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Use and Abuse of Energy and Climate Scenarios—A Week of Controversy on Scenarios

Christian Breyer[a] *and Michael Jefferson*[b]

Motivations underlying the research

Energy and climate scenarios, and all other scenarios, are controversial, because they touch strategic issues, and also affect very basic operational discussion, such as the choice of the fuel mix, or the degree of trading between companies and nations. This article documents a controversial exchange of ideas via email between the two opponents, about energy and climate scenarios, following the Plenary Session on "Long-term Energy Scenarios at the 41st International IAEE conference in Groningen (June 12, 2018), concretely between June 16 and 22, 2018 (with the panel organizers and IAEE staff always kept in cc). One of the opponents, Michael Jefferson, contributed to the first scenario exercise by Shell, the World Energy Council, and others; the other opponent, Christian Breyer, is Professor of Solar Economy at LUT University, and focusses on scenarios with 100% renewable energies. In addition to the lively and open debate, the controversy also contains a wealth of important references to scenario analysis.

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Energy Outlooks Compared: Global and Regional Insights

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Scenarios are a widely used tool to assess the conditions and effects of alternative future developments in the energy sector. Scenarios can be defined as consistent and coherent descriptions of alternative futures that help explore the range of plausible futures rather than aiming at finding the most probable among them.

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For this study, we consider prominent energy scenarios with different characteristics and methods. First, we consider the World Energy Outlook (WEO), which is published by the International Energy Agency (IEA)—an intergovernmental, public body established in the framework of the OECD—and arguably the most prominent energy outlook. We also consider the energy outlooks published by the World Energy Council (WEC), a global energy body with UN accreditation; the international oil companies Royal Dutch Shell, BP, Equinor, and ExxonMobil; as well as the research institution MIT; and the scientist-led civil society organisation Energy Watch Group (in cooperation with LUT University). Moreover, we add our own recent energy outlook to the comparison: four scenarios that are the result of research at the Resource and Environmental Market division at the German Institute for Economic Research DIW Berlin (DIW-REM).

Most organisations develop several scenarios in the same outlook with the desire to englobe a large range of potential futures. As the uncertainty and, hence, the spread between scenarios, increases over time, the entire range of potential futures is often referred to as the "scenario cone". The outermost limits of this cone are scenarios that are objectively impossible, followed by futures that are possible but not necessarily plausible. Plausible scenarios, in turn, occupy the cone's core. Scenarios that extrapolate current trends most closely are usually called 'probable' scenarios, whereas (un-)preferable scenarios can be found at the core's boundaries. We typically refer to them as "best" ("worst") cases.

We also distinguish whether scenarios are exploratory (i.e. what will happen in a specific setting?) or normative (i.e. what should happen?). Both are entirely different ways to approach scenarios: Exploratory scenarios start in the present and analyse how the future evolves given certain conditions and assumptions. Normative scenarios (" target scenarios") are futures that are constructed deliberately to reach a certain final state, for example an emissions target. In the energy world, for instance, an exploratory scenario could analyse which energy mix will unfold towards 2050 if a certain policy is adopted, while a normative scenario could assume ("target") a carbon-free energy sector by 2050 and analyse a pathway from today to that 2050 world.

Many of the outlooks discussed in this article contain "best cases" and "worst cases", for which the line between explorative and normative is blurry. Their deliberate aim is to illustrate (un-)preferable futures. Yet, they are explorative in nature as long as they were generated based on (present) drivers (as opposed to pre-defining a final target).

All scrutinized outlooks deal with the entire energy system on the supply and the demand side, including the ones by the major oil companies. They are, hence, more comprehensive than sectoral scenario analyses. We include outlooks that are recognised strongly by both an academic and a non-academic audience. Moreover, we have chosen outlooks from different kinds of actors that create scenarios (a government agency, private energy companies, research institutions, and civil society). Limiting the scope of the survey to nine outlooks allows us to present detailed remarks with regards to the individual outlooks. At the same time, we want to present the existing variety of potential trajectories and do not limit our analysis to 2°C scenarios.

We collect meta information on the scenarios and energy system indicators (primary energy demand and fuel shares on the global and the regional level) which provide compact overviews. We make several observations that may inspire future research.

First, the various outlooks exhibit different degrees of an elaborate qualitative side with the inclusion of storylines and the analysis of drivers. There is no clear pattern as to whether outlooks with a strong qualitative foundation would entail fundamentally different trajectories than outlooks without. We have found, however, that some of the outlooks with a stronger qualitative side show more mid-term fluctuations, i.e. their numerical trajectories tend to be non-monotonous, potentially as a result of the qualitative input. Moreover, missing a qualitative elaboration makes it harder to assess a scenario's social, technological and political feasibility.

