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Energy Systems Modelling

SETIS

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Editorial

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Policy-makers need up to date information, meaningful figures and analysis on the impact of policy measures. Energy systems modelling can provide them with all of this. This is my experience as a European Commission policy-maker who has used energy system modelling for seven years. At least three modelling challenges remain: energy market changes, model combinations and transparency.

Up to date information: Energy system modelling needs to be based on the latest trends and, unlike macro modelling, it has the opportunity to be informed by recent data. An example is the EU Reference Scenario 2016 (see Canton et al.), which projects energy, transport and greenhouse gas (GHG) emission trends to 2050.

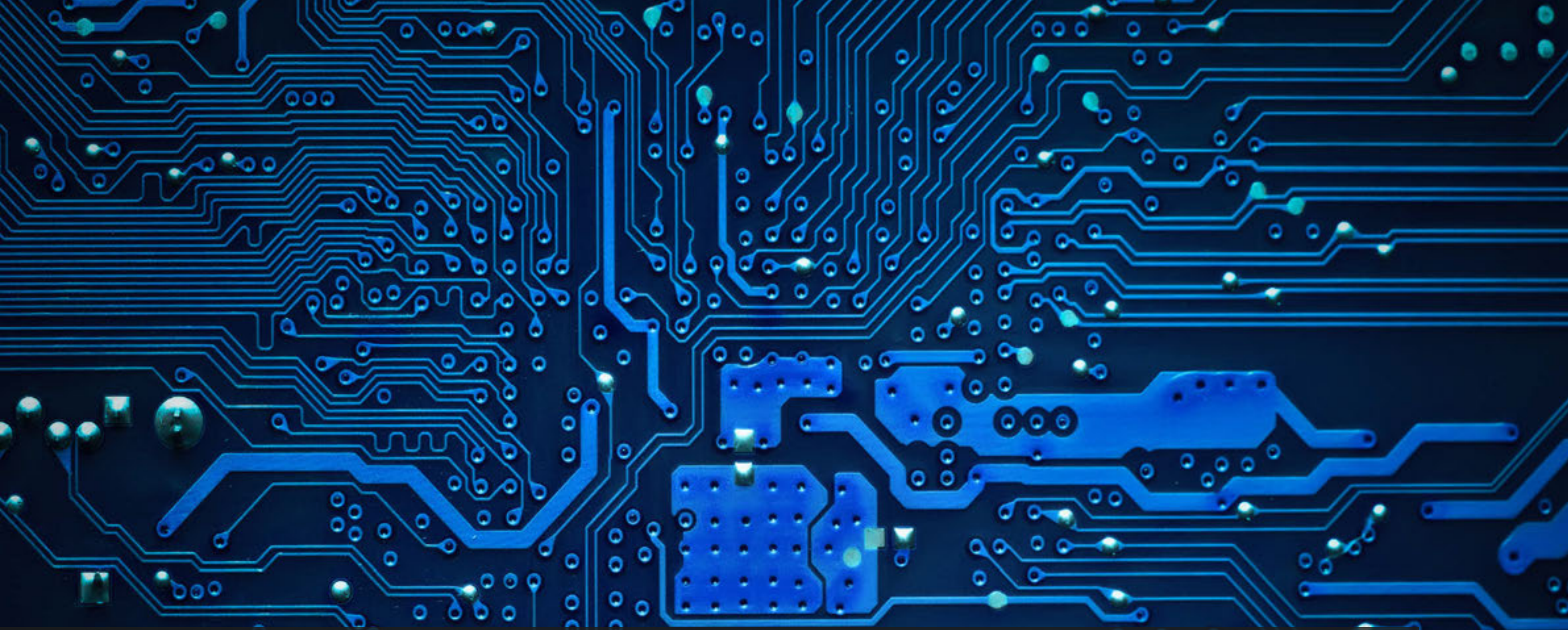
Meaningful figures: Minus 40% in 2030, 60% in 2040 and 80% in 2050. This is the EU's GHG emission reduction pathway (compared to 1990) derived by energy system and non-CO_2 emission modelling for the Commission's Low-Carbon Economy Roadmap in 2011. It is a good example of how modelling has informed policy-makers in setting the GHG target for the EU's 2030 climate and energy framework.

Policy impact analysis is the most difficult task. How to appropriately reflect existing policy instruments and their interactions? How to simplify the essence of future policies for policy scenarios? It is here that the "system" component of energy system modelling is most important. For example, a possible future carbon price trajectory resulting from the interplay of the legally determined amount of EU Emission Trading System allowances and the changing conditions of energy supply and demand can only be generated by a model which covers all these elements.

Three challenges: First, energy markets change profoundly. Supply actors have multiplied and electricity market dynamics have changed with the policy-led diffusion of renewables, while interconnections are becoming more important. These trends are set to continue and will be reinforced with the rise of energy storage and demand response. This is a challenge in particular for energy models of which the basic structure has often been developed in times of public monopolies or of oligopolistic competition of large suppliers. Second, interactions between the energy system and other parts of the economy are of increasing policy relevance. The debate on the sustainability of the increasing use of biomass is only one example. The EU's GHG effort-sharing targets could only be properly analysed by combining energy system models and models which cover the agriculture, forestry and waste sectors. How to best operate such combinations to ensure robust and timely analyses remains a challenge. Third, despite significant improvements, combining complex modelling with transparency remains a challenge, and stakeholders' demands are increasing in this respect.

My colleagues and I look forward to seeing how existing and new energy system models address these challenges while continuing to provide quantitative information to policy-makers that is up to date and policy relevant.

Dr Jan Nill works at the European Commission, Directorate-General Climate Action. He has been responsible for climate policy-related EU energy modelling from 2009 to 2016. Currently he works as policy officer in the unit CLIMA C.2 Governance & Effort Sharing, mainly on the Effort Sharing Regulation Proposal on binding annual emission reductions by Member States from 2021 to 2030 and the monitoring of energy and greenhouse gas projections. Jan holds a PhD in economics from the University of Kassel.



SET-Plan Update

The European Strategic Energy Technology Plan (SET-Plan) aims to transform the way we produce and use energy in the EU, with the goal of achieving EU leadership in the development of technological solutions capable of delivering 2020 and 2050 energy and climate targets.

Energy system models allow us to understand the impact, and thus consider the 'design', of changes in the energy system. This is increasingly important for an energy system in transition that should absorb increasing levels of intermittency whilst meeting the objectives of security, sustainability and competitiveness and placing the consumer at the centre. The following is a non-exhaustive chronological overview of some selected actions taken to support the development and use of energy system models in EU energy planning, in addition to a more general look at recent actions in support of the SET-Plan.

Energy System Modelling

- Some background on the energy modelling activities carried out at the Joint Research Centre (JRC), the European Commission's science and knowledge service, is available at the European Commission Science Hub, together with the resulting publications dating back to 2005.
- In 2013, the Joint Research Centre published a report on the JRC-EU-TIMES model: Assessing the long-term role of the SET-Plan energy technologies. The main objective of this report was to present the main inputs and assumptions used in the JRC-EU-TIMES model, developed by two former[1] JRC institutes: the Institute for Prospective Technological Studies (IPTS) and the Institute for Energy and Transport (IET). The model is designed to analyse the role of energy technologies in meeting Europe's energy and climate change-related policy objectives. It models the uptake and deployment of technology and its interaction with the energy infrastructure, including storage options, in an energy systems perspective.
- In August 2014 the Directorate-General for Energy launched a public tender aimed at developing a new tool, METIS, to model the European energy system, properly customised to the European Commission needs. METIS is expected to accurately simulate the main aspects of the European energy system and be calibrated with data from the current EU energy system (covering all 28 Member States). The European Commission will use this to explore and analyse the effects of different policies and trends at the regional, national and European levels by running several scenarios for different time horizons. The modelling effort will focus mainly on the electricity, gas and heat sectors, both for the short-term and the medium- to long-term. The contract was awarded in December 2014 to a consortium led by Artelys.
- The JRC organised an expert workshop on "Addressing flexibility in energy system models" in December 2014. The objective of the workshop was to gather experts from modelling teams dealing with these problems from different perspectives, ranging from energy system-wide to detailed sectoral energy models, in order to share and compare modelling approaches and results, and identify gaps and potential solutions.
- Following the workshop on "Addressing flexibility in energy system models", in 2015 the JRC published a report on Addressing flexibility in energy system models in which it summarised the presentations and findings from the 2014 workshop.
- Also in 2015, the JRC published the JRC-EU-TIMES report

1 The DG JRC is organised in Directorates as of July 2016.

Bioenergy potentials for EU and neighbouring countries. This report was the first in a series of reports on low-carbon energy technologies potentials, and addressed the quantification of current and future biomass potential contribution to decarbonisation pathways of the energy system. The data sets produced are input into the JRC-EU-TIMES model to analyse the main drivers of future biomass use within the energy systems.

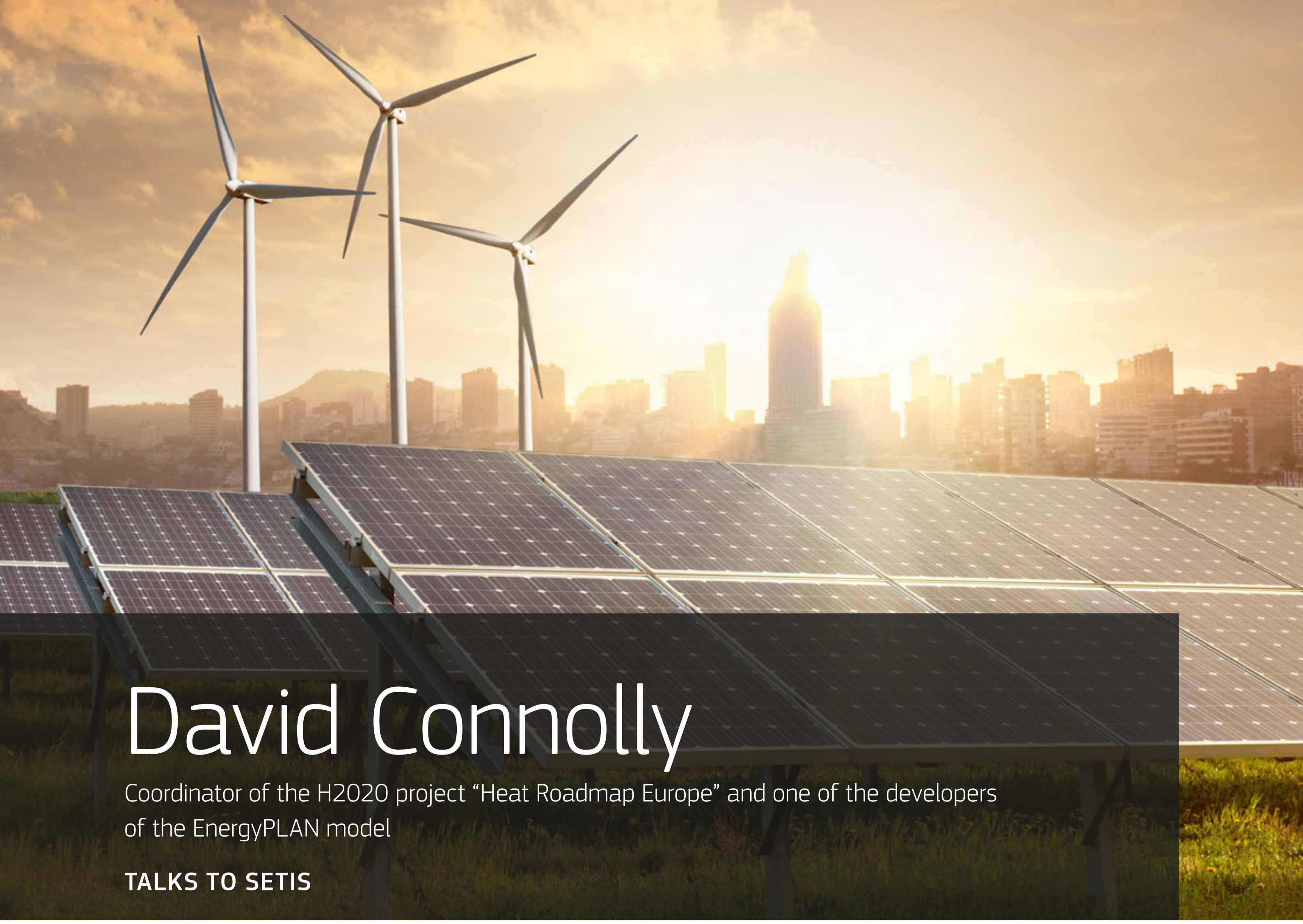
- In April 2015, the European Commission issued a call for tenders for a Study on the Macroeconomics of Energy and Climate Policies. This major project, awarded to a consortium led by Cambridge Econometrics and including E3Modelling and Trinomics as partners, is currently ongoing and will extend the capability of two global energy-economy-environment models to give a fuller impact assessment of the policies designed to promote energy efficiency and the transition to a low-carbon economy. The two models have been chosen to represent two very different traditions in economics: post-Keynesian macro-econometric modelling (the E3ME model) and Computable General Equilibrium modelling (GEM-E3).
- In December 2015 the Executive Committee of the European Energy Research Alliance (EERA) agreed to launch a Joint Programme on Energy Systems Integration (ESI). A sub-programme on modelling aims to develop integrated energy system models that capture the strong physical, economic and regulatory interactions that exist within energy systems and that fully utilise increasing volumes of data.
- In February 2016, the MEDEAS project held its kick-off meeting. Funded under Horizon 2020, this project aims to use open source software to design a new energy-economy model for the future EU transition to a low-carbon energy system.
- On June 30, 2016 the EU's Innovation and Networks Executive Agency (INEA) organised a workshop on Energy System Modelling with the objective of bringing together the four H2020 projects funded under the topic "LCE 21 – 2015: Modelling and analysing the energy system, its transformation and impacts" to identify possible synergies and/or overlaps. Apart from MEDEAS project the other 3 awarded projects of the LCE21-call are REEEM, REFLEX and SET-Nav.
- In July 2016, the EC published its latest edition of the EU Reference Scenario 2016, which projects energy, transport and greenhouse gas emissions trends in the EU up to 2050. The Reference Scenario is a projection of where our current set of policies coupled with market trends are likely to lead. The EU has set ambitious objectives for 2020, 2030 and 2050 on climate change and energy, so the Reference Scenario allows policy-makers to analyse the long-term economic, energy, climate change and transport outlook based on the current policy framework.
- Also in July 2016 the JRC published a new issue of the GECO 2016: Global Energy and Climate Outlook. Road from Paris, which examines the effects on greenhouse gas emissions and energy markets of a reference scenario where current trends continue beyond 2020; of two scenarios where the Intended Nationally Determined Contributions have been included; and of a 2°C scenario in line with keeping global warming below the limits agreed in international negotiations. The report presents an updated version of the modelling work supported by the European Commission's Directorate-General for Climate Action (DG CLIMA) in the UNFCCC negotiations that resulted in the Paris Agreement of the COP21 in December 2015.
- In August 2016, the JRC published a technical report laying out the modelling approach that is implemented in the POTEnCIA modelling tool (Policy Oriented Tool for Energy and Climate Change Impact Assessment). This model was developed by the JRC's former Institute for Prospective Technological Studies (IPTS) to assess the impacts of alternative energy and climate policies on the energy sector, under different hypotheses about surrounding conditions within the energy markets.
- In September 2016, the JRC, DG RTD and the United States Department of Energy organised an expert workshop on "Understanding the Water-Energy Nexus: Integrated Water and Power System Modelling", where approximately 70 European and US scientists from academia, government and industry involved in power system modelling gathered in order to compare and exchange state-of-the-art modelling methodologies and best practices, identifying gaps and potential solutions. The discussions took into account modelling and data-related methodological aspects, with their limitations and uncertainties, as well as possible alternatives to be implemented within power system models.

General SET-Plan related news and activities from JRC/SETIS

- The Joint Research Centre published a number of reports in 2016. In addition to the reports covered in the last SET-Plan update, the JRC has published a report titled Mapping regional energy interests for S3P-Energy, the main goal of which was to carry out a first identification of regions with common energy technology interests according to their smart specialisation strategies.
- On July 20 2016, the Commission presented a set of measures to accelerate the shift to low-carbon emissions in all sectors of the economy in Europe. The package will help Member States prepare for the future and keep Europe competitive. It is part of the EU's strategy for a resilient Energy Union with a forward-looking climate policy.
- The European Parliament adopted the EU Strategy for Heating and Cooling at a plenary session on 13 September 2016. The resolution recognises the huge untapped potential of using recoverable heat and district heating systems and the fact that "50%

of the total EU heat demand can be supplied via district heating".

