Objective:

This is for evaluating extant impacts of the Common Agricultural Policy and trade policies on production, income, markets, trade, and the environment, on the global and regional scales.

Methodology:

CAPRI is designed for scenario analysis. It is a comparative static model, which technically means that the market equilibrium simulated for a given point in time does not involve lags or leads of endogenous variables. As such, if several points in time are simulated, these simulations may be performed in any order or in parallel. CAPRI combines bottom-up and top- down approaches.

Target function:

Sequential iteration between the market and supply modules.

Geography	Sectoral coverage	Input data	Output data
EU27, Norway, Turkey, the western Balkans	Covering about 280 regions (NUTS 2 level) or even up to 10 farm types for each region (in total 2,450 farm-regional models, EU27)	Crop acreages, farm sizes, agricultural production CAP instruments, e.g., premiums and quotas Income indicators by type of activity and region Household/market balances and unit prices at the national level Policy variables on regional/national levels (premiums, quotas) and EU level (tariffs, administrative prices) Farm and market balance statistics Agricultural prices and price indices Market balances, tariff rates, preferential trade agreements, bilateral trade flows	Demand, supply and trade for 60 agricultural and processed products

Model POLES

Objective:

A comprehensive simulation model for worldwide energy supply, demand and prices. It provides quantitative, scenario-based, empirical and objective analysis of the energy sector for key stakeholders: private companies, governments, international organisations.

Methodology:

This is a world energy-economy integrated partial equilibrium simulation model of the energy sector, with complete modelling from upstream production to final user demand and greenhouse gas emissions. It simulates technology dynamics and follows the discrete choice modelling paradigm in the decision-making process. It determines market shares (portfolio approach) of competing options (technologies, fuels) based on their relative cost and performance while also capturing non-cost elements like preferences or policy choices.

POLES-JRC covers the entire energy sector, from production to trade, transformation and final use for a wide range of fuels and sectors. In addition, non-energy greenhouse gases as well as air pollutants are covered, be they associated with the energy sector or with other economic activities.

Target function:

Market equilibrium.

Timeline	Geography	Sectoral coverage	Input data	Output data
1990 to 2050 (1-year increments)	54 consuming countries +12 regions; including all EU member states and EU surroundings (UK, Norway, Iceland, Switzerland, Turkey)	Oil, gas, coal, biomass markets Fossil fuels, nuclear energy, hydro energy, biomass, wind, solar, other RES Energy transformation sector (hydrogen, e-fuels) Sectors: industry, transport, buildings, agriculture	Resources, macroeconomics, technologies, climate and energy policy	International prices, consumption, production, GHG emissions

Model LISFLOOD

Objective:
It is a hydrological rainfall-runoff model that is capable of simulating the hydrological processes that occur in a catchment. Modelling capabilities include

- flood forecasting,
- assessing the effects of river regulation measures,
- assessing the effects of land-use change, and
- assessing the effects of climate change.

Methodology:
The model can be applied across a wide range of spatial and temporal scales. Long-term water balance can be simulated (using a daily time step), as well as individual flood events (using hourly, or even smaller, time intervals).

Input data	Output data
Treatment of meteorological input variables Rain and snow Frost index soil Interception Sub-grid variability in land cover Snowmelt Infiltration Evaporation and interception Runoff Surface runoff Preferential flow (bypass of soil layer) Exchange of soil moisture between the two soil layers and drainage to the groundwater Sub-surface and groundwater flow and river channel flow	The model's primary output product is channel discharge. All internal rate and state variables (e.g., soil moisture) can also be written as output. Also, all output can be written as grids, or time series at user-defined points or areas.

Model WOFOST

Objective:
It is a simulation model for the quantitative analysis of the growth and production of annual field crops

Methodology:
It is a dynamic model that explains daily crop growth on the basis of the underlying processes, such as photosynthesis, respiration, and how these processes are influenced by environmental conditions.

Target function:
The model simulates the growth of agricultural crops in interaction with the environment, including weather, soil, and agricultural management.

Timeline	Geography	Sectoral coverage	Input data	Output data
	The world	Agriculture	Yield, planting area, weather, soil, nutrients.	Total crop biomass and crop yield, as well as variables such as leaf area and water use by plants.

Sources: PRIMES MODEL 2013-2014 Detailed model description E3MLab/ICCS at National Technical University of Athens, European Commission web-site (https://ec.europa.eu/clima/policies/strategies/analysis/models_en),
Model GLOBIUM description
https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/globiom_en.pdf,
Short Description of the GEM-E3 model
(https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/gem_e3_en.pdf),
GEM-E3 Model Documentation (https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/gem-e3-model-documentation),
PROMETHEUS MODEL A tool for the generation of Stochastic Information for Key Energy, Environment and Technology Variables
(https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/prometheus_en.pdf),
Model CAPRI description (https://www.capri-model.org/dokuwiki/doku.php),
JRC PESETA IV project, POLES-JRC model documentation 2018 update Despres, J., Keramidas, K., Schmitz, A., Kitous, A., Schade