Second, to varying degrees, world-wide outlooks seem to neglect the regional dimension. This manifests in varying degrees of regional coverage where some outlooks provide virtually no regional numbers or developments, but also in the quality of the numerical indicators. Many regional trajectories towards

2050 are can be categorized better by outlooks (i.e. by the publishing organisation) than by content (e.g. best cases vs. worst cases).

Third, regarding the success of climate change mitigation, a variety of options seems to be plausible. Some scenarios rely on a very strong role of renewables, others on a substantial role of negative emission technologies with fossil fuel use, yet others on assuming decreasing energy demand. This means that neither the share of renewables nor future energy demand are good indicators to assess whether a scenario is effective in climate change mitigation. While some scenarios with high shares of renewables fail to curb emissions, other scenarios with lower renewable shares eventually succeed in it. Similarly, while some climate-friendly scenarios consider a stagnation of primary energy demand, others exhibit growth rates of primary energy demand even above those of other futures without successful climate change mitigation. Moreover, our survey backs the observations that current paths are incompatible with the Paris Agreement's 2°C target.

Fourth, our observations have raised concerns about a lack of transparency in data and methods but also about differences in accounting across the outlook spectrum.

We conclude that—while there is no consensus between outlooks on how to attain low-emission futures towards 2050—the actual inclusion of a qualitative analysis of drivers and storylines helps ensure the political, social and technological feasibility of scenarios.

Projecting Energy and Climate for the 21st Century

Sergey Paltsev [a]

1. Motivations underlying the research

The growing evidence of severe climate change impacts on human life and the global economy has created the increasing need for an assessment of low-carbon pathways. Energy and climate scenarios have an important role to play in assessing the energy system transition required to mitigate climate challenges. Energy and industrial companies, governments, civil society and other stakeholders need to align their strategies with the science-based targets while continuing economic growth and development including providing reliable and affordable energy. Numerous expert groups and individual researchers produce energy scenarios and analyze their implications for climate.

While the ultimate goal of zero- or near-zero global emissions is clear, the timing and trajectory to achieve low-carbon economic system are subject to substantial uncertainty driven by policy structures, technological progress, and societal pressures. As a result, most of the scenarios that do not force a particular outcome (like net-zero emissions or certain percentage of renewable energy) diverge substantially from the scenarios that define a set of particular desired outcomes and explore the ways to achieve those outcomes.

For the Paris Agreement process, countries have submitted their plans to reduce greenhouse gas (GHG) emissions. Numerous studies have shown that the current pledges, formulated as Nationally Determined Contributions (NDC), are inadequate to bridge the gap between the resulting emissions in the next decade and the least-cost pathways to stay below 1.5°C or 2°C. The current emission pathways imply the global warming by around 3°C by 2100 with a continuing increase in temperature afterwards. Despite the efforts to accelerate the energy transition, the progress has been rather slow. The motivation for this paper is to explore the major dimensions of the major long-term energy and climate forecasts and to compare their similarities and reasons for their diversity. We search for some robust findings for the energy system mix developmet and the required efforts for de-carbonization. Cinsidering both medium-term and longer-term trajectories, we look at the dynamics of technology mix evolution required to achieve deep de-carbonization goals to assess if dominant technologies are performing differently in different emission mitigation regimes.

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2. A short account of the research performed

Focusing on the most-established periodically-updated outlooks, we compare their forecasts with the integrated approach from the MIT Joint Program Outlook that can be used for a quantitative analysis of decision-making risks associated with different energy pathways. We start with a short description of historic trajectories for global primary energy use and related CO_2 emissions. Then we contrast the historic trends with projections of global energy in the next couple decades, up to 2040.

We distinguish between the descriptive or "the best guess" scenarios and prescriptive scenarios. Descriptive scenarios are constructed to provide the "most likely" outcomes under the current policies. Prescriptive scenarios are constructed to explore the required energy trajectories to reach a particular target (e.g., achieving certain percentage of renewables, the 2°C target, or net-zero emissions by a certain date).

For an analysis of the descriptive scenarios, we explore the Stated Policies Scenario from the 2019 IEA World Energy Outlook, the 2019 BP Evolving Transition Scenario, the 2019 ExxonMobil Outlook Scenario, and the Paris Scenario from the 2018 MIT Joint Program Outlook. For prescriptive scenarios, we focus on the Sustainable Development Scenario from the 2019 IEA World Energy Outlook, the 2019 BP Rapid Transition Scenario, the 2018 Shell Sky Scenario, and the 2°C Scenario from the 2018 MIT Joint Program Outlook. We compare their views on the roles of fossil fuels (natural gas, oil, coal) and renewables in their contribution to the global primary energy. To provide an example of an integrated approach that combines the long-term projections for energy, emissions, and the resulting climate variables such as temperature, precipitation, sea level rise, and ocean acidity, we discuss the MIT Joint Program Outlook that assesses several 2°C and 1.5°C scenarios.