- In his State of the Union Address in September 2016, European Commission President Jean-Claude Juncker highlighted that smarter energy use combined with ambitious climate action is creating new jobs and growth in Europe and is the best investment in Europe's future and in the modernisation of the European economy.
- In the context of the process towards a SET-Plan Integrated Roadmap and Action Plan, organisations (universities, research institutes, companies, public institutions and associations) involved in research and innovation activities in the energy field are invited to register in the European energy R&I landscape database, which aims at facilitating partnerships and collaboration across Europe. Registration is open to stakeholders from the EU and H2020 associated countries. Organisations are able to indicate their area of activity according to the energy system challenges and themes, as identified in the SET-Plan process towards an Integrated Roadmap and Action Plan. The database is publicly available on the SETIS website.
- During the last SET-Plan Steering Group meeting in September, four agreements on strategic targets and priorities were endorsed by the SET-Plan Steering Group and relevant stakeholders. The agreed Declarations of Intent concern the Key Actions 1 & 2, and 9 and 10 of the Integrated SET-Plan dedicated to Europe "Being n°1 in renewables" regarding ocean and deep geothermal energy, "Renewing efforts to demonstrate carbon capture and storage (CCS) in the EU and developing sustainable solutions for carbon capture and use (CCU)" and "Maintaining a high level of safety of nuclear reactors and associated fuel cycles during operation and decommissioning, while improving their efficiency". The most recent Steering Group meeting took place in Brussels October 19.
- The 9th SET-Plan Conference 'Energy Union: towards a transformed European energy system with the new, integrated Research, Innovation and Competitiveness Strategy' is to take place in Bratislava, Slovakia on 30 November - 2 December 2016.
- Two JRC-organised side-events are to be held in the margins of the SET-Plan Conference. The first is a workshop to present the recent findings and inputs of SETIS to the State of the Energy Union report and its added value for the overall progress of EU innovation in the energy sector. This workshop will also present the Technology Innovation Monitoring (TIM) tool developed by the JRC. The second workshop will deal with Funding innovative low-carbon energy demonstration projects in the context of the NER 300 programme.



David Connolly

Coordinator of the H2020 project “Heat Roadmap Europe” and one of the developers of the EnergyPLAN model

TALKS TO SETIS

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What are the main insights that we aim to achieve through the development of energy system models?

Energy system models help us understand the impact of making changes to the energy system before we make them. The insights tend to vary significantly depending on the time-horizon in question. Some models focus on the short-term (years ahead) so they usually model existing technologies within existing financial frameworks, such as a model that analyses how to dispatch a power plant on the electricity markets we have today. Other models focus more on the long-term (decades from now), so they can provide insights for more radical changes to the technologies, institutions, and markets we have today. For example, these models will often include wave power or power-to-gas, both of which are not even commercially available right now. EnergyPLAN is primarily designed to analyse the large-scale integration of renewable energy and energy efficiency, based on the Smart Energy Systems concept. Renewable energy still provides a relatively small amount of our energy today, so analysing ‘large-scale integration’ requires a long-term perspective over many decades. EnergyPLAN is therefore focused on radical changes to our energy system compared to today, but it also simulates the energy system on an hourly basis to account for intermittency from renewable energy.

Tell us a little about the EnergyPLAN model and its energy system analysis procedures.

EnergyPLAN is primarily a simulation model, but it also includes some optimisation. I would equate the ‘user’ of EnergyPLAN to a ‘designer’: the user designs an energy system in EnergyPLAN in terms of demands, capacities, efficiencies, and costs and once it is complete, the user simulates how that energy system performs. However, to carry out the simulation, the user must also instruct the model how to ‘optimise’ its decisions during each hour of the simulation. In other words, the optimisation tells the simulation how to make its decisions during each hour of the year.

The most common optimisation we use in EnergyPLAN is called the ‘technical optimisation’, where the main objective is to reduce the energy consumed during the simulation. Alternatively, the user can use an ‘economic optimisation’ where the model will reduce the cost of the energy system during the simulation. It is important to note that the optimisation only refers to the operation of the energy system during each hour and not to the ‘design’ of the energy system. In other words, the capacity of wind turbines in your energy system will not be altered during the economic optimisation, but the way those wind turbines operate each hour may be.

How does the EnergyPLAN model compare with other models; what are its distinguishing features?

I would define EnergyPLAN's niche in the mix of models that currently exist as: it simulates all sectors of the energy system on an hourly basis after they have undergone radical changes. It can do this due to a combination of the following key characteristics:

- It can simulate radical changes for renewable energy and energy efficiency, since it considers all major technologies that exist today (including district heating) as well as technologies which are not commercially available yet, such as hydrogen production, biomass gasification, carbon capture, and electrofuels.
- The model considers the entire energy system, including electricity, heating, cooling, industry, and transport, so the impact of changing the heat sector is reflected in the other sectors also.
- EnergyPLAN is an hourly model so it ensures that demand and supply are always met on hourly basis across the electricity, district heating, and gas networks.
- It accounts for synergies across all sectors on an hourly basis when integrating renewable energy, which is based on the Smart Energy System concept. It is very important to consider these synergies when quantifying the impact of future due to the additional flexibility that these synergies create for intermittent renewables like wind and solar.

How does the EnergyPLAN model contribute to the design of energy planning strategies?

It quantifies the impact of implementing large-scale penetrations of renewable energy and energy efficiency, usually in terms of energy, emissions, and costs. By quantifying the impact, we can often reveal that some decisions are much more or less significant than policy-makers realise. A very good example of this comes from our Heat Roadmap Europe work. Initially, policy-makers thought that district heating was very expensive, especially due to the construction of the pipes in the streets. However, by quantifying this, we have been able to demonstrate that district heating is cheaper than natural gas in many countries. Even more surprising, during this calculation we found out that the pipes in the ground are one of the smallest costs for a district heating scheme, even though they are the most visible since they require construction on the streets. This is very

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important for policy-makers: for example, recently we were advising a local municipality about the roll out of district heating in their city. They were focusing on the cost of the pipes in the street since they assumed this would have the most influence on the overall economic viability of the project. However, after quantifying the breakdown of the cost for them, they could see that the price of the heat supply had a much bigger influence than the price of the pipes, so we recommended that they focus their efforts on securing a low and stable heat supply price. This is a very specific example, but in most studies EnergyPLAN changes perceptions like this on a broader energy-system scale. For example, it has previously been used to demonstrate how 100% renewable energy systems have comparable costs to fossil-fuel based energy systems, which can be found at: www.SmartEnergySystem.eu.

A key objective of EnergyPLAN is to aid in the design of 100% renewable smart energy systems. How will it achieve this?

Our results to date indicate that the key to 100% Renewable Energy and the Smart Energy Systems concept is integrating the various sectors: electricity, heating, cooling, industry, and transport. Historically these sectors have evolved individually from one another: power plants producing electricity, boilers creating heat, and combustion engines providing transport. We need to remove this 'sectoral approach' and move towards an 'energy system' approach, since this will create many new opportunities for both energy efficiency and renewable energy integration.

Let's take the electricity and heat sectors as an example, since many EU countries have already started connecting these in recent decades. If these sectors are designed in isolation then the power plants will only produce electricity, but if these two sectors are designed in combination with one another, then it is very likely that combined heat and power (CHP) plants will be most economical. A power plant has an efficiency of 30-50% for electricity generation, whereas a CHP plant has an efficiency of 80-90% for electricity and heat production together. Hence, there is often a significant improvement in energy efficiency by replacing a power plant with a CHP plant, something we quantified for five EU countries in the recent STRATEGO project: these countries are Croatia, Czech Republic, Italy, Romania, and the United Kingdom.

Similarly, if we try to optimise the integration of renewable electricity with a sole focus on the electricity sector, then we will limit our solutions to those that exist within the electricity sector such as interconnection, demand-side management, batteries, and pumped hydroelectric storage. However, if we optimise across the electricity and heat sectors together, then we will be able to use cheaper alternatives for the integration of renewable electricity such as heat pumps and thermal storage. We already see this in Denmark, where large-scale electric boilers are integrating more wind power via thermal on the district heating network. This is often a cheaper solution since thermal storage is approximately 100 times cheaper than electricity storage, so we often use EnergyPLAN to quantify how much additional wind power we can accommodate due to the connection between the electricity and heat sectors.

EnergyPLAN also connects cooling, industry, and transport with the electricity and heat sectors to identify synergies that increase energy efficiency and renewable energy. By using this sectoral approach, 100% renewable energy systems become more economically viable and thus more likely to be implemented.

How does your model accommodate new technologies and new research and development?

We try to release a new version of the model every 6 months on the website. Updates are very closely linked to the research projects that we are involved in and existing technologies within EnergyPLAN are regularly updated if we identify a new consideration in one of these projects. New technologies tend to be included over time rather than all at once. For example, power-to-gas originally began as an additional electricity demand for hydrogen production, but as we learned more about the technology, it evolved into individual components in the process such as electrolysers, hydrogen storage, carbon capture & recycling, and biomass gasification.

David Connolly

David Connolly is an Associate Professor in Energy Planning at Aalborg University in Copenhagen, Denmark. His research focuses on the design and assessment of 100% renewable energy systems, with a key focus on the integration of intermittent renewables (such as wind and solar power), district heating, electric vehicles, and the production of electrofuels/synthetic fuels for transport.

The EU Reference Scenario 2016

Approach

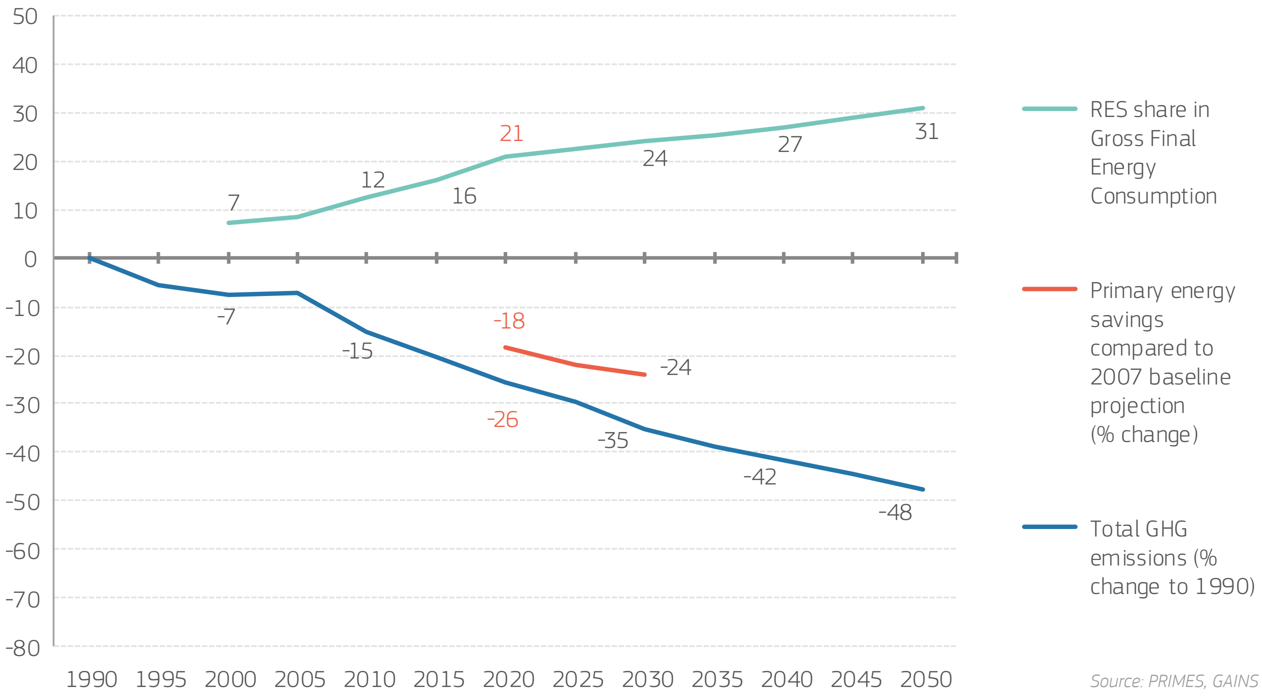
The European Commission's policy decisions are underpinned by thorough analyses and impact assessments. When developing and implementing the Energy Union Strategy, the Commission uses a wide range of mathematical models and tools to explore policy proposals and evaluate their potential energy, transport, economic, social and environmental consequences.

The EU Reference Scenario is one of the European Commission's key analysis tools used in the context of the Energy Union. It is updated regularly as it projects the impact of current EU policies on energy and transport trends as well as changes in the expected amount of greenhouse gas emissions. It provides projections on a five-year period up until 2050 for the EU as a whole and for each EU country. It is not designed as a forecast of what is likely to happen in the future. It rather provides a benchmark against which new policy proposals can be assessed.

On 20 July, the European Commission published its latest Reference Scenario: the EU Reference Scenario 2016 (REF2016). With the active participation of national experts from all EU countries, the European Commission worked in partnership with a modelling consortium led by the National Technical University of Athens to develop REF2016, making use of a range of different models.

The projections are based on a set of assumptions, including on population growth, macroeconomic and oil price developments, technology improvements, and policies. Regarding policies, projections show the impacts of the full implementation of existing legally binding 2020 targets and EU legislation. As such, they also show the continued impact post 2020 of policies such as the EU Emissions Trading System Directive (including the Market Stability Reserve), the Energy Performance of Buildings Directive, Regulations on ecodesign and on CO_2 emission standards for cars and vans, as well as the recently revised F-gas Regulation. Such policies notably influence current investment decisions, with impacts on the stock of buildings, equipment and cars, which have long-lasting effects post-2020 on GHG emissions or energy consumption.

Figure 1: Projection of key policy indicators



Source: PRIMES, GAINS

Results

REF2016 is set up to meet the binding **energy and climate targets** for 2020, the latter being achieved as a result of existing policies. However, it shows that current policies and market conditions will deliver neither the EU's 2030 targets nor the long-term 2050 objective of 80 to 95% greenhouse gas (GHG) emission reductions. Overall GHG emissions decrease by 26% in 2020, 35% in 2030 and 48% in 2050. GHG emissions from sectors covered by the Effort Sharing Decision are projected to decrease by 16% in 2020 and by 24% in 2030 below 2005 levels, less than emissions in sectors covered by the EU Emission Trading System. In 2020, the renewable energy share (RES) in gross final energy consumption reaches 21%, while in 2030 it increases slightly further, reaching 24%. In addition, the energy efficiency 2020 non-binding target is not met in REF2016, the scenario projecting a reduction in primary energy savings (relative to the 2007 baseline) of 18% in 2020, and, respectively, 24% in 2030.

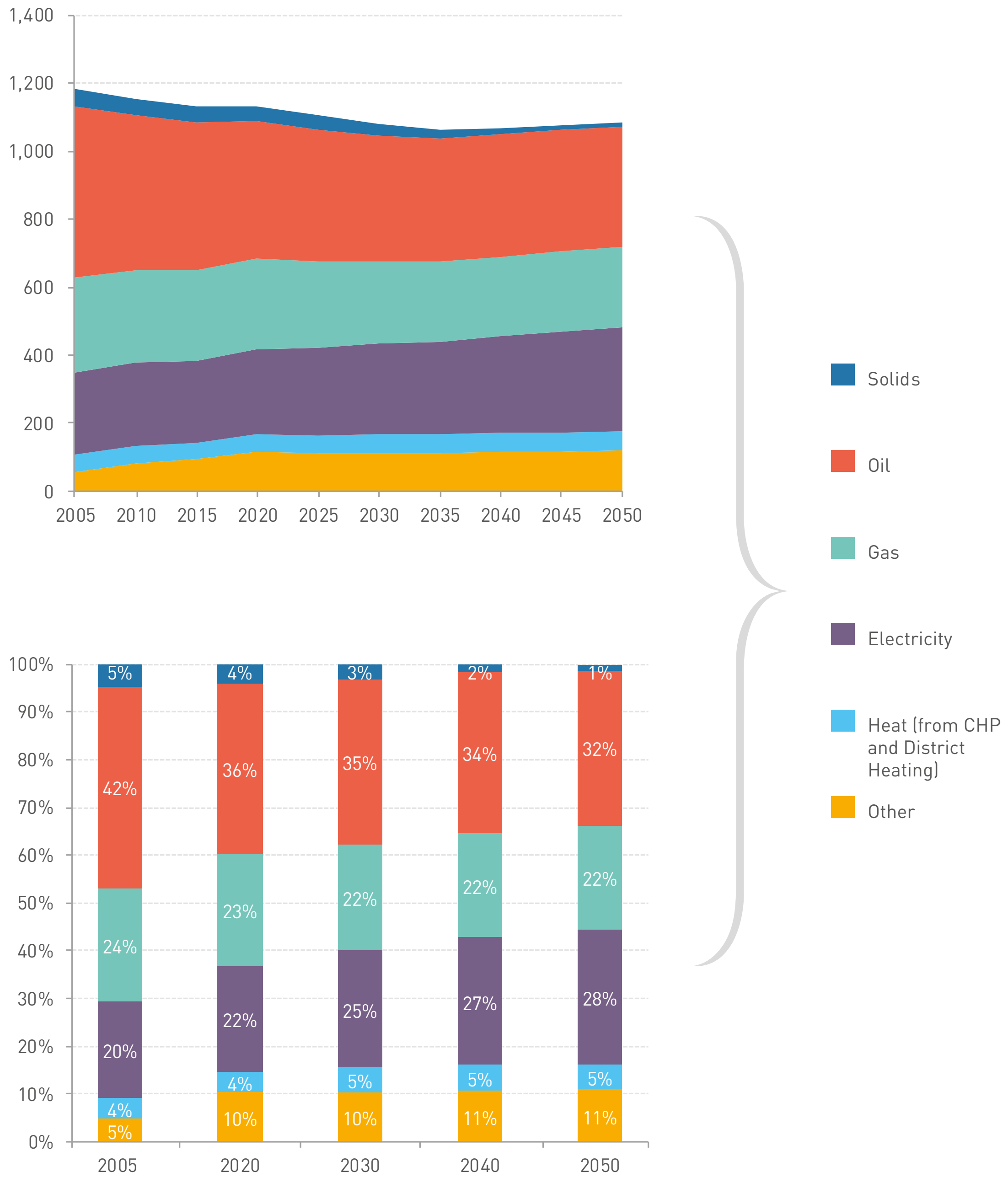
The EU's energy production is projected to continue to decrease from around 760 Mtoe in 2015 to about 660 Mtoe in 2050. The projected strong decline in EU domestic production for all fossil fuels (coal, oil and gas) coupled with a limited decline in nuclear energy production is partly compensated by an increase in domestic production of renewables. Biomass and biowaste will continue to dominate the fuel mix of EU domestic renewable production, although the share of solar and wind in the renewable mix will gradually increase.