3. Main conclusions and policy implications of the work

We find that projecting energy and climate is getting more challenging because of a clear divergence between descriptive (i.e., those that track the stated policies) and prescriptive (i.e., those that show a path to a particular target) scenarios. It is also getting more difficult to assess the credibility of numerous declarations related to the de-carbonization goals, such as aspirations to achieve full energy access in a few years, to reform energy prices, and/or to reach the net zero emissions in some countries and/or sectors.

Exploring the major energy outlooks for the shares of energy types in the global primary energy use, we find that under the current policy (descriptive scenarios), the fossil fuel share is projected to be reduced from the current (2018) contribution of about 80% to around 73–76% in 2040. In the scenarios consistent with the 2°C goal (prescriptive scenarios), the fossil fuel share is further reduced to about 56–61%. On the other hand, the share of wind and solar (which is the majority in the "other renewables" category) is increasing to 6–13% in the descriptive scenarios and to 17–26% in the prescriptive scenarios. While the shares of renewables differ between the outlooks, none of the scenarios envisions the complete de-carbonization of energy in the next 20 years.

Looking at the projections up to 2100, we show that the seemingly winning in the medium-term technologies may not be the dominant long-term solution for de-carbonization. We conclude that the pathway for a particular technology depends on many economic and political variables, and rather than been informed by a single or several scenarios, a range of projections that encompass plausible futures provides a good guidance for a strong decision-making.

Arctic oil and public finance: Norway's Lofoten region and beyond

Klaus Mohn[a]

The Arctic hides a substantial potential in terms of petroleum resources. According to the USGS (2008), more than 400 billion oe of oil and natural gas are yet to be discovered in this part of the world. Managed properly, these resources can be converted to reserves, revenues, and financial wealth for the

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host countries, and large gains could arise for the general public of resource-rich countries, via government spending and/or tax relief.

Norway's Lofoten region is an appropriate example. With a large resource potential, the waters off the coast of the Lofoten region are viewed as highly attractive by the oil companies. This study combines resource estimates from the Norwegian Petroleum Directorate (NPD; 2010) with economic theory and industry data to calibrate a Reference scenario for the valuation of direct economic effects from Lofoten oil and gas activities, followed by a range of sensitivity analyses and alternative scenarios.

A contribution of this study is the integration of resource valuation in a framework of resource revenue management and public finance, enabling an assessment of the financial contribution to public finance and fiscal capacity from a defined expansion of oil and gas exploration acreage. I specifically explore the potential contributions from Lofoten oil and gas extraction to public finance in Norway, under their their oil fund mechanism and the fiscal policy rule. Parallel implications for other resource-rich countries with territorial interests in the Arctic circle are then explored and discussed in light of resource assessments by USGS (2008).

My Reference scenario suggests that oil and gas extraction in the Lofoten region would allow the government to increase annual fiscal spending by NOK 3.6 bn (USD 450 M), or offer a corresponding amount in tax relief. In other words, the Reference scenario of this study suggests that the willingness to pay for protection of the Lofoten region at least will have to exceed NOK 521 (USD 65) per capita per year. A full investigation of indirect and external costs and benefits go beyond the scope of this study, which is limited to direct economic effects, and in particular the implications for public finance. Even so, my approach may still prove useful for the evaluation of indirect and external effects both in Norway and elsewhere in the world. Specifically, if the sum of indirect and external costs falls short of the net present value of direct effects, the policy signal is that opening should be considered for new oil and provinces in the Arctic. And conversely, if the net present value of indirect and external costs exceed the net direct benefits, one should think twice before the oil industry is let into new areas in the Arctic.

On the Techno-economic Benefits of a Global Energy Interconnection

Christian Breyer,[a] Dmitrii Bogdanov,[a] Arman Aghahosseini,[a] Ashish Gulagi,[a] and Mahdi Fasihi[a]

1. Motivations underlying the research

The global energy supply in the coming decades is framed by several challenges. Climate change mitigation requires defossilisation of energy supply by mid-21[st] century to a net-zero greenhouse gas (GHG) emission society. Renewable electricity has been utilised and expanded for more than 100 years for the case of hydropower to achieve an installed capacity base of more than 1100 GW for an excellent energy return on energy invested characteristics, based on highest technical lifetimes of all power generating technologies. Since the 2000s, two variable renewable electricity (VRE) technologies, solar photovoltaics (PV) and wind energy, have received very high growth rates of about 46% and 22% per year, respectively, leading to a total installed capacity of about 500 GW and 593 GW, respectively, by the end of 2018. The advantage of these two major VRE technologies is their enormous scalability and huge resource potential, exceeding total global energy demand by orders of magnitude, particularly for the case of solar energy. The achieved cost level of about 20–25 €/MWh and 25–30 €/MWh for solar PV and wind energy, respectively, at very good sites, brings both technologies to the forefront as a major source of energy in the 21[st] century. A future energy system will be mainly built on solar and wind energy and thus will have high shares of renewables in the energy system.