The EU's import dependency shows a slowly increasing trend over the projected period, from 53% in 2010 to 58% in 2050. RES deployment, energy efficiency improvements and nuclear production (which remains stable) counteracts the strong projected decrease in the EU's fossil fuel production.

The EU power generation mix changes considerably over the projected period in favour of renewables. Before 2020, this occurs to the detriment of gas, as a strong RES policy to meet 2020 targets, very low coal prices compared to gas prices, and low CO_2 prices do not help gas to replace coal. After 2020, the change is characterised by further RES deployment, based on market conditions, but also a larger coal to gas shift, driven mainly in anticipation of increasing CO_2 prices. Variable RES (solar and wind) reach around 19% of total net electricity generation in 2020, 25% in 2030 and 36% in 2050, demonstrating the growing need for flexibility in the power system. The share of nuclear decreases gradually over the projected period despite some life time extensions and new built, from 27% in 2015 to 22% in 2030.

Primary **energy demand** and GDP continue to decouple, which is consistent with the trends observed since 2005. Energy efficiency improvements are mainly driven by policy up to 2020 and by market/technology trends after 2020. With regard to the fuel mix in final energy demand, there is a gradual penetration of electricity (from 20% in total final energy use in 2005 to 28% in 2050). This is because of growing electricity demand as compared to other final energy use and to some electrification of heating (heat pumps) and to a limited extent of the transport sector.

Figure 2: Evolution of final energy demand by fuel (Mtoe – above, shares – below)



Source: PRIMES

Investment expenditures for power supply increase substantially until 2020 driven by RES targets and developments, but slow down thereafter, until 2030, before increasing again from 2030 onwards notably due to increasing ETS carbon prices reflecting a continuously decreasing ETS cap based on the current linear factor. New power plant investment is dominated by RES, notably solar PV and wind onshore. Investment expenditures in demand sectors over the projected period will be higher than in the past. They notably peak in the short term up to 2020, particularly in the residential and tertiary sectors, as a result of energy efficiency polices.

Energy system costs increase up to 2020. Large investments are undertaken, driven by current policies and measures. Overall, in 2020 energy system costs constitute 12.3% of GDP, rising from 11.2% in 2015, also driven by projected rising fossil fuel prices[2]. Despite further fossil fuel price increases, between 2020 and 2030 the share remains stable and decreases thereafter, as the system reaps benefits from the investments undertaken in the previous decade (notably via fuel savings). In this period, the share of energy system costs in GDP is gradually decreasing, reaching levels close to 2005 by 2050.

2 Total system costs include total energy system costs, costs related to process-CO_2 abatement and non-CO_2 GHG abatement.

Joan Canton

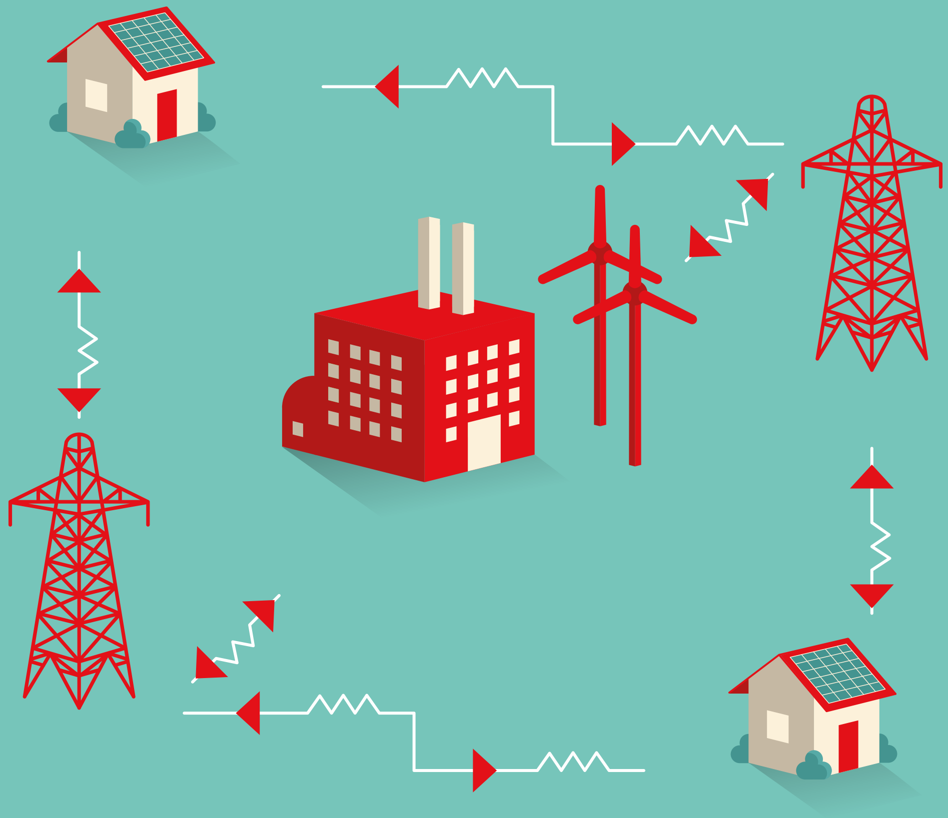
Joan Canton is an Economic Analyst at the European Commission's Directorate-General for Energy, focusing on the modelling of energy systems, supporting the preparation of the Commission's Impact Assessments on climate and energy issues, as well as on monitoring the implementation of the Energy Union Strategy. Before working for DG Energy, he worked in DG Climate Action and in DG Economics and Financial Affairs. He holds a PhD in economics from the University of Aix-Marseille and has worked as an Assistant Professor in the Economics Department of the University of Ottawa (Canada).

Cristina Mohora

Cristina Mohora received a Master's Degree in Financial and Monetary Policies from the Academy of Economic Studies in Bucharest and a PhD in Economic Modelling from Erasmus University Rotterdam. After holding an academic position at the Academy of Economic Studies in Bucharest and a research position at Université Libre de Bruxelles, she joined the European Commission in 2008. Between 2008 and 2010, Cristina has been involved in the energy system modelling work at the Directorate-General Energy and Transport. Since 2010 she has been responsible for the modelling work coordinated by the economic analysis unit of the Directorate-General Mobility and Transport.

Jan Nill

Dr Jan Nill works at the European Commission, DG Climate Action. He has been one of the coordinators of the EU Reference Scenarios 2013 and 2016. Currently he works as policy officer in the unit CLIMA C.2 Governance & Effort Sharing. Jan holds a PhD in economics from the University of Kassel.



Marc Oliver Bettzüge

Director of the Institute of Energy Economics at the University of Cologne (ewi) and President of the Supervisory Board of ewi Energy Research & Scenarios.

TALKS TO SETIS

Tell us a little about ewi Energy Research & Scenarios and the work that you do.

ewi Energy Research & Scenarios is a non-profit organization focussing on applied economic research on energy markets and energy policy. We have a team of about 35 people, many of them simultaneously pursuing their PhD at the University of Cologne. Besides conducting research projects, we also offer research and development support as well as economic advice to government, organisations and companies. Thus, we regularly provide decision-makers with sound quantitative support based on our strong economic and modelling expertise.

What role do energy system models play in your research?

Energy system models are at the analytical core of our research. We run, and continuously improve, models of global fuel markets as well as the European electricity, gas, and heat markets. The distinctive feature of our modelling approach is the strong emphasis on economic theory alongside a deep understanding of the relevant technologies. Thus, the insights generated from our models reveal important findings about economic interdependencies and effects on top of mere technology-based analysis.

How do you ensure the robustness of your simulation tools?

Robustness is ensured by consistency-checks, back-testing and economic review. Consistency-checks verify that model results are internally consistent, e.g., energy balance sheets are correct, no technological boundaries are infringed etc. Back-testing runs the model with historical data, which is a viable way for identifying possible shortfalls of the model. However, due to fundamental difficulties with accurate back-testing in a complex energy environment, we also add what we call "economic review of the models", namely checking models and model results with respect to their fit with economic theory and observed and foreseeable market behaviour.

How can energy systems modelling contribute to a successful energy transition in Europe?

Energy systems models are important analytical tools to assess potential market developments, including their reaction to certain political measures. Hence, decision-makers in the energy domain may use such models to obtain a more profound information base for their decisions and actions. Importantly, however, it should be stressed that models typically generate scenarios – not forecasts. Hence, it is important for decision-makers, and the general public, to adequately interpret the meaning of scenarios before coming to conclusions about their implications. Therefore, we have designed our models as "anti-black boxes", and we devote a lot of time and effort to supplying transparency and interpretation alongside our scenario analyses.

What has your research revealed to be the most urgent issues facing the European energy system?

There is of course a difference between urgency and importance. From an economic perspective, the most urgent issue in electricity is the increasing geographic imbalance between supply and demand in the European electricity system, exacerbated by a rather slow expansion of the grid and an inadequate configuration of bidding zones. For the gas supply system, our models suggest that urgent decisions around Nord Stream 2 have wide-ranging political ramifications which should be transparently taken into account. With respect to importance, our models consistently show that the insufficient alignment of EU and national energy policies leads to inefficient and ineffective outcomes with respect to mitigating CO_2-emissions in Europe. Thus, a fundamental overhaul of the political approach to energy and climate policy would be very reasonable from an economic perspective.

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Marc Oliver Bettzüge

Dr Marc Oliver Bettzüge has been a professor of economics, in particular energy economics, and Head of the Chair of Energy Economics - Department of Economics - at the University of Cologne since 2007. He is also Managing Director and Chairman of the Management Board of the Institute of Energy Economics at the University of Cologne (EWI). Professor Bettzüge has been a member of the German Parliament's Study Commission on Growth, Wellbeing and Quality from 2011 to 2013. In addition he plays an active role in various committees and advisory boards.

A better life with a healthy planet: pathways to net-zero emissions

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Energy transitions are not new

The world's energy system is entering a major transition. Transitions have happened before. The nineteenth and twentieth centuries saw growth in the use of coal, and then oil and natural gas when the modern combustion engine took off. But since around the 1970s, whilst there's been plenty of growth in the use of energy, the mix of fuels has been relatively static. More recently, with additional concerns over local and atmospheric emissions, the world is seeing impressive rates of growth in wind and solar power – a new era of transition.

Shell Scenarios help to navigate uncertainties about the future

Shell has been using scenario planning for over 40 years to help deepen its strategic thinking. The scenarios help decision-makers to explore the features, uncertainties, and boundaries shaping the future landscape, and to engage with alternative points of view.

Our scenarios consider long-term trends in economics, geopolitical shifts and social change as well as technological progress and the availability of natural resources. They are based on plausible assumptions about future development, and include the impact of different patterns of individual and collective choices.

Shell's Energy Scenarios are underpinned by quantitative modelling

Shell's World Energy Model (WEM) provides a rigorous quantitative framework to underpin the logic of our scenarios. Together with Shell's Global Supply Model, the WEM is a core tool exploring alternative evolutions of energy demand in different countries and in different sectors, helping to maintain system consistency, to explore the most significant factors in policy, technology and consumer choices, and to examine the impacts in one part of the world made by shifts in another.

Shell's latest Scenarios publication, "A Better Life with a Healthy Planet. Pathways to Net-Zero Emissions," takes the most optimistic features of our 2013 "New Lens Scenarios" – Mountains and Oceans – and combines them with individually plausible further shifts in policy, technology deployment, circumstances, and events that might move the world onto a new, even lower-emission trajectory, resulting in net-zero emissions on a timescale consistent with global aspirations.

Future energy demand will at least double

This work starts by attempting to quantify the magnitude of future energy demand. As we consider the future development of economies, and assume significant energy efficiency improvements, we estimate that an average of about 28,000 kWh of primary energy per person is approximately required to support the decent quality of life to which people naturally aspire.

And if we assume a future population of around 10 billion people by the end of the century, and multiply it by 28,000 kWh per capita, we see that the global energy need would be about 280 trillion kWh a year – roughly twice the size of the current energy system.

Hydrocarbons alongside renewables

Across the energy system, it's likely that different degrees of decarbonisation and energy efficiency will be achieved at different paces, in different places, and in different sectors of the economy.

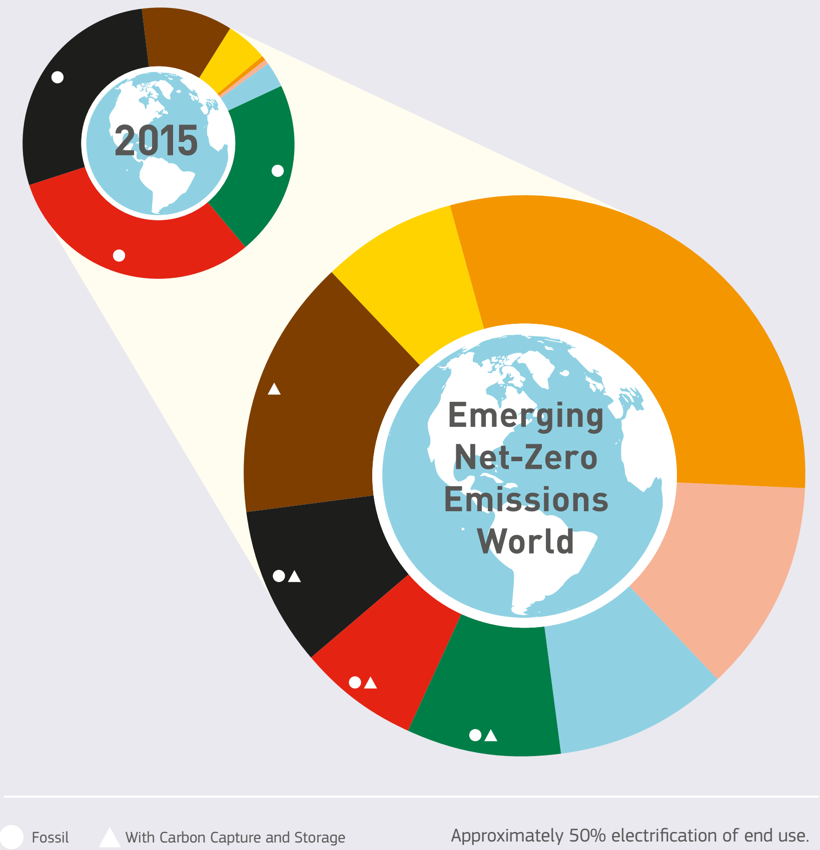
To arrest the accumulation of greenhouse gases in the atmosphere, the world will eventually need to see overall emissions to drop to net-zero. In a net-zero emissions world[3] with a decent quality of life enjoyed by the majority of the population, renewable energies will dominate, and together with nuclear could make about three quarters of the energy supply carbon neutral. But renewables primarily produce electricity, which currently counts for less than one-fifth of energy use. The production of chemicals and plastics would continue to rely on feedstock from oil and gas, and where high temperatures or dense energy storage are required – such as in many industrial processes like iron/steel/cement manufacture or heavy freight or air transport, we will see the continued need for hydrocarbon fuels.

Electrification is key for low CO_2 and high efficiency

In order to achieve both low emissions and high efficiency, the electricity market share will need to grow from one fifth of the energy consumed to at least a half. Electrification needs be particularly high in households and service sectors, but needs to extend further into other sectors such as food processing and light manufacturing. For passenger transport, hydrogen fuel cell and electric drives should become common, while for aviation, shipping and freight hydrocarbons will likely remain important.

3 A world in which the amount of carbon released is balanced by an equivalent amount sequestered or offset.

Figure 3: Plausible energy mix in an emerging net-zero emissions world



ENERGY SOURCE	GAS	OIL	COAL	BIOENERGY	NUCLEAR	SOLAR	WIND	OTHER
2015	21%	31%	28%	11%	5%	0.5%	0.5%	3%
Net-Zero emissions world	9%	7%	9%	15%	8%	30%	12%	10%

For a world with widespread prosperity, the energy system will double over the course of this century.

Source: Shell analysis

Carbon Capture and Storage is indispensable

It's important to note that a net-zero emissions world is not necessarily a world without any emissions anywhere. It's a world where remaining emissions are offset elsewhere in the system. To both mop up remaining emissions and provide opportunities for 'negative' emissions, the world will need widespread deployment of carbon capture and storage (CCS).

Incentivising the transition

Achieving a net-zero emissions world at pace will require significant developments in new technology deployment; industrial, agricultural and urban practices; consumer behaviour; and policy frameworks which shape, incentivise or mandate these transitions. It will also entail high levels of collaboration between policymakers, businesses and civil society.

Governments need to provide financial incentives via carbon prices or taxes for avoiding emissions and remove energy subsidies where they still exist. This allows the market to find the optimal energy mix at lowest costs.

Sensible measures for progress towards a net-zero emissions world

Analysing the likely evolution of demand across key areas of the economy, something of a logical order-of-priority of actions emerges:

1. Stimulating efficiency measures and extending electrification across the economy wherever and whenever possible;
2. Sustaining momentum of renewables growth, particularly solar PV and wind, and maximising the ability of the grid to handle their intermittency;
3. Accelerating the switch from coal to gas to immediately reduce power sector emissions while ensuring supply to meet demand – a way of keeping cumulative emissions to a minimum during the transition;
4. Improving buildings and city infrastructure to lower energy service demand significantly;
5. Accelerating government-directed efforts to promote low-carbon technologies and infrastructures, including nuclear, CCS, hydrogen transport, responsible bioenergy and sustainable forestry, agriculture and land-use practices.

Concluding remarks

We hope that our latest Scenarios work will help build shared insights and perspectives among businesses, national governments and civil society more broadly. A shared understanding would not only accelerate the near-term actions to reduce CO_2 emissions, but also the deeper structural transformations required to sustain decarbonisation and economic growth in the longer term.

For more information visit: www.shell.com/scenarios

Note: Shell Scenarios are part of an ongoing process used in Shell for 40 years to challenge executives on the future business environment. We base them on plausible assumptions and quantification, and they are designed to stretch management to consider even events that may be only remotely possible. Scenarios, therefore, are not intended to be predictions of likely future events or outcomes and investors should not rely on them when making an investment decision with regard to Royal Dutch Shell plc securities. While we seek to enhance our operations' average energy intensity through both the development of new projects and divestments, we have no immediate plans to move to a net-zero emissions portfolio over our investment horizon of 10-20 years.

Wim Thomas

Wim Thomas is Shell's Chief Energy Advisor and also leads the Energy Analysis Team in Shell's Global Scenario Group. He has been with Shell for over 30 years. Wim is also Chairman of World Petroleum Council UK National Committee, a Distinguished Fellow of the Institute of Energy Economics Japan, and a former chairman of the British Institute of Energy Economics in 2005. He holds a postgraduate degree in Maritime Technology, Delft University, the Netherlands.

Alistair Buckley

co-author of 'A review of energy systems models in the UK: Prevalent usage and categorisation'

TALKS TO SETIS

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What are the main insights that we aim to achieve through the development of energy systems models?

In the past, the main use of academic and policy-led energy models was to understand the flows of traditional energy resources in the contexts of value for money and security of supply. More recently, the emphasis of academic modelling has been to understand low-carbon energy transitions and, in doing this, the models need to look much further into the future and try and predict how the system will evolve and what consequences such an evolution will have. However I think that the real challenge when we develop models is to understand who the intended audience is and whether that audience is listening. From an academic point of view, the end goal is typically to get your model used in a policy context. However, policy-makers often typically have already invested in their own models and, as we found as a spiller from our research, in terms of getting used, the language, culture and added value of a model is as important as the technical accuracy or scope.

How do these models help to balance uncertainty in the energy system?

We reviewed a range of academic and policy models of energy systems but, in terms of balancing uncertainty in the energy system, a key interaction is the use of a range of different models by system operators. Short term energy security needs to be negotiated alongside the transition to a more sustainable energy system, so highly accurate and numerical operational models need to be in conversation with future scenario-based models. In the UK, the National Grid "Gone Green" scenario model is a good example of how this is done in practice. "Gone Green" sits at the interface between the system operator National Grid and their day-to-day operational modelling, with policy-led transitional models held by the UK government energy department (now as part of the department for Business, Energy and Industrial Strategy) and academic energy models. It is cited formally and informally across these stakeholders and has a big role in discussions around transitions in the UK energy system.

You recently conducted a review of energy system models in the UK. What were the main findings from this review?

We found that the majority of publications of modelling results came from only a very few different models and that the policy documents cite the same models as the academic literature. This is a good thing, as it means that the academic and policy communities are joined up. From our research I think it's fair to say that there isn't the same international travelling of energy systems modelling as in other science and technology fields. The models that we found cited in the UK science and policy literature were mainly home-grown. It would be interesting to do a comprehensive study to see where models have travelled internationally and how this has impacted on energy policy in those countries.

What are some of the limitations of existing energy system modelling tools?

I think one of the major challenges is the integration of qualitative research from the social sciences around scenarios and policy changes. It's all very well having highly accurate and granular energy flow models for different future generation mix scenarios but if the transition to these scenarios is entirely dependent on political factors at both the EU, national and local level then the model is kind of irrelevant. I think investment in new approaches to the democratisation of modelling with participation from key stakeholders would be very interesting. We have attempted this in a UK-based research project and found computational energy models to be impenetrable by most of these stakeholders.

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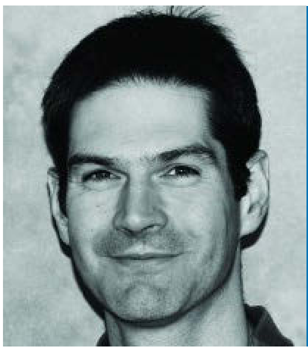
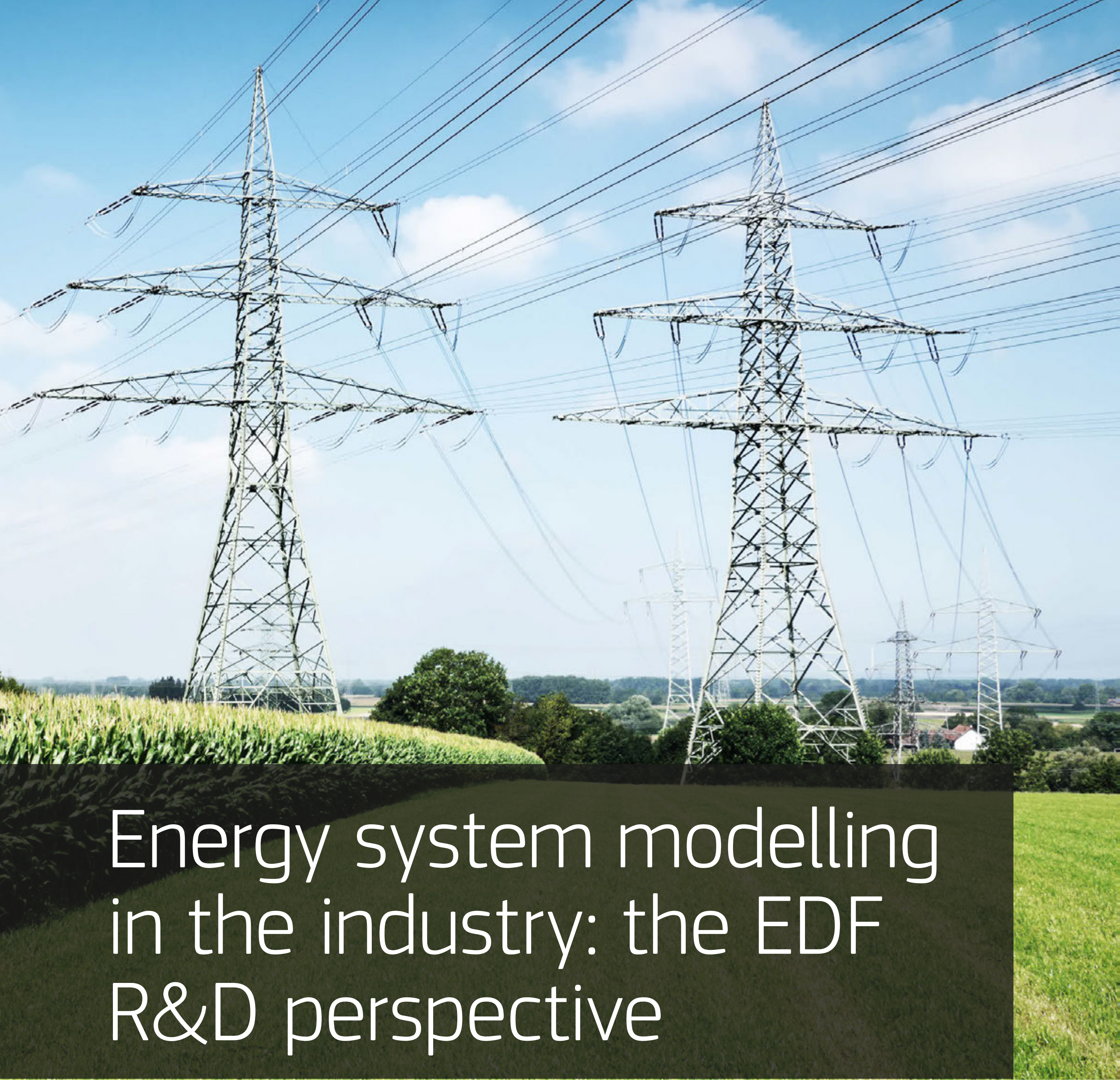
Based on your review, do you have any recommendations regarding the optimisation of modelling capacity?

I think that opening up all energy based data across the academic, policy and system operator communities would result in a step change in integration of the different modellers. Access to data is a key constraint in modelling and open data sources would allow validation of different models across different scenarios. This, in turn, would result in a wider variety of stakeholders to use a wider variety of models. I think this would be highly beneficial.



Alistair Buckley

Alastair Buckley is a senior lecturer in the department of physics at the University of Sheffield. His research investigates the integration of solar PV into future energy systems from technological and socio-technical viewpoints. His Sheffield-based research team has developed real-time PV power monitoring for the UK transmission network.



Energy system modelling in the industry: the EDF R&D perspective

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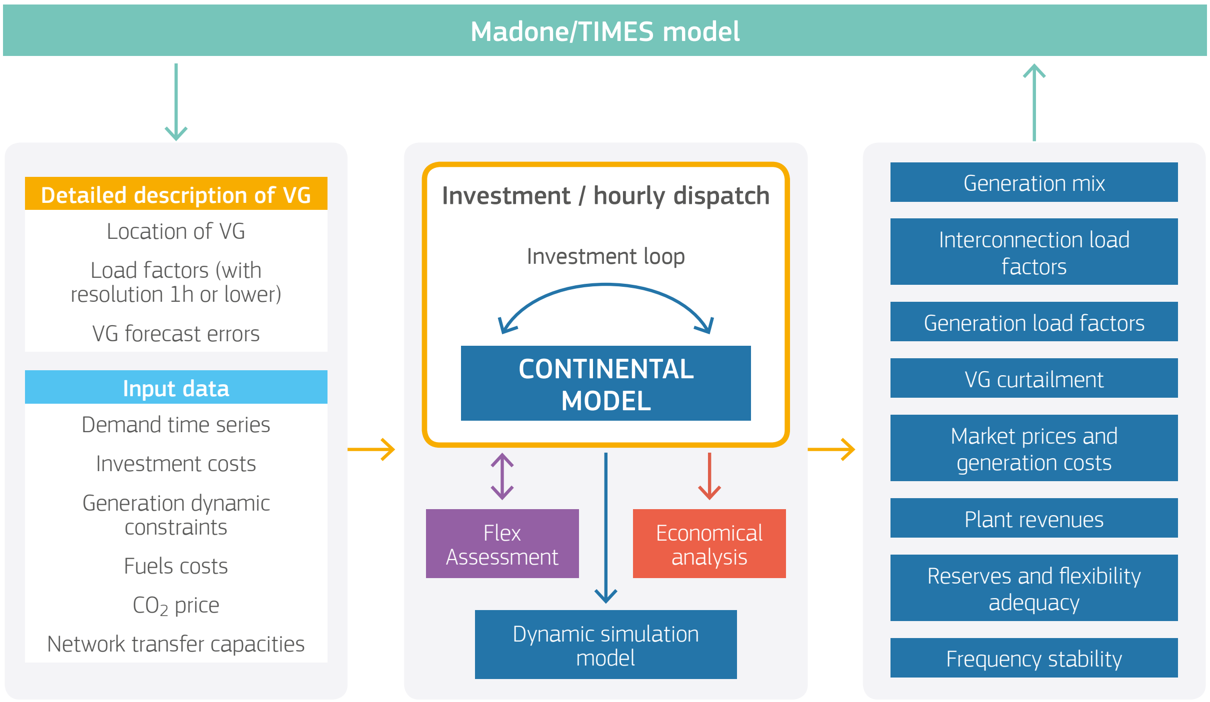
Energy system modelling is a key tool for EDF R&D. It is used to evaluate the impact of energy policies (renewable deployment, EU ETS), to recommend business strategies and analyse business opportunities based on evolutions in the energy/power systems and to contribute to the public debate.

Multi-energy analysis is gaining increased attention, as more interactions between electricity, heat and cold, and gas systems create promising opportunities for decarbonisation (for instance, by developing more efficient usages or sharing flexibilities for a better integration of variable renewables). Some major challenges need to be addressed: modelling these interactions is complex, and can lead to overly complex models or, on the contrary, to the use of significant simplifications. These simplifications must be made carefully, especially when modelling power systems, as they can easily distort the results and lead to a partial understanding of the system's complexity.

More specifically, energy system modelling is often linked to one type of modelling, namely models based on TIMES, representing the interactions between several energy vectors. These models make it possible to simulate and optimise decarbonisation scenarios over several decades, which makes them highly interesting. However, most TIMES models do not currently allow for a detailed enough

Figure 4: EDF chain of models



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representation of the electricity mix. In particular, they generally cannot give specific insights on the needs for flexibility related to the growing penetration of wind and solar sources (for example, as these models do not use hourly steps or multi-scenario approaches, rules of thumb are needed to decide on the required peaking capacity - an approach that has obvious limitations).

EDF R&D has led a major effort in recent years to study the implications of various energy scenarios on the electric power system. Various approaches were tested and developed in-house. One of these, used in "Technical and economic analysis of the European electricity system with 60% RES",[4] consists of using a "chain of models" (instead of a single model), with each model in the chain making it possible to study and grasp various key impacts of wind and solar integration in power systems.

The CONTINENTAL model (see Langrené et al)[5] is the main step in the modelling chain described below. The input data and hypotheses (such as the CO_2 price, demand level, etc.) come from energy scenarios, which are sometimes established using large energy systems models (such as the EDF R&D Madone/TIMES model, or the JRC model (see Simoes et al)),[6] which then constitute the first step of the modelling chain. The CONTINENTAL model's[5] outputs can also be fed into other modules/models, constituting the last steps in the chain, as described below. The following paragraphs describe in more depth the core model and the sub-modules developed.

In order to study the impact of wind and solar, the core power system model (CONTINENTAL) needs to feature some minimum characteristics to provide credible insights. These "minimal/recommended requirements" have been well discussed in the research community in recent years, and the most often cited are:

- **Hourly base And multi scenarios** of demand and variable generation: assessing the need for back up generation implies being able to take into account extreme events that can happen over a few hours, in certain years. The use of average profiles (for instance, only peak and off-peak steps, on one average day per month) cannot capture such events.

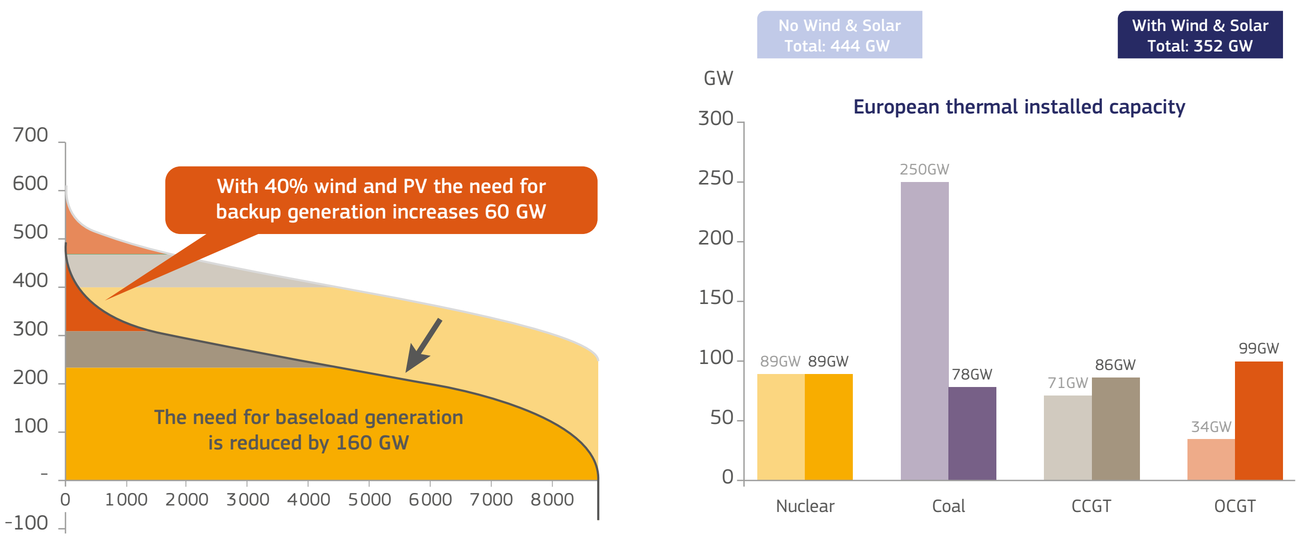
4 Alain Burtin, Vera Silva, "Technical and economic analysis of the European electricity system with 60% RES", EDF R&D, June 2015.
5 Nicolas Langrené, Wim van Ackooij, and Frédéric Bréant, "Dynamic Constraints for Aggregated Units: Formulation and Application", IEEE transactions on Power Systems, Vol 26, no. 3, August 2011.
6 Sofia Simoes, Wouter Nijs, Pablo Ruiz, Alessandra Sgobbi, Daniela Radu, Pelin Bolat, Christian Thiel, Stathis Peteves, "The JRC-EU-TIMES model, Assessing the long-term role of the SET-Plan Energy technologies", JRC Scientific and Policy Report, 2013.