The outline of the future energy system is based on solid fundamental insights and respecting sustainability guardrails. However, it is not yet discussed in broad what may be the optimised power system structure. Two poles are scientifically discussed and can be summarised as the Super Grid approach and

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a decentralised Smart Grid approach. The paper features the Super Grid approach from major regions and continents to a global perspective, so that the potential of a global energy interconnection can be discussed.

2. A short account of the research performed

A global energy interconnection has been suggested first by Buckminster Fuller 1971. In 1992, the Global Energy Network Institute shifted the view for utilising renewable energy sources. Kurokawa linked the concept of a global grid to the abundant global solar energy resource available in the 2000s. Liu further lifted the discussion on global energy interconnection in recent years.

Most of the studies outline the energetic benefits of the Super Grid approach, but often lack in comparative economic analyses showing that a Super Grid approach would lead to lower energy system cost than a decentralised energy system. The team of Breyer showed in recent years that major regions in the world would benefit from a Super Grid approach.

The Super Grid results clearly reveal the enormous benefits of the Super Grid approach. The most remarkable research result is the cross-border electricity trade from the highly decentralised approach to the Super Grid approach of 17%. Consequently, it can be concluded that the cost optimised power system shows mainly decentralised characteristics which are further supported by centralised elements of a Super Grid to achieve a least cost solution, which leads to the concept of a Super Smart Energy System.

The main research question of this paper is 'What are the techno-economic benefits of integration of the major regions to super region clusters or an integrated global energy interconnection'. The hypothesis is that a further integration benefit is observed from a two-level integration of sub-national regions to countries and major regions. Results indicate that the economic optimum for geo-spatial power sector integration can be achieved on the level of major regions. A global energy interconnection may be still beneficial, but the respective electricity trade can be expected to be more within the major regions.

This may lead to the conclusion that the largest power system integration benefit may be already realised in interconnecting the sub-national regions to 23 global regions, whereas a further level of interconnection does not lead anymore to substantial cost reduction. A global energy interconnection does not lead to a global uniform cost level, since the power line interconnection adds to the cost, which requires respectively lower electricity generation for an overall cost reduction. In addition, first research insights are available for global energy interconnection of electricity-based products, which do not need power transmission interconnections for global trade.

Another effect requires more attention in global energy interconnection research: competition of long-distance power transmission with very low-cost electricity generation and low-cost storage technologies. Cost decline of solar PV is linked to stable and high learning rates for PV modules and systems. Respective learning rates for battery storage and electrolysers are also above average. The relative cost decline of power transmission technologies are much lower and not comparable to the above mentioned technologies. These trends lead to a relative decline in competitiveness of long-distance power transmission and more locally and regionally structured energy systems.

3. Main conclusions and policy implications of the work

Existing research clearly finds economic benefits of a power system integration of decentralised regional systems for a major region and on a continental level, whereas for clusters of major regions a global electricity interconnection cannot generate comparable additional benefits. This study represents the very first results of a global energy interconnection, including 9 major regions and 23 regions, calculated in full hourly resolution and for achieving highest levels of sustainability.

Comprehensive global energy interconnection research should enlarge the scope of energy from electricity to all relevant energy carriers of a sustainable future energy system, namely synthetic hydrocarbons (SNG, Fischer-Tropsch liquid fuels), methanol, ammonia and liquefied hydrogen. A high global granularity of geo-spatial structuring may reveal the relative range of economic benefits generated by power transmission, which may be complemented by progress in understanding future trade patterns for renewable electricity-based PtX fuels and chemicals and their respective transportation costs.

Lessons from Modeling 100% Renewable Scenarios Using GENeSYS-MOD

Pao-Yu Oei,[a] Thorsten Burandt,[b] Karlo Hainsch,[c] Konstantin Löffler,[d] and Claudia Kemfert[e]

1. Motivations underlying the research and a short account of the research performed

The main aim of models has never been to provide numbers, but insights (Huntington, Weyant, and Sweeney 1982)—still challenges prevail for modelers to use the best configuration of their models to actually provide helpful insights. This becomes even more complicated due to increasing complexity of the energy system transition through the potential and need for sector coupling as well as rising international connections. When the first scenarios with 100% renewable energy supply were published, back in the 2000 years, they were generally considered as "out-of-the-box" thinking, if not completely utopic. By the end of 2019, however, there are now numerous studies, which elaborate 100% renewable energy scenarios using different models.

This paper showcases specific characteristics and challenges for energy system modelling of 100% renewable scenarios. The findings are based on various applications and modifications of the framework Global Energy System Model (GENeSYS-MOD) examining different regional characteristics for high renewable configurations in the world, China, India, South-Africa, Mexico, Europe, Germany, and Colombia. GENeSYS-MOD is based on the well-established Open Source Energy Modelling System (OSeMOSYS), an open-source software for long-term energy system analyses. The paper elaborates on our experiences of the last years of choosing the best, yet still computable, configuration of GENeSYS-MOD (section 2) with respect to spatial (section 3) and temporal resolution (section 4) as well as sufficient detailed description of the energy system transition effects (section 5) and result interpretation (section 6). The aim of this paper is therefore twofold, to better understand and interpret existing models as well as to improve future modeling exercises.