- **Multi-zone modelling** (i.e. modelling exchanges between countries in the European system): national studies often use a "single zone" model, using rough approximations for the level and prices of imports and export. As the European grid gets more integrated and interconnected, the impact of these simplifications should be re-assessed regularly. The CONTINENTAL model makes it possible to feature a European multi-zone market.

- **Water reservoirs and pump storage management**: Hydro resources and existing pump storage are key providers of flexibility – most models rely on simplified rules of thumb and a deterministic vision to dispatch these energy-constrained resources. Such simplifications might under- or overestimate the role of these resources, while a stochastic modelling of hydro (such as the one used in CONTINENTAL) gives a more realistic view.

- **Detailed modelling of thermal unit constraints**: dynamic constraints such as minimum on/off time, start-up costs, minimum stable generation, etc. are important when estimating the system flexibility – modelling these constraints generally implies very strong increases in problem complexity and computing time. It might therefore not be possible to always model them, but sensitivities to these parameters should be considered.

Figure 5: European load duration curve of demand and net demand with 60% RES (left) and structure of the generation mix with and without wind and PV generation (right)



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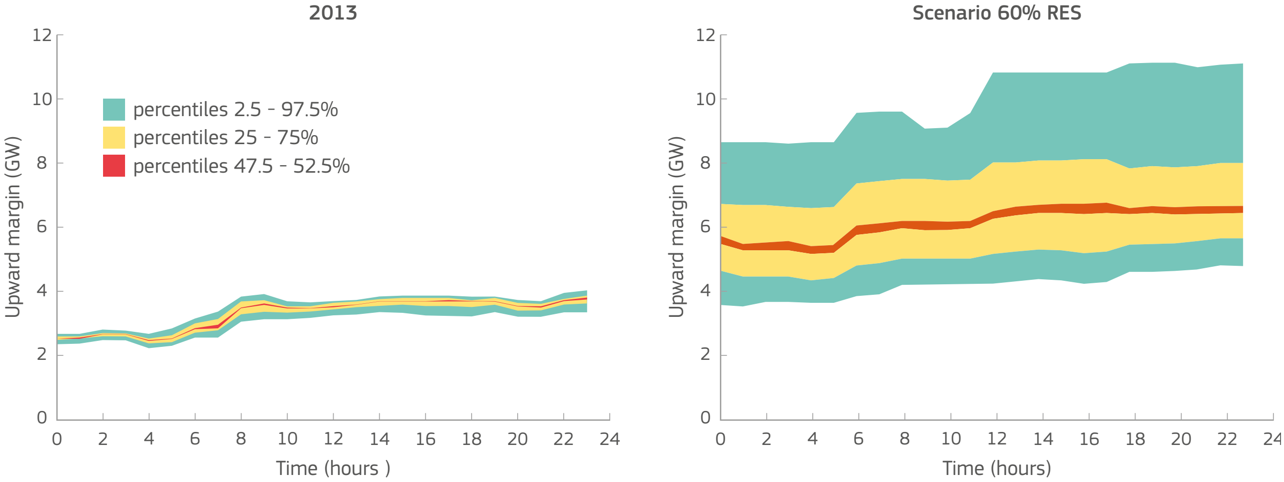
Additionally, such models should make it possible to analyse the need for different types of back-up fossil generation (e.g. the share of combined cycle versus open cycle gas turbines) – in the EDF modelling chain. The so called "investment loop" makes it possible to establish a least cost back-up generation fleet, respecting a predefined adequacy criteria (a 3/y hours Loss of Load Expectation). Figure 5 gives an example of how thermal generation would evolve from a European system with 0% wind and solar to one with 40%.

However, as already mentioned, adding too many features at once in one single power dispatch model might not always be a good option: the computing time is likely to increase sharply, but also (and perhaps more importantly) it might limit the possibility to understand all the phenomena at play in a high RES system (when models become overly complex, there is a risk that they become for most people a mysterious black box, instead of a tool that allows a better understanding by engineers and economists).

Figure 6: Day-ahead operating in 2013 and the simulated operating margin for the scenario "60% RES" for France during summer



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Therefore, for its 2015 study[4], EDF R&D developed additional sub-modules using output data from the power system model to analyse specific power system issues, such as the need for operational margins compared to the available flexibility ("FlexAssessment" – see Figure 6), or the behaviour of frequency ("Dynamic stability module"), without modifying (and making more complex) the core power system model itself.

The CONTINENTAL model and the various sub-modules make it possible to simulate one year periods. So, it is not possible directly to propose evolution scenarios, for which TIMES models are better suited. It would, however, be possible to extend the "chain of models" and to back-feed information into the TIMES model (such as, for example, a better vision of the required thermal back-up generation). Interaction between models in this way can be a great tool to build decarbonisation scenarios that take into account both multi-energy interactions and the strong specificities of electrical power systems.

The "chain of modelling" discussed here is one example where modelling has provided significant insights into the implications and challenges of a high RES European scenario for the electricity system.[4] EDF R&D, already with a long history of energy modelling, is continuing to work on energy system modelling, in an effort to keep increasing our understanding of the current and future challenges of the electricity and energy systems.

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Timothée Hinchliffe

Timothée Hinchliffe is project manager on energy storage economics at EDF R&D. His main focus over the past five years has been the assessment of energy storage needs through the use of modelling, and considering the competition with other flexibility levers such as interconnections or demand response. Timothée holds a Master's in Electrical engineering from Supelec.

Miguel Lopez-Botet

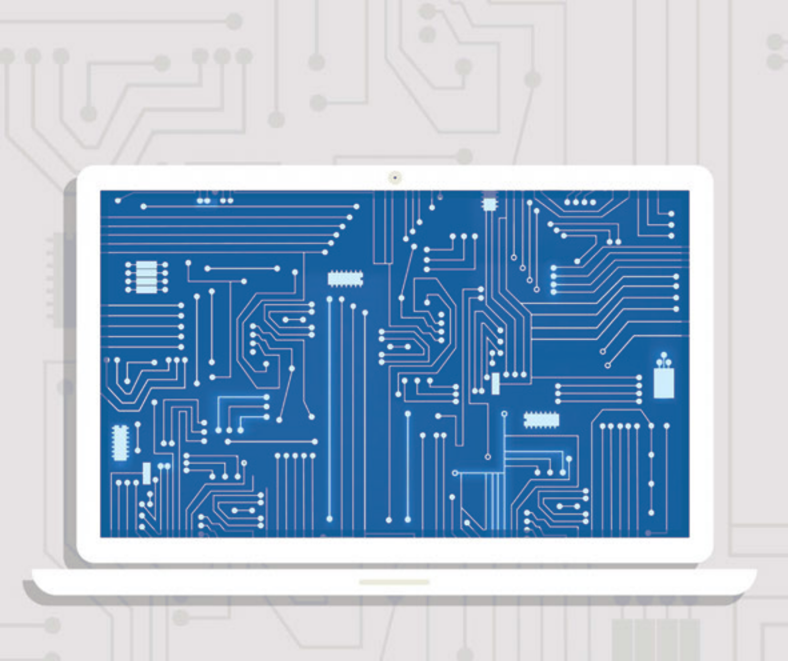
Miguel Lopez-Botet is the manager and technical leader of a project team responsible for "Analysis of future energy mixes" within EDF R&D. His main research topics are generation expansion planning and operation, the integration of wind and solar PV generation and the value of flexibility and ancillary services.

Paul Fourment

Paul Fourment graduated in energy engineering from the Ecole Polytechnique (Paris). He has worked for three years at EDF R&D as a research scientist on renewable integration in the European Power System. His work deals in particular with the power system's flexibility needs, the articulation between nuclear and renewable technologies, and the cohabitation between global and local systems.

Dr. Vera Silva

Dr. Vera Silva is the director of the EDF R&D research program on "Energy systems and markets" and a senior researcher at EDF R&D in the field of "operation of electricity systems and markets". She has 18 years' experience in the power systems industry and before joining EDF in 2009 she worked as a research assistant at the Control & Power research group of Imperial College London and at the University of Manchester.



METIS: the new short-term energy system model explored by the Directorate-General for Energy

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METIS is a research project of the European Commission's Directorate-General for Energy (DG ENER) for the development of energy simulator software with the aim to further support ENER's evidence-based policy-making. It is developed by a consortium (Artelys, IAEW, ConGas and Frontier Economics) as part of Horizon 2020 and is closely followed by DG ENER.

Software description

Unlike other simulators, *METIS will be owned and operated by DG ENER*, with the support of the Commission's in-house science and knowledge service, the Joint Research Centre. The intention is to have an in-house tool that can quickly provide insights and robust answers to complex economic and energy related questions, focusing more on the short-term operation of the energy system and markets. METIS was used, along with PRIMES, in the impact assessment of the Market Design Initiative.

METIS is an energy model that covers, with high granularity (geographical, time etc.), the whole European energy system for electricity, gas and heat. In its final version it should be able to simulate both system and market operation for these energy carriers, on an hourly level for a whole year and under uncertainty (capturing weather variations and other stochastic events). METIS works *complementary* to long-term energy system models (like PRIMES and POTEnCIA) as it focuses on simulating a specific year in greater detail.

METIS has a modular structure that makes it easy to extend the software through the addition of new modules or the adjustment of existing ones. The model runs are performed by software dedicated to large energy system optimisation[7]. All components and modules are managed by a platform[8] providing a common framework and set of interoperable libraries.

Although intended to be a detailed output-tool, significant emphasis is also placed on its user-friendliness and fast operability. The end goal of METIS is that it can be used not only by expert modellers, but also (trained) policy-makers and analysts.

With the first version of METIS having been delivered in January 2015, new versions are expected to be delivered gradually over the next two years, including additional modelling capabilities related to electricity and gas markets, heat and demand side modelling.

METIS Studies

Parallel to the software development, the consortium will be producing studies using METIS. These are intended to be technical studies of around 50 pages in length, fully exploiting the available capabilities of the METIS software. The scope of the studies is threefold:

(a) Investigate topics that are deemed important for DG ENER,

7 *Crystal Optimization Engine*, property of Artelys.
8 *Artelys Crystal Platform*, property of Artelys.

providing quantitative results associated with the impact of the examined policies or aspects of the energy system;

(b) Present the capability and appropriateness of the software to address policy questions of interest to DG ENER;

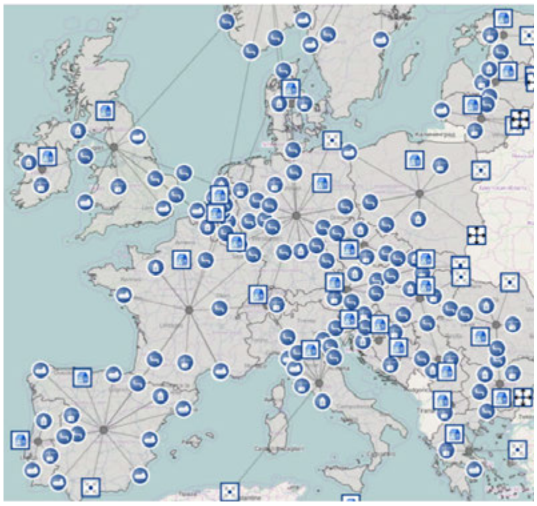
(c) Provide ready templates for DG ENER in order to perform similar studies in the future.

Which policy questions can METIS answer and which ones can't it?

Upon final delivery, METIS will be able to answer a large number of questions and perform highly detailed analyses of the electricity, gas and heat sectors. It will be possible to tackle a number of topics with METIS for the whole EU and/or for specific regions/Member States (the list below is indicative):

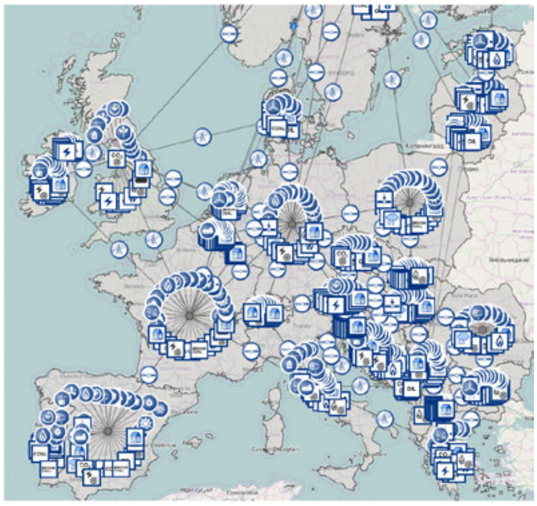
- The impacts of mass Renewable Energy Source integration on the energy system operation and markets functioning (for one or all sectors);
- Modelling of electricity and gas markets under different market designs;
- Modelling of electricity and gas flows between zones;
- Cost-benefit analysis of infrastructure projects, as well as impacts on security of supply;
- Generation adequacy analysis;
- Studying the potential synergies between the various energy carriers (electricity, gas, heat);
- What is the cost/saving of a specific measure for a given year?
- Impact of new energy usages (e.g. electrical vehicles, demand response) on the network reinforcement and generation costs.

Figure 7: Gas model



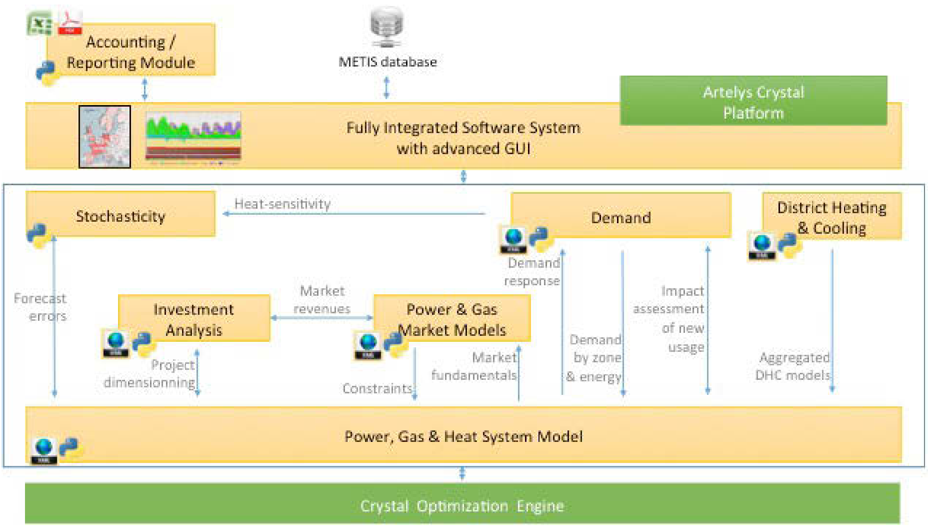
Source: METIS

Figure 8: Power model



Source: METIS

Figure 9: METIS module architecture



Source: METIS

On the other hand METIS is not designed to answer (at least in the initial stage) the following questions (again, the list is indicative):

- Any type of projection for the whole energy system;
- Optimal investment planning (capacity expansion) for the EU generation or transmission infrastructure[9];
- Impacts of measures on network tariffs and retail markets;
- Short-term system security problems for the electricity and gas system (requiring a precise estimation of the state of the network and potential stability issues);
- Flow-based market coupling and measures on the redesign of bidding areas.

Transparency

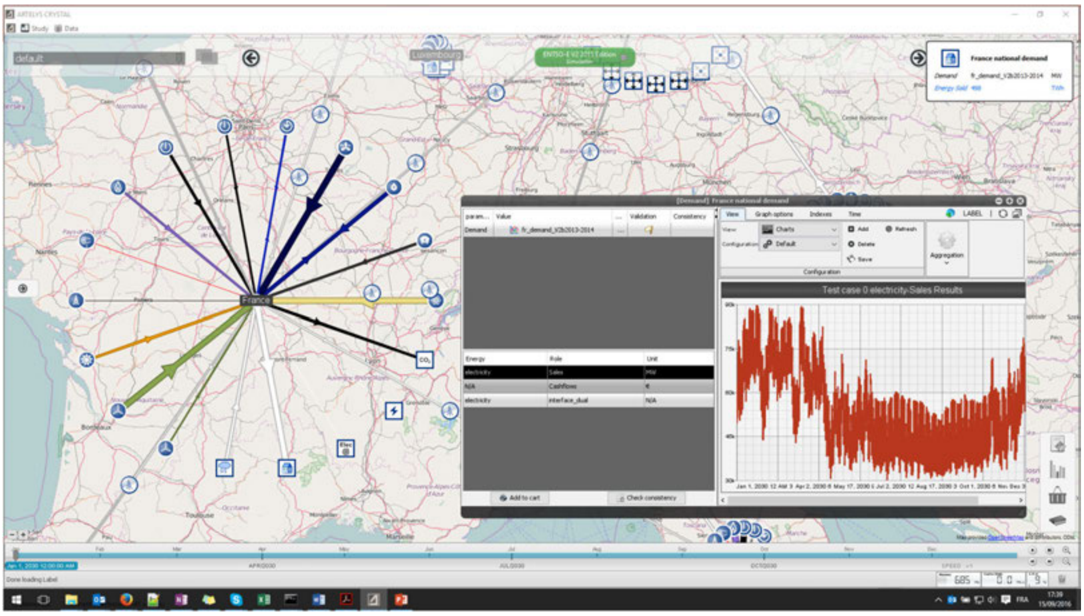
METIS will be fully transparent concerning the modelling techniques applied, with the final goal of being able to offer the relevant source code and non-commercial data inputs. Furthermore, all technical documentation and studies produced will be made available.

For transparency reasons, all deliverables related to METIS, including all technical specifications documents and studies, are intended to be published on the website of DG ENER[10].