2. Main conclusions and policy implications of the work

This paper underlines the importance of a fast renewable application to slow down global warming and to prevent a climate catastrophe. This transition, at the same time, goes along with the possibility of creating millions of new jobs and providing electricity access to many regions in the world. Relying on the existing mathematical models to calculate such optimal configurations of more sustainable pathways and technology choices, however, goes along with several model(er)'s biases, elaborated in more detail in the paper. Being aware of these model(er)'s biases can help to improve future modeling work allowing for a better interpretation of the still helpful insights that energy system models can provide. Even though many uncertainties of the future energy system prevail and regional challenges differ a lot; still some general no regret options can be identified from our experiences: i) Reduce energy demand through the enhancement of behavioral changes as well as technological improvements such as efficiency gains; ii) Investment in renewables enables the energy system transition and provides numerous job opportunities for people around the globe; iii) Avoid additional investments in fossil fuel infrastructure (i.a. mines, oil riggs, harbor terminals, gas pipelines) which might otherwise create lock-in effects as well as potential sunk investments—by 2020, no new infrastructure should be constructed which is not compatible with a zero carbon society; and iv) Weaken the fossil fuel regime and support alternative actors to ease a faster transition to more sustainable energy forms.

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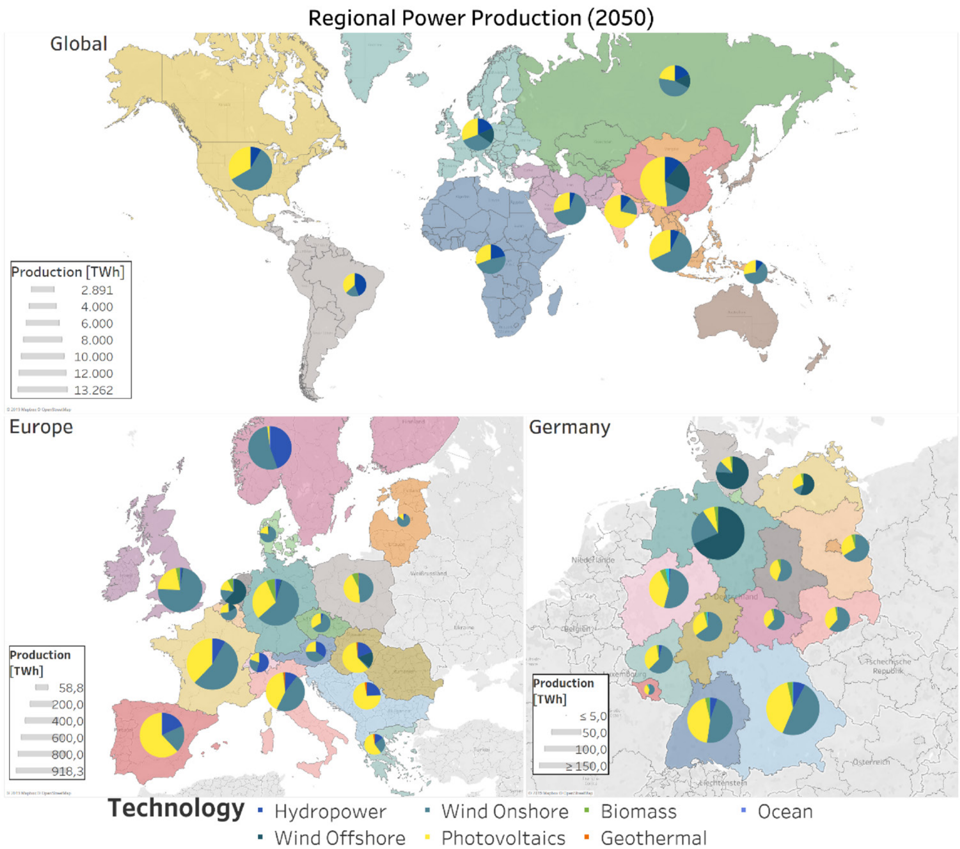

FIGURE 1

Scaling down 100% Renewable scenarios—for the World, Europe and Germany.

Source: Own illustration based on several own previous works.

Energy Transition Pathways to a Low-carbon Europe in 2050: The Degree of Cooperation and the Level of Decentralization

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1. Motivations underlying the research

The European Union is in an ongoing debate on how to reach the 2050 carbon emission targets to fulfil the commitment of the Paris Agreement. In this regard, the SET-Nav research project (2016–2019) brought together a large European consortium of energy and climate modelers to analyze

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strategies to decarbonize all energy sectors as well as the end use. It started from the technological focus of the European Union SET-Plan and developed several comprehensive, cross-sectoral scenarios—the SET-Nav pathways. The pathways show that—while several options are still at hand—the next years' decisions on the European energy system are critical in order to achieve a low-carbon energy future.

The objective of the SET-Nav project is to support strategic decision making in Europe's energy sector, enhancing innovation towards a clean, secure and efficient energy system. The motivation of the SET-Nav pathways is to reflect a new level of understanding of interactions and interdependencies between actors, technologies and policy interventions in Europe's energy-economic system. The framing of the SET-Nav pathways storylines considers two key uncertainties: the level of cooperation (i.e. cooperation versus entrenchment) and the level of decentralization (i.e. decentralisation versus path dependency). The modelling assumptions for these pathways were an 85-95% emissions reduction by 2050; 40% as an intermediate reduction target in 2030 and meeting all reduction goals by 2020. The pathways serve two main purposes: first, to determine main drivers and critical uncertainties and second, to highlight outcomes and consequences. The former are modelling parameters, the latter are modelling results. Drivers are policies or intermediate actions, for example. Outcomes consist of costs, the electricity mix or infrastructure developments, among others. Specifically, in this paper, we presents the overall analysis of the SET-Nav pathways for the energy demand sectors (buildings, transport, and industry) and the electricity supply mix in Europe.

2. A short account of the research performed

Four pathways analyse a European energy transition to achieve an 85-95% emissions reduction by 2050. The approach is based on a unique suite of linked models developed in the SET-Nav project. The models combine several perspectives with different sectoral priorities but also by integrating the energy consuming sectors - buildings (heating and cooling), transport, and industry - with the power-producing sector thus reflecting the increasing sector coupling within the future energy system. In addition, the central point of connection among the models is that all interpreted the pathways storylines for their respective sector and hence some common data inputs were harmonized (e.g. fossil fuel prices, technology costs, CO_2 budget and price).

The analysis provides a large range of results that quantify the pathway narratives from today until 2050. They include the electricity mix, the modal split in transportation, the heat mix and energy consumption by industry among others. Hence, the research conveys a greater picture of the energy transition, which allows comparing several development paths and their limits and challenges of the politico-technology-energy system.

3. Main conclusions and policy implications of the work

Each pathway exploration of decarbonisation options (under different circumstances) provided an understanding of the effect of different policies in reducing greenhouse gases. Such as the prohibition of conventional transport (internal combustion engine), the power system expansion, re-configuration of distribution grids, and others. An interesting insight is that debated technologies such as CCS, nuclear energy and coal can be dispensed for other effective decarbonisation alternatives. Moreover, all the pathways envision a decisive reduction of emissions by 2030 and the successful expansion of renewable energy sources (in particular wind power) as a main driver. Hence, new technologies (batteries, hydrogen or bio-gas) will be crucial for the decarbonization of non-electricity sectors or providing balancing options for variable renewable energy sources in the power sector. In short, main conclusions and policy implications:

- More research and public support will make decentralised heat supply and heat pumps an important part of the demand side
- To decarbonise industry, extending the ETS with a minimum price as well as expanding public RD&I (research, development and innovation) funding are important measures.

- A CO_2 tax as the central element of a broader energy tax reform could provide the incentives needed for fuel switching.
- Policies to overcome barriers to energy efficiency are also crucial, as is pushing sales of electric vehicles and inducing a modal shift from cars to public transport, car-sharing, cycling and walking.

How Incumbent Cultural and Cognitive Path Dependencies Constrain the 'Scenario Cone': Reliance on Carbon Dioxide Removal due to Techno-bias

Isabell Braunger[a] and Christian Hauenstein[b]

1. Motivations underlying the research

The necessity to reduce greenhouse gas (GHG) emissions to zero within the next decades to mitigate anthropogenic climate change is generally acknowledged. Yet, how to achieve this reduction remains an open debate. In this context, the use of scenarios has become common practice in order to study long-term developments necessary to reach climate targets. The scenario results enable an informed debate about climate change policy (e.g., costs, impacts, prerequisites). However, there are legitimate methodological and substantive criticisms and uncertainties with regard to scenarios.

What characteristics define a useful and scientifically well-designed scenario, as well as the choice of scenarios representing the range of plausible future developments, remain debated issues as this symposium on "Scenarios" shows. These issues are highly relevant beyond the scientific context, considering the "constitutive force" of expectations created by scenario results. These expectations condition wider social conceptions over what are realistic or unrealistic future developments, and ultimately what policies might be adopted. In order to be able to use scenarios even more profitably for climate policy decisions, it is necessary to continue a critical and reflected debate on scenarios, as it was initiated here in this symposium. To this end, we would like to provide additional impulses in this concluding article.