9 The planned version of METIS will include some capacity expansion capability, able to optimise the capacity of certain transmission and generation assets. Future versions of METIS may have additional capabilities.

10 Once operational, the envisaged link is expect to be the following: https://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis

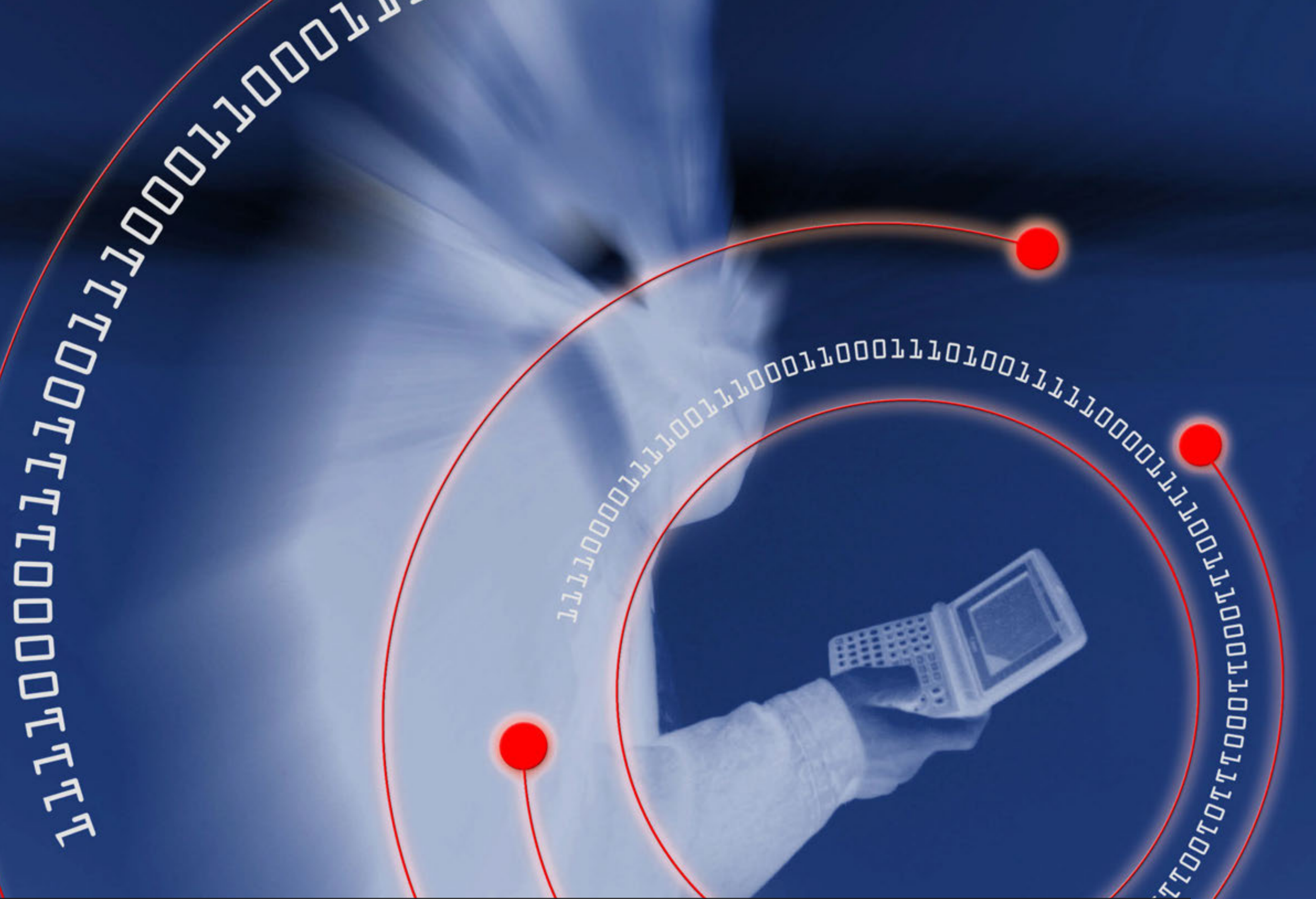
Figure 10: Performing studies with METIS – screenshot from user interface



Source: METIS

Kostis Sakellaris

Kostis Sakellaris joined the Economic Analysis Unit of the European Commission's Directorate-General for Energy in 2012. He has been working in the modelling team since then, heavily involved in a number of energy-related impact assessments and projects (METIS, Market Design, 2030 Energy and Climate Framework, Reference Scenario). Prior to that, he worked as an electricity market expert in the Markets and Competition Unit of the Greek Regulatory Authority for Energy. He graduated as a mathematician in Athens, Greece and holds an MSc in Mathematical Finance from the University of British Columbia, Canada.



The importance of open data and software for energy research and policy advice

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Given the uncertainty and complexity of the energy system, quantitative models are vital tools to explore alternative scenarios and help guide public policy. Yet most models and data remain inscrutable "black boxes" – whether small econometric models or large linear optimisation models with hundreds of thousands of input variables. In contrast to closed models, "open" models imply that anyone can freely access, use, modify, and share both model code and data for any purpose (Open Knowledge Foundation, 2015).[11] In this article we argue why energy data and models urgently need to become open; discuss the key reasons why many are currently not; and propose some next steps for the energy research community.

Why models and data should be open

Given the critical guidance that energy models and data provide to decision-makers, they should be made open and freely available to researchers as well as the general public, for four reasons:

1. **Improved quality of science.** Transparency, peer review, reproducibility and traceability lead to higher quality science. Yet these principles are almost impossible to implement without access to models and data (DeCarolis et al., 2012; Nature, 2014).[12] Human error is inevitable under pressure to deliver, and model mistakes can have profound implications. For example, the Reinhart-Rogoff[13]

11 Open Knowledge Foundation, 2015. Open Definition 2.1 - Open Definition - Defining Open in Open Data, Open Content and Open Knowledge [WWW Document]. URL http://opendefinition.org/od/2.1/en/ (accessed 3.15.16).

12 DeCarolis, J.F., Hunter, K., Sreepathi, S., 2012. The case for repeatable analysis with energy economy optimization models. Energy Economics 34, 1845–1853. doi:10.1016/j.eneco.2012.07.004; Nature, 2014. Journals unite for reproducibility. Nature 515, 7–7. doi:10.1038/515007a

13 Herndon, T., Ash, M., Pollin, R., 2014. Does high public debt consistently stifle economic growth? A critique of Reinhart and Rogoff. Camb. J. Econ. 38, 257–279. doi:10.1093/cje/bet075

spreadsheet error arguably skewed the international debate on austerity (Herndon et al., 2014)[14]. Such incidents serve as warnings against poor programming practices such as a lack of auditing, as well as closed models and data: it was only through sharing the spreadsheet that the errors were discovered.

2. **More effective collaboration across the science-policy boundary.** Better and more transparent science itself ought to enable better policy outcomes. Academic peer review routinely does not check model arithmetic and data validity, and so a separate process of quality assurance is required. While mostly absent from academic practice, this is often implemented as a formal procedure in government (e.g., DECC, 2015)[15]. Unlike academics, governments often model for numbers rather than insight. The specific numbers can be of great societal importance, such as the level at which to set subsidies or the cost of specific policies. Often, the most important aspect is the quality or transparency of input data, rather than the novelty of the modelling methodology. In large datasets used in government decision-making, traceability and referencing can become major problems, as civil servants developing models and data are often not trained scientists. Openly available, collaboratively developed datasets and reference models would allow the burden of this work to be shared more widely, and across both academia and government.

3. **Increased productivity through collaborative burden sharing.** Collecting data, formulating models and writing code are resource-intensive, while research funding and time are scarce resources. Society benefits if researchers avoid unnecessary duplication and learn from one another. Individual researchers gain more time to spend on pressing research questions rather than redundant work on model or dataset development. Furthermore, research only matters if it is seen and used, and open-access publishing has been shown to increase readership and citations (McCabe and Snyder, 2014)[16]. Since openly shared code or data is more likely to be known to others, it is more likely to be used and further improved. This benefits the original researcher through peer recognition and academic credit, and moves the research community as a whole forward.

4. **Profound relevance to societal debates**. Reengineering the energy landscape will affect everyone, producing winners and losers. A balanced societal and political debate requires transparent arguments based on scientific justifications, but escalating concern about reproducibility in some fields is shaking public confidence in scientific research (Goodman et al., 2016)[17]. Finally, besides the practical considerations outlined above, there remains the ethical argument that research funded by public money should be available to the public in its entirety.

Why they are (mostly) not open

Despite these arguments, we see four main reasons why closed models and data may remain attractive and rational in some cases:

1. There is a range of valid ethical and security concerns, particularly with data. Researchers may have access to data containing commercial sensitivities or personal information (particularly relevant when moving towards more decentralised smart grids with their focus on individual households).

2. Openly sharing details of models, analysis and data can create unwanted exposure. Flawed code or data can discredit research results and cause embarrassment to their authors, but only if they are visible. Some may also fear that inexperienced researchers will use an open model or open data to produce flawed analysis that reflects poorly on its original authors.

3. It is time-consuming to write legible and reusable code, track processing steps, write documentation and respond to feature requests. Because model and dataset development are large investments, it is often rational for researchers and institutions to maintain "trade secrets" to compete for third-party research funding: a classical collective action problem where individual actors are trapped in a suboptimal non-cooperative equilibrium.

4. Finally, there is simple institutional and personal inertia, often alongside complex and uncoordinated institutional setups.

While understandable from the perspective of individual actors, collectively these engender a sense of mistrust in complex, impenetrable models and enigmatic datasets. For example, the European Commission faced criticism for using the proprietary PRIMES model to deliver key results for its Energy Roadmap 2050 (Helm et al., 2011).[18] More significantly, the UK's decarbonisation was arguably delayed for years by models that underestimated the scale of the challenge due to opaque and heroically optimistic cost assumptions for onshore wind (House of Lords, 2005).[19]

14 Herndon, T., Ash, M., Pollin, R., 2014. Does high public debt consistently stifle economic growth? A critique of Reinhart and Rogoff. Camb. J. Econ. 38, 257–279. doi:10.1093/cje/bet075
15 DECC, 2015. Quality Assurance tools and guidance in DECC [WWW Document]. URL https://www.gov.uk/government/collections/quality-assurance-tools-and-guidance-in-decc (accessed 6.2.16).
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What needs to be done

Individual researchers and research groups must understand the practicalities of open code and data. These range from issues like considering the intended target audience and choices such as licensing and distribution channels. Pfenninger et al. (2016)[20] give guidance specifically for energy research. More importantly, the energy research community as a whole needs to move forward on several fronts:

1. **Work towards reducing parallel efforts and duplication of work.** There should be better coordination between different modelling efforts. This can include the development of common code bases, common datasets, community standards to ensure interoperability, and coordinated efforts to enable third-party verification of model-based results.

2. **Increase transparency and reproducibility.** Community efforts towards tested and documented code packages for specific tasks can serve an important purpose. But one-off analyses created for specific papers, or code that is written with the understanding that it will never be made public, may be poorly documented and structured, meaning its release would be of limited use.

3. **Change incentives and bring aboard different stakeholders.** The energy research community and specifically the emerging open modelling and open data communities must engage with other stakeholders to ensure institutional and academic recognition for open energy models, and to start tackling the harder problems that follow. Open and transparent research is not currently incentivised: in fact, the opposite is often perceived as advantageous for scientific career advancement. Changing these incentives will require efforts not only from researchers themselves but also from their employers, from grant agencies, and other stakeholders like publishers (Nosek et al., 2015).[21]

Given the importance of rapid global coordinated action on climate mitigation and the clear benefits of shared research efforts and transparently reproducible policy analysis, the community still has much work ahead.

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20 Pfenninger, S., Schmid, E., Wiese, F., Hirth, L., Davis, C., DeCarolis, J.F., Fais, B., Krien, U., Matke, C., Momber, I., Müller, B., Pleßmann, G., Quolin, S., Reeg, M., Richstein, J.C., Schlecht, I., Shivakumar, A., Staffell, I., Tröndle, T., Wingenbach, C., 2016. Benefits, challenges and solutions for open energy modelling. Open Energy Modelling Initiative Working Paper. URL https://openmod-initiative.github.io/openmod-working-paper/ (accessed 1.7.16).

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Dr Lion Hirth

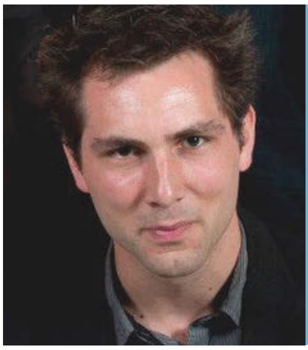
Dr Lion Hirth is a post-doctoral researcher at the think tank MCC, a fellow at the PIK research institute, and director of the consulting firm Neon. His research interest lies in the economics of wind and solar power. He has been concerned with open energy data in a number of projects and maintains the open-source power market model EMMA.

Dr Stefan Pfenninger

Dr Stefan Pfenninger is a member of the Climate Policy Group at ETH Zurich, Switzerland. He holds degrees in environmental science, environmental policy, and environmental engineering. His research interests span the challenges and opportunities in the clean energy transition, particularly the modelling of futures with high shares of wind and solar energy.

Joseph DeCarolis

Joseph DeCarolis is an Associate Professor in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. His research is focused on the interdisciplinary assessment of technologies and public policies that promote long-term energy sustainability. He is particularly interested in developing robust decision-making strategies for climate mitigation by conducting analysis with technology-rich energy system optimisation models.



Sylvain Quoilin

Sylvain Quoilin obtained a European Doctorate in Mechanical/Energy Engineering in 2011 at the University of Liege (Belgium), where he then became lecturer. He is now a scientific officer at the Joint Research Centre of the European Commission, focusing on energy policy support and on the modelling of future European energy systems.

Iain Staffell

Iain Staffell is a lecturer in Sustainable Energy at Imperial College London, holding degrees in Physics, Chemical Engineering and Economics. His research centres around decarbonising electricity, ranging from the economics of battery storage and nuclear power to modelling the integration of renewables into electricity systems.

The Nordic Energy Technology Perspectives 2016

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The Nordic Energy Technology Perspectives (NETP) series assesses how the Nordic region can achieve a carbon-neutral energy system by 2050. NETP 2016 marks the second edition in the series, the first having been published in 2013, and presents technology pathways towards a near-zero emission Nordic energy system in addition to in-depth scenarios tailored to inform policy-making in the region.

The analysis conducted in NETP 2016 is presented around the Nordic Carbon Neutral Scenario (CNS), which calls for an 85% reduction in emissions by 2050 (from 1990 levels).[22] To achieve this target, three macro-level strategic actions are elaborated. The first of these calls for the planning and incentivisation of a Nordic electricity system that is significantly more distributed, interconnected and flexible than at present. The second calls for the accelerated development of technology that will increase the decarbonisation of long-distance transport and the industrial sector. Finally, the third strategic action aims to tap into the positive momentum of cities to strengthen national decarbonisation and energy efficiency efforts in transport and buildings.

22 The Nordic 4°C (4DS) entails a 42% reduction and serves at the baseline.

Achieving a carbon-neutral energy system

The Nordic countries have already decarbonised aspects of their energy systems, having decoupled CO_2 emissions from GDP growth over two decades ago. However this process will have to pick up in pace if the CNS is to be achieved. Policy and technology innovation will be crucial in this regard. The policies and technologies implemented to date have already captured the most cost-effective opportunities to weaken the link between economic growth and emissions, leaving greater challenges in sectors where progress has been more difficult.

The CNS requires a dramatic change in the composition of primary energy supply, coupled with aggressive energy efficiency policies that substantially reduce demand. Under the scenario, bioenergy surpasses oil as the largest energy carrier, with total demand for biomass and waste increasing from almost 306 million MWh in 2013 to over 444 million MWh in 2050. However, the most dramatic transformation of the Nordic power and heating system will come from the combination of a decline in nuclear and a significant build-out of wind power, resulting in generation that far exceeds domestic demand, even when reduced nuclear generation is figured in.

With an increase from 7% of electricity generation in 2013 to 30% in 2050, wind will displace fossil and nuclear. While the transition of heating networks from fossil fuels to heat pumps and electric boilers will add flexibility to an integrated power and heat system, the increase in wind generation will put new demands on how the electricity market is organised. Hydropower will be increasingly valuable for regulating the market, but will not suffice on its own. The increase in variability will require balancing through a combination of flexible supply, demand response, storage and electricity trade. Increased trade will reduce system costs and enhance flexibility, but long lead times in setting up interconnectors and strengthening the grid may delay achieving full potential.

Industrial sector decarbonisation the greatest challenge

The 60% reduction in the CO_2 intensity of industry called for in the CNS will require aggressive energy efficiency combined with other measures, such as switching fuel and feedstock to lower-carbon energy mixes, and the deployment of low-carbon innovative processes, including CCS. Increased international cooperation will also be required, for example through international carbon pricing or energy performance auditing mechanisms, as these will play a key role in mitigating the risks of the low-carbon investments needed to decarbonise industry, thereby reducing potential impacts on competitiveness.

Achieving the CNS will require a 10% increase in investments over that needed for the 4DS[22] target in the period from 2016 to 2050, representing an additional investment of about EUR 298 billion.[23] The greatest relative investment increases are required in buildings and industry, with an increase of 47% required in the five industrial sectors analysed, which together account for 80% of the total final energy use by industry in the Nordic region. This represents a cumulative investment of around EUR 27 billion, mainly associated with energy efficiency improvements and the deployment of low-carbon innovative processes. At EUR 179 billion, the largest share of additional cumulative investment is accounted for the by transport sector.

23 US$ 333 billion.

Radical transformation of transport

Transport, which currently accounts for almost 40% of Nordic CO_2 emissions, delivers the greatest emission reduction in the CNS. Transport requires a dramatic emissions slash – from about 80 million tonnes of CO_2 in 2013 to just over 10 million tonnes in 2050. This target can be achieved through a three-pronged 'avoid-shift-improve' strategy of reducing transport activity (avoid), shifting to more efficient or less carbon-intensive transport modes (shift) and adoption of more efficient or less carbon-intensive transport technologies and fuels (improve). Improvements to technologies and fuels will play the largest role in the transformation of transport, largely because avoid and shift strategies have already been deployed.

In the face of steadily rising demand for transport services, the success of taxation and subsidy approaches in power and heat generation will provide a solid foundation for similarly assertive policies in transport. Consequently, transport's overall energy use in the CNS will decrease by over 20% compared to 2000, despite a 70% increase in overall passenger and freight activity. Under the scenario, electricity accounts for 10% of final energy use in transport in 2020, but thanks to the high powertrain efficiency of electric motors, electricity's share of transport activity is much higher: 64% of road and rail passenger kilometres and 42% of road and rail freight activity.

Furthermore, the CNS requires a tripling of the current rate of improvement in space heating energy intensity of Nordic buildings. This will be achieved primarily through the deep energy renovation of existing buildings, which will constitute 70% of the Nordic stock in 2050. Energy efficiency gains in buildings can unlock biomass and electricity for use in other sectors, avoiding infrastructure investments in power and heat and CO_2 emissions in transport and other sectors.

Nordic Energy Research

Nordic Energy Research is an intergovernmental organisation supporting and coordinating sustainable energy research in the Nordic region. It is the platform for cooperative energy research and policy development under the auspices of the Nordic Council of Ministers. Nordic Energy Research's governance structure is closely connected to both the national political systems of the five Nordic countries as well as the intergovernmental Nordic system. This creates a constant interaction between research strategies, results and key issues on the political agenda. For more information, see Nordic Energy Research's strategy.

Recommendations

The NETP 2016 stipulates that governments will need, individually and in a coordinated manner, to play a lead role in stimulating actions to achieve the set targets. Specifically, actions in four key areas are identified. Governments will need to strengthen incentives for investment and innovation in technologies and services that increase the flexibility of the Nordic energy system. Furthermore, efforts will be required to boost Nordic and European cooperation on grid infrastructure and electricity markets.

It will also be necessary to ensure the long-term competitiveness of Nordic industry while reducing process-related emissions. For this, governments will have to act to reduce the risk of investment in low-carbon industrial innovations and use public funding to unlock private finance in areas with significant emission reduction potential but a low likelihood of independent private sector investment.

Finally, governments in the region will have to act quickly to accelerate transport decarbonisation by using proven policy tools such as congestion charges, differentiated vehicle registration taxes, bonus-malus regimes and altered parking fees. At the same time they should step up investments in cycling, public transport and rail networks. Implementation of these short-term policy recommendations will create the framework conditions for the ambitious partway outlined by the CNS to be achieved.

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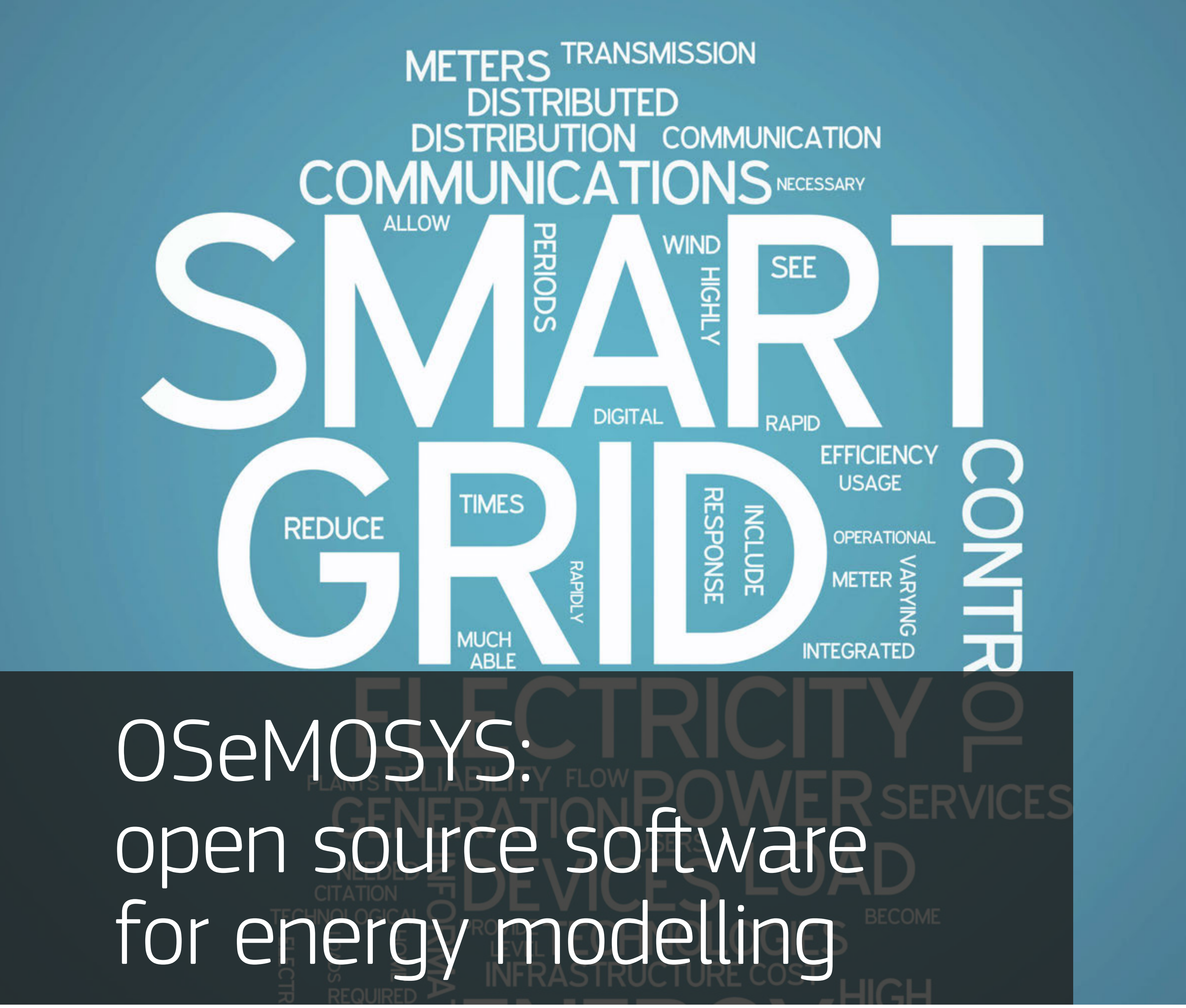

OSeMOSYS: open source software for energy modelling

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OSeMOSYS is a free, open source and accessible energy systems model generator. It can generate small village energy models to global multi-resource integrated assessment tools. It can be used to assess energy supply security, investment outlooks, and GHG mitigation strategies.

In general terms, it calculates what investments to make, when, at what capacity and how to operate them to meet the said policy target(s) at the lowest cost.

It is therefore used to develop models to inform policy design and is part of the largest Horizon 2020 LCE21 energy modelling research effort REEEM.org. Furthermore, it is used to underpin selected outputs of the DG Energy InsightEnergy.org think tank, and is used by national governments in the EC and beyond for medium to long-term planning. Outside of Europe, it was used for the World Bank and the United Nations Economic Commission for Africa. Therein the development (and trade between) the electricity sector of every African country was analysed. In the former, the focus was understanding the climate resilience of the system under different futures. In the latter, the scale of investment for the world's fastest growing continent was quantified. A similar effort for South America is being used to understand that continent's infrastructure development. Models generated have been broad and useful.

OSeMOSYS.org was launched at Oxford University in 2011 at a UK Energy Research Centre (UKERC) meeting and included co-authors from University College London (UCL), the United Nations Industrial Development Organization (UNIDO), University of Cape Town (UCT), Stanford University, the Paul Scherrer Institute and others. It was in response to the observation that all countries need to assess the quantitative evolution of their energy sectors due to energy's highly strategic role in development. At the time there were no open source optimising energy system model generators available to do so. All aspects of the tool are open, this includes the code, the mathematical programming language and the solvers used.

Currently administered by KTH (the Royal Institute of Technology, Sweden) its uptake in an academic setting is accelerating. Scores of universities, academic papers and a growing number of governments are taking the tool up to use in academic and real-world analysis. This bodes well, as the community contributing to its development both grows and adds critically academically reviewed advances. Importantly, it also ensures that there are a multitude of 'service providers' should commissioned studies need to be undertaken.

It also features as part of a broader initiative (called Optimus Community) led by the UN. Further starter data-sets and off the shelf models are being developed to help make open reviewed data available to be built on rapidly. Initial data sets being developed

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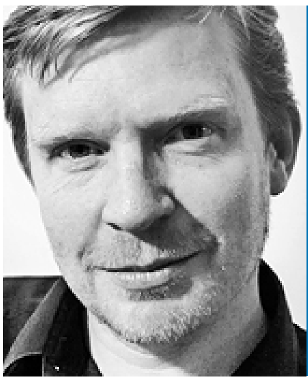
include all EU, African and South American countries. The aim is to cover the globe with peer-reviewed open access data.

While there is a growing community of users and applications, a special focus is Europe. Focusing on the SET-Plan, at the heart of the REEEM.org project are integrated European energy system models. One of the tools being developed is an OSeMOSYS generated model. That model (together with a more detailed MARKAL-TIMES model developed by the University of Stuttgart) will determine the cost optimal technology pathway to match supply with demand in all EU countries in technological detail. It will provide the backbone to a tailored evaluation of the impact of SET-Plan technologies.

To do so, information from several other models is being integrated. The OSeMOSYS-generated model will focus on being an open-source engagement tool. It will replicate and highlight the key underlying dynamics of the integrated European energy system. (This will be complemented by e-learning tools to build capacities and share expertise based on the assessments performed in this project.) It will enable answers to questions like what research funding and increased investment cost would be required to meet SET-Plan objectives, in addition to setting out detailed sub-targets - and their implications.

The model generator can be downloaded from OSeMOSYS.org. Therein, resources, papers, data sets and code in the free mathematical programming language GNUMathProg can also be downloaded. Recently the code has been translated into more than one language (or 'technology') and is currently available in GAMS (a popular language amongst economists) and Python (a widely used open source language). You can sign up to the OSeMOSYS newsletter on the website, where tools are also available to download. Furthermore, in the next few weeks a new interface is to be released, and a global summer school is to be launched.



Mark Howells

Mark Howells directs the division and holds the chair of Energy Systems Analysis (KTH-dESA) at the Royal Institute of Technology in Sweden. His group leads the development of some of the world's premier open source energy, resource and spatial electrification planning tools; he has published in Nature Journals; coordinates the European Commission's think tank for Energy; is regularly used by the United Nations as a science-policy expert; and is a key contributor to UNDESA's 'Modelling Tools for Sustainable Development Policies'.

Shared experiences in integrated energy systems modelling

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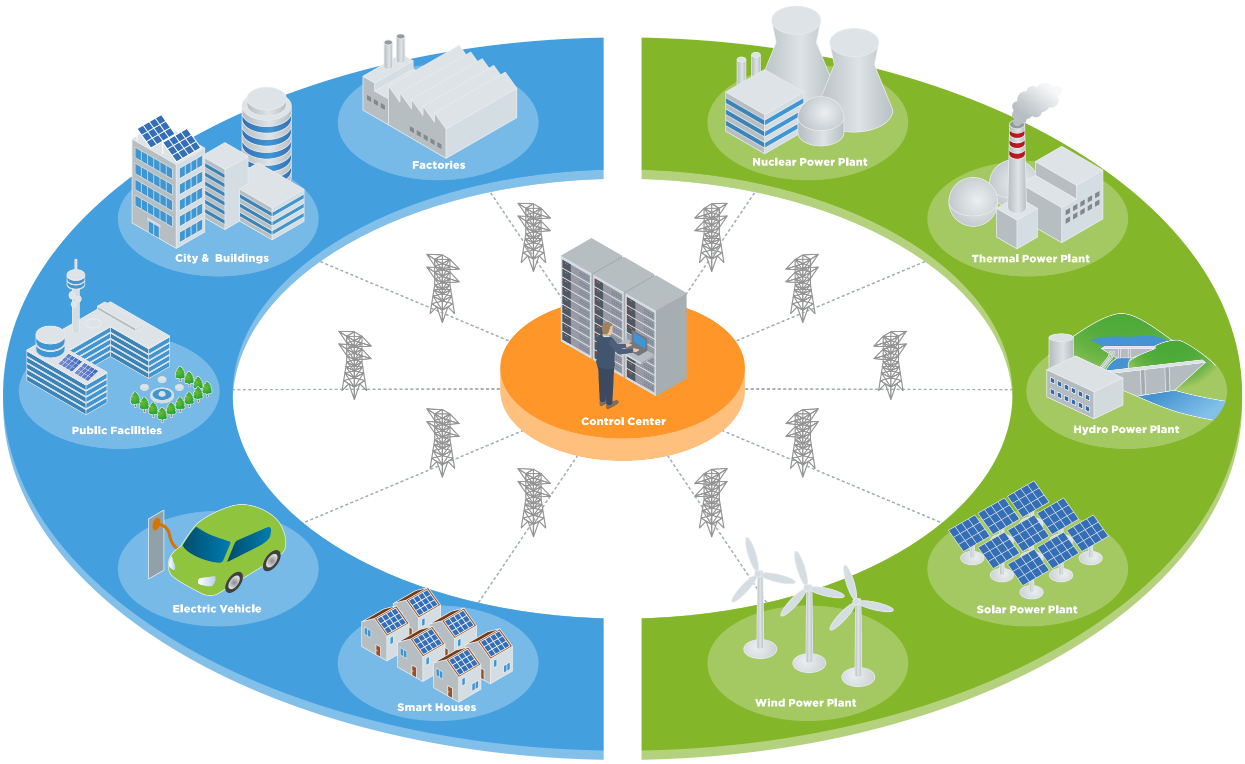
A key challenge in achieving a successful transition to a low-carbon Europe is implementing the correct suite of policy measures that are based on robust evidence. Today policy-makers across Europe draw on integrated energy system models to inform long range climate mitigation and energy policy choices. Established European models such as PRIMES, TIMES, MESSAGE, EnergyPLAN and newer models such as POTEnCIA and OSeMOSYS consider all modes of energy (electricity, heating and transport) across all sectors of the economy in an integrated fashion, rather than treating individual modes in isolation which can lead to poorly informed insights.

Our research in integrated modelling started with a specific focus on the wider energy system in Ireland. We use the TIMES integrated model,[24] which is a techno-economic optimisation framework developed over the past 40 years through the International Energy Agency's (IEA) Energy Technology Systems Analysis Program (ETSAP). The model allows users to generate future energy system pathways to meet energy needs at least cost, subject to user defined constraints. TIMES optimises for energy service demands (i.e. the utility we get from

24 The TIMES Integrated Energy Model of Ireland was funded by the Environmental Protection Agency (EPA) and Sustainable Energy Authority of Ireland (SEAI).



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energy use) such as lighting, heating, passenger kilometres, tonnes of steel and cement etc. This is significant because as a society we don't intentionally use energy, but rather have requirements for mobility, lighting, goods etc. In all, TIMES considers a wide range of over 1,300 technologies in the timeframe to 2050 from light bulbs, cars, fridges, heaters, boilers, power plants, bio refineries etc.

Early in our research we recognised a number of limitations to our modelling techniques and identified key areas that required improvement. One of these areas was how integrated models like TIMES dealt with variable renewable generation such as wind and solar power. Many integrated models have a simplified temporal and technical resolution of the power system in order to keep problems computationally manageable, however this comes with the trade-off of poor representation of variability within the models. To resolve this issue, we developed soft-linking techniques to link the energy system model to dedicated power system models. This allows us to leverage the strength of high-resolution technical and temporal power system models. In doing this we could account for greater temporal resolution (15 minute or hourly simulations) and also capture important technical characteristics of the power plants such as ramp rates, start costs etc. We recently expanded these techniques to include the full EU 28 power and gas systems with water as our next target for development. The geographical expansion of the research was partially driven by the need to model greater interconnected markets (both gas and electricity) within the EU and also to understand the distribution of effort for decarbonisation across all EU Member States. Soft-linking techniques has the advantage that it allows us to verify the technical robustness of simulations but comes with the challenge that an extra model must be maintained and it requires modeller judgement on feedback to the energy system model.

Another challenge was the integration of land-use and agriculture into our models. Ireland is unique in Europe as over 30% of GHG emissions come from agriculture. This research required us to work closely with agricultural scientists to develop a framework where we could account for these emissions and model the interactions, particularly for land use competition, between the energy sector and agricultural sector. Our current research on land use and agriculture has an important focus on the role of bioenergy and the implications of indirect land use change (ILUC) and recent amendments to the Renewable Energy Directive (so called 'ILUC directive'). While the science of ILUC is at an early stage our initial results point to increased costs for decarbonisation when ILUC is considered.