A look at various scenarios (and related model configurations) reveals that the range of plausible future developments is narrow. Considered developments are primarily in the technological sphere and on the energy supply side. Many scenarios assume a comprehensive implementation of Carbon Capture, Transport, and Storage (CCTS), as well as Carbon Dioxide Removal (CDR) to balance high shares of fossil fuels in the future. Contrarily, considerations of societal changes leading to energy demand reductions are rather absent. Yet, the reduction of energy demand is essential to meet GHG reduction targets without corrupting other social and environmental sustainability objectives. Especially CDR technologies have sparked a heated debate regarding adverse side-effects and ethical concerns.

In previous research, we could not find a satisfactory explanation for this inconsistency between the diversified problem definition and the technology-centered solution approaches. We call this imbalance *techno-bias*, which we understand as focus on technological solutions without a solid scientific basis for it. The simpler depiction in scenarios as well as path dependencies, powerful incumbent actors, and economic interests are certainly reasons why the focus is on the supply side and technological solutions. However, in our opinion, these cannot explain the strong bias alone, since it is the core task of science to study and assess the entire range of plausible options.

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2. A short account of the research performed

With our analysis we want to contribute to understand the origin of the techno-bias. We therefore (1) illustrate the techno-bias based on the IPCC report and (2) assess how the techno-bias is caused by cultural and cognitive path dependencies. With this we would like to contribute to overcome this bias in scenario development and thereby broadening the scenario cone. We focus in our analysis on CDR because this large-scale technology solution plays a central role in mitigation scenarios and at the same time, the risks of a one-sided reliance on this approach are particularly drastic. However, technological solutions include not only CDR technologies but also solutions such as RES and technologically generated efficiency gains. In chapter 2, we analyze the currently available research on CDR technologies (those included in the IPCC report) to assess the potential mismatch between current knowledge, existing uncertainties and the optimistic future projections. In chapter 3, we perform based on the results of this assessment a theoretical analysis of the underlying scientific processes and transfer the resulting insights into the process of scenario development. We base our analysis on various approaches of feminist theory. These approaches allow a reflection and critique of scientific practice as well as a contextualization of underlying values and norms. Chapter 4 concludes our findings and formulates some impulses how this techno-bias can be broken up and what points need to be considered to improve future scenario building in the context of climate change mitigation.

3. Main conclusions and policy implications of the work

We argue that the selection of prominently represented scenarios (such as in the IPCC 1.5°C report) is narrowed down on technological supply side and CDR solutions because historically grown and practiced thought patterns trigger this focus. These thought patterns are characterized by dualisms, including human-nature and male-female dualism. The former makes it seem possible to control nature through technology and the latter makes the assumption plausible that control through technology is more powerful (since associated with male attributes) than behavioral change (since associated with female attributes). Our findings show that to achieve a more open and objective debate about possible climate change mitigation measures and pathways we need to reconsider underlying assumptions and biases influencing the scenario building process. Therefore we suggest inter alia to include more inter- and transdisciplinary approaches into the scenario building process, to fully consider the complexity of ecological systems, and assess the feasibility (e.g., political, social, economic) of mitigation measures.

Polar Vortexes in New England: Missing Money, Missing Markets, or Missing Regulation?

Jeff D. Makholm[a] and Laura T. W. Olive[b]

1. Motivations underlying the research

The United States has more than 20 years of experience in dealing with a continent-wide, highly competitive gas market and several competitive power markets in various states. Despite such a reasonably lengthy history of energy market competition, these two competitive energy markets sometimes visibly fail to intersect successfully with one another. The periodic experience in New England with its "polar vortex" weather events (when high-pressure in the Pacific displaces a pocket of very cold air that typically circulates around the North Pole, bringing Arctic temperatures to North America) is a case in point. During the last two polar vortex events (in 2014 and 2018), power prices exhibited sustained price spikes seemingly indicative of a lack of useful and efficient infrastructure.

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Is energy regulation about clearing away obstacles to efficient spot and capacity markets—finding the "right scarcity price" (a traditional neoclassical perspective)? Or is energy regulation about creating ways to harness the public's ability to fund useful supply infrastructure that markets cannot themselves provide (an institutional perspective)? Of course, the neoclassical perspective works in some cases and the institutional perspective in others. But we have found that New England's electricity market, under periodic "polar vortex" weather conditions, provides a case study for assessing these two economic points of view, head-to-head. Additional interstate gas pipeline infrastructure to support the region's new-found gas-fired generating fleet would appear to easily pay for itself in lower consumer electricity prices—even in the comparatively short term. But New England's wholesale power market evidently cannot support such capital investments. In response, the states in New England have themselves tried an institutional approach to their problem, but they have so far been unable to overcome opposition in the courts and from the power producers who look toward such cold weather-induced price surges as a source of earnings.

The clash between neoclassical and institutional perspectives on energy regulation appears throughout the world. New England, however, provides a unique case—a place with no indigenous fuels that is literally "at the end of the line" for US energy infrastructure. The region's gas consumers benefit from competitive access to the highly competitive US gas market at commodity prices less than half of those in the world's other major gas markets. Those gas consumers are effectively insulated from the effects of the polar vortex having provided through their respective state regulators the funds for the interstate supply infrastructure needed to deal with polar vortexes and more. But not the region's electricity markets; which, while based on the familiar power market model (i.e., locational marginal prices attached to a transmission system administered by a regional power pool), remains exposed.

2. A short account of the research performed

As is the case when looking closely at any region's energy supply infrastructure, history matters, and we describe how both the region's gas and electricity markets reached their current state of development. That is, how the gas market reformed to support "Coasian" rivalry in interstate pipeline capacity and how the electricity market formed through the unbundling and deregulation of the generating arms of the New England's traditional vertically-integrated utilities. Further, we describe the transition from a generating sector traditionally relying substantially on oil and coal to a market where virtually all new capacity has come in the form of gas and renewables—expunging oil and coal from the normal electricity generating merit order.

We also chart the history of local spot gas and electricity prices, how they spiked during the 2014 and 2018 polar vortexes, and how those costs to consumers compare to the cost of expanding interstate pipeline capacity that would effectively alleviate such spikes.

3. Main conclusions and policy implications of the work

We conclude that the New England case study, centered around the polar vortex events, demonstrates the weakness of what we describe as an "economic folk theorem"—that in restructured gas and electricity markets, everything other than the regulation of the local distribution network facilities can be left to the market. Even in the most vigorous gas market in the world, state regulatory action reaches far upstream from the boundaries of New England's regulated local distributors to support the kind of transaction-specific, immobile and sunk-cost infrastructure that interstate pipelines represent. Because of that state regulatory action, there is no "missing money" in gas markets.

For its part, however, New England's restructured electricity market has lost the ability to support that kind of useful and efficient pipeline infrastructure through its power markets. This is, to us, not a failure to make the right market, or to find the right scarcity price. It is a failure to recognize that certain types of energy infrastructure investments—interstate gas pipelines in particular—require the institution of public interest regulation to assess need and harness the credit of the region's millions of energy consumers.

Competitiveness of Energy-Intensive Industries in Europe: The Crisis of the Oil Refining Sector during 2008 to 2013

Robert Marschinski,[a] Jesus Barreiro-Hurle,[a] and Ruslan Lukach[a]

1. Motivations underlying the research

Oil refining is the process of converting crude oil into products like gasoline, kerosene, etc. The close to 100 refineries located in the European Union constitute an important economic factor, accounting for around 100.000 jobs directly and significantly more that are indirectly linked to the industry. Oil refining plays a strategic role for energy security, given the vital role of oil products in many economic activities (chemical industry, transport sector) and for society at large (residential heating, private transport).

Historically, the United States and Europe were the two leading refining regions in the world, representing 20% and 19%, respectively, of the total global refining capacity in year 2000. In 2014, the US still accounted for almost the same share, whereas the European Union's markedly declined to 14.6%. During this period the US' total refinery capacity grew in absolute terms, while the EU's actually contracted by 9% between 2000 and 2014.

These facts epitomize what was widely perceived as 'the crisis in European refining', which fully unfolded after 2008, and thus directly followed the so-called 'golden age' of refining from 2005 to 2008. This article's objective is to understand why Europe quite suddenly experienced such a crisis and the shut-down of 13 of its refineries.

Various hypotheses have been made on what the reasons for these EU capacity reductions were. Some authors point to structural overcapacity, arisen as the consequence of falling EU domestic demand and strong competition from new refineries in the Middle East and Asia. On the other side, industry itself has highlighted the costs of EU environmental and energy regulation.

2. A short account of the research performed

Despite its prominence in the media, the European 'refining malaise' has so far not been analyzed quantitatively, most probably due to the lack of reliable performance data, such as gross and net refining margins, operating costs, energy costs, etc. Such data is generally confidential and therefore not publically available. Some sources provide estimated refining margins, but these by themselves are still insufficient to analyze the drivers of the observed economic performance.

In the present study we can make use of otherwise unavailable proprietary data, allowing analyzing the economic performance (in terms of net cash margins) of EU refineries vis-à-vis five important competitor regions: US Gulf Coast, US East Coast, Middle East, Russia, and the aggregate of South Korea & Singapore.

The economics of refining is based on the difference between the costs of crude oil and the aggregate value of the derived petroleum products (gasoline, diesel, kerosene, etc.)—called 'crack spread' in the business jargon. Refineries incur various types of costs when converting crude oil into marketable products, ranging from the purchase of energy feedstock (often natural gas) and chemicals to personnel costs and logistical costs. With the available data we can first identify diverging trends in regional economic performance (i.e. net margin per barrel of process crude oil), and then quantify the different economic components' contribution to the evolution of the overall performance. This allows understanding whether the EU refining sector shows a worsening performance and, if so, to identify the drivers of this trend.

3. Main conclusions and policy implications of the work

Our analysis confirms that between the years 2000 and 2012 average EU net