Like many research groups across Europe, we have seen our integrated models expand in size and complexity. Complexity is unavoidable in such large models due to the multi-dimensional and intricate nature of energy systems, but complexity has to be balanced with the inherent uncertainty in long range inputs such as fuel prices and macroeconomic estimations. The challenge of making models computationally manageable has often forced us to look at our simplifications and heuristics and ask the question, “are we making our models better or just getting the wrong answer quicker?” A recent focus of our research is trying to understand what level of complexity is appropriate in long term models given the uncertainty in inputs, and trying to understand how this value of complexity diminishes as we look into the future. We have found it beneficial to explore multiple pathways and seek out commonality between pathways rather than focus on deterministic solutions.

High-performance computing offers exciting possibilities for further development of integrated modelling, however many of the current architecture processes are challenging to parallelise. Projects like ‘BEAM-Me’ in Germany are investigating the potential for high-performance computing to enhance energy system models, and it will be interesting to see what developments occur.

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Above all we have learned that modelling the future is a humble science and great care must be taken not to confuse model insights for predictions. Human behaviour, economic volatility and technology readiness are but a small section of elements that have big influence on resulting pathways from models. We must be aware that the boundaries of the energy system don’t stop at the end of the pipeline or cable; they extend in to our lives, communities, and wellbeing. Current modelling efforts primarily have a techno-economic focus, however the challenge of decarbonisation, and more recently the greater level of decarbonisation required by the Paris Agreement will require our modelling community to look outward to other disciplines to inform pathways that we as a society are willing to travel on together.

Dr Paul Deane

Dr Paul Deane is a research fellow with the Energy Policy and Modelling Group in University College Cork in Ireland. He has been working in the energy industry for approximately 15 years in both commercial and academic research. His research activities include integrated energy systems modelling to assess holistic pathways to low carbon energy futures. Paul is also a member of the Insight_E group which is a European, scientific and multidisciplinary think-tank.

Mark O'Malley

Director of the International Institute for Energy Systems Integration

TALKS TO SETIS

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What does Energy System Integration involve and what value does it bring?

Energy Systems Integration (ESI) is the process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment.

Energy systems have evolved from individual systems with little or no dependencies into a complex set of integrated systems at scales that include customers, cities, and regions. This evolution has been driven by political, economic, and environmental objectives. As we try to meet the globally recognised imperative to reduce carbon emissions through the deployment of large renewable energy capacities while also maintaining reliability and competiveness, flexible energy systems are required. This flexibility can be attained through integrating various systems: by physically linking energy vectors, namely electricity, thermal, and fuels; by coordinating these vectors across other infrastructures, namely water, data, and transport; by institutionally coordinating energy markets; and, spatially, by increasing market footprint with granularity all the way down to the customer level (Figure 11).

ESI is a multidisciplinary area ranging from science, engineering, and technology to policy, economics, regulation, and human behaviour. It is this focus simultaneously on breadth and depth that makes ESI such a challenging and exciting area.

ESI is one of several global social and engineering trends that will shape the solutions to the key challenges of the next decades: resource stress, climate change, megacities, urbanisation, cybersecurity, and infrastructure resilience. ESI is an umbrella concept that encompasses activities tackled in the context of smart grids (grid modernisation) and smart cities. However, these two approaches are more limited, with one focused on a single energy vector (electricity) and the other limited in geographical scale to a city – so they may miss important opportunities that can arise by considering all energy vectors and all scales.

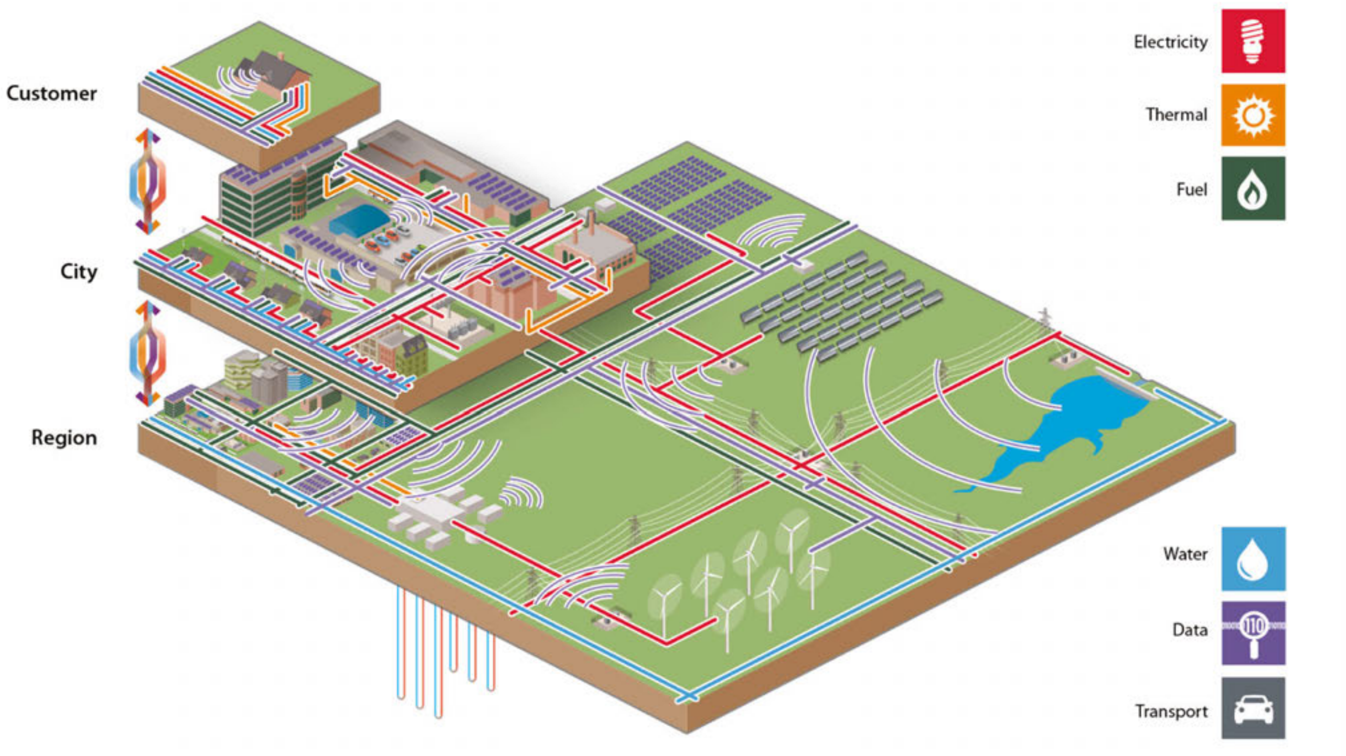
The value of ESI is in coordinating how energy systems produce and deliver energy in all forms to reach reliable, economic, and or environmental goals at appropriate scales. Analysis and design of integrated energy systems can inform policymakers and industry on the best strategies to accomplish these goals.

What are the principal objectives of the European Energy Research Alliance, Joint Programme on Energy Systems Integration and the International Institute for Energy Systems Integration?

The importance of ESI is being recognised globally. Most significantly, ESI is a central theme running through the European Commission's Strategic Energy Technology Plan (SET-Plan) Integrated Roadmap. It is also a central theme of the Clean Energy Ministerial and a major research theme with the U.S. Department of Energy national laboratory complex.

In February 2014 the US Department of Energy, National Renewable Energy Laboratory and Pacific Northwest National Laboratory co-hosted an invitation only workshop on ESI in Washington DC. There were 40 senior level attendees with 29 from the US, 10 from Europe and one from China. The workshop was designed to validate the importance of ESI as an emerging interdisciplinary scientific area and gauge the appetite for the establishment of an institute – the International Institute for Energy Systems Integration (iiESI). It was agreed by all participants that ESI is an important and emerging area and that forming an organisation such as iiESI was very positive and timely. The role and value of iiESI in fostering international collaboration, stimulating the sharing of knowledge and providing independent analysis was recognised by all. The independence of iiESI was seen as a fundamental characteristic, in particular with respect to valuing of particular technologies/solutions deployed in the energy system. iiESI as a formal organisation came into being in July 2016 as a global institute aimed at tackling the challenges of energy systems integration through global collaboration and education. **Formalising iiESI as a global, member-driven organisation of leading ESI scholars and practitioners provides a structure for leveraging each other's experiences and expertise, coordinating research agendas, and sharing best practices from around the world.** The establishment of a formal institute will allow the group to expand and grow to meet the changing needs of the ESI community.

Figure 11: Energy Systems Integration



Source: iiESI

There is also a new European Energy Research Alliance (EERA) Joint Programme (JP) in ESI. An EERA JP is created by interested organisations that define a joint research agenda for a topic included in the SET-Plan. EERA JPs coordinate research based on the participating institutions own resources. In addition, the JP can obtain supplementary funding from national or EU sources. The aim is to gradually increase the amount of dedicated funding to the JPs. This will allow a JP to widen and deepen coordination. **EERA JP ESI seeks to bring together research strengths across Europe to optimise our energy system, in particular by benefiting from the synergies between heating, cooling, electricity, renewable energy and fuel pathways at all scales.** The energy elements of the water and transport system are also included, as is the enabling data and control network that enables the optimisation. The EERA JP ESI is designed to develop the technical and economic framework that government and industries will need to build the future efficient and sustainable European energy system.

What are the main ESI research challenges and how can they be overcome?

In March 2015, Imperial College London hosted an iiESI workshop, on ESI Research Challenges. This was attended by 38 experts from Europe, USA, Africa, Asia, Russia and Australia. The disciplines represented ranged from Engineering, Economics, Social Sciences, Mathematics and Physics, and industry was also represented. Not surprisingly one of the main outcomes of the workshop was the "need to combine economic, social, and political perspectives with engineering knowledge". The need for education and dissemination featured strongly. In trying to identify research challenges however, the need for clear definitions of ESI and of "optimality" in an integrated energy system was apparent. There was little or no consensus on the optimality issue despite some follow up teleconferences and email exchanges.

Each energy system will approach ESI from a different starting point (e.g., an urban area in the developed world will have a different approach compared to a rural area in the developing world). It is crucial to define the geographical scope as well as the components, the boundaries, and the influence of the surroundings. For example, renewable integration is the driving force of ESI in many regions, but not all. In some regions, the main drivers are increased combined heat and power (CHP), increased efficiency, a shift from coal generation to natural gas, or simply electrification. Different incentives, decision-making processes, and access to capital due to location or scale will result in very different energy systems and approaches to ESI (e.g., a government can invest in high-voltage transmission, while individuals will not). As each energy system develops, it will be necessary to constantly re-evaluate the system in order to assess how it is best coordinated.

Developing coordinated systems through ESI analysis requires a proper understanding of the different actors involved, along with their motivations, their incentives, and the information they have access to. From a whole-system perspective, the actors in each energy domain tend to act on the information they have in ways that maximise benefits for their domain, but not for the entire energy system. For example, each user consumes based on their own requirements, each market values certain financial outcomes, and each government serves its own social or political motivations – but there may be no coordination across these domains to determine the best option for all actors involved. Poor outcomes can potentially arise from this lack of information and/or coordination, and may not be monetary in nature; a poorly executed energy transition could result in energy systems that lack technical integrity, social equity, and/or political acceptability.

The considerations that govern ESI are numerous and complex, and the outcomes and their value can be difficult to define. One of the first steps to determine this value is to define a set of robust metrics spanning the engineering and social sciences (e.g., financial impacts, emissions costs, resiliency, public health considerations, social utility, etc.) to measure and highlight the various benefits. Any set of definitions or metrics will have to be flexible enough to accommodate a wide range of circumstances. Metrics also need to be simple enough to allow for an overall holistic understanding of how the different aspects interact.

The main outcome of the London Workshop is the need for the global research community to adopt a common and clearly understood common language and consensus on the scope of the ESI. This is needed before a detailed interdisciplinary research roadmap for ESI can be articulated with confidence.

Because ESI is a broad topic that includes all types of energy sources and end-use applications, it is helpful to categorise examples of ESI into a few areas. Here we provide several examples of ESI that have been organised into three "opportunity areas": streamline, synergise, and empower.

Streamline refers to improvements made within the existing energy system by restructuring, reorganising, and modernising current energy systems through institutional levers (i.e., policies, regulations, and markets) or investment in infrastructure. Increasing the flexibility of energy end use has potential system-wide benefits and could create new markets for products and services. However, capturing these benefits will require proper regulatory and market structures, new operational and planning paradigms, physical energy network characteristics, an integrated communications system, and suitably flexible end-use products. Many of these are currently lacking in the

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existing energy system and require a system-wide understanding to deliver pragmatic and sustainable solutions. Developing more integrated energy system-wide policies will enable better management of uncertainties.

More integrated energy networks and proper functioning real-time locational markets will reward capacity and flexibility. In addition, the removal of institutional barriers between distribution and transmission systems will allow better integration of distributed resources and facilitate regional integration. By providing standardised requirements, updated interconnection and interoperability standards and grid codes will streamline the energy sector.

Investment in the appropriate infrastructure within the integrated energy system will improve flexibility. Expansion of the electrical transmission grid will enable flexibility by aggregation across scales. Pipeline infrastructure is required to increase the penetration of bio and/or synthetic fuels. Investment in data infrastructure will enable consumers to more fully participate in the energy system and will improve energy network operations through forecasting and analytics.

Synergise describes ESI solutions that connect energy systems between energy domains and across spatial scales to take advantage of benefits in efficiency and performance. To date, the coupling of heat and electricity sectors has focused on the supply side (e.g., CHP) for fuel-saving purposes. However, at the system level, its inherent inflexibility can lead to sub-optimal overall system performance. A good example of this is wind curtailment in China, which is in part due to the inability of physically inflexible CHP plants to reduce electricity production while providing heat. ESI solutions that integrate heat storage into the CHP plant are being developed and indicate a shift from the supply side to the demand side (e.g., electrical heating of water, thermal storage in buffers and heat pumps). It is possible to capitalise on "virtual storage" where the flexibility in one part of the system (e.g., heat, transport, water, etc.) can be integrated with, for example, the electricity system, and used in a similar manner to electricity storage. This virtual storage can be significantly cheaper than dedicated storage, as it does not require large capital investment – but it does require a more integrated energy system. Demand management (e.g., controlling heating and cooling loads) technologies currently being deployed and developed are in part leveraging this virtual storage. However, ESI proposes that it is at a grand scale where fuel, thermal, water, and transport systems will be systematically planned, designed, and operated as flexible "virtual storage" resources for the electricity grid (and vice versa). There is also the potential to use the natural gas fuel grid to create energy storage through the "power-to-gas" concept.

Empower refers to ESI actions that include the consumer, whether through their investment decisions, their active participation, or their decisions to shift energy modes. Investments in energy efficiency are increasingly recognised as a cost-effective way to reduce energy demand and can lead to system-wide benefits that include upstream capital and operational savings. From an overall energy system point of view, energy efficiency at the level of an individual building may be in conflict with the flexibility that the demand side can provide to the grid. Energy efficiency improvements or targets also contribute to broader social and policy goals, notably macro-economic efficiency, industrial productivity, public budget balance, security of supply, and health benefits. This building-level investment needs to be made by the consumer. The formerly totally separated sectors of transport and electricity may become more integrated through plug-in electric (hybrid) vehicles and car batteries, but the consumer needs to accept this mode of transport. The potential in some regions for thermal grids has been raised, but questions remain as to how large they should be, how best to integrate them into the electricity grid, and, importantly, how consumer requirements will be ensured and whether consumers will accept them.

What is the role and main requirements of modelling in ESI?

Modelling plays a critical role in ESI research. Modelling is a means, not a goal in itself.

ESI is most valuable at the physical, institutional, and spatial interfaces, where there are interactions and new challenges and opportunities for research, demonstration, and deployment to reap its commercial and societal benefits. Therefore these interactions must be understood, quantified, analysed and then solutions designed and deployed. As the systems are complex, typically distributed with physical, economic and regulatory aspects, it is only possible to investigate them effectively and at reasonable cost by using good models. These models need to focus on the interfaces and will need to represent all major energy producing and consuming sectors with sufficient temporal and geographical granularity to be able to truly represent the ESI challenges and opportunities. Of particular importance is uncertainty in operations and in investment time scale, which needs to be captured. The need for high quality data cannot be over emphasised. Models are only as good as the data that is used to tune model parameters, validate models, develop scenarios and input data sets etc.

These models allow us to address unanticipated feedbacks in the system, identify efficient strategies, evaluate possible market design and policies, etc. Modelling is needed to understand how to achieve cost effective integration of energy sectors, what are the most promising new pathways and technologies and how the system performance may change under different scenarios and policies. Modelling therefore needs to simulate the physical system as well as the energy market, regulatory framework, underlying uncertainty in weather and longer-term resources and all the way to consumer behaviour, and how the actors' decisions (operational and investment decisions) affect the performance of the physical system, and how regulation affects the actors' decisions.

An extremely wide set of diverse models do exist. However, focus typically is on sectors and energy carriers, individually. Overall energy sector (or economy wide) models exist, but often lack technical detail, crucial to account for the variability of renewable energy sources such as wind and solar photovoltaic. The scope of ESI models needs to be larger than that of traditional models. The ideal model would include all the above-mentioned dimensions, the physics as well as the market, but this is neither feasible nor practical. **As a result, the challenge is to develop a suite of models than can be used together. Preferably this should be made in a way that enables much better co-operation between model developers and users across the globe. Well-defined interfaces between models, open source code and high quality open source data would help to avoid duplicate effort.** Different types of models are needed for different questions: simulation and optimisation, short term and long term, physical and market models.

Mark O'Malley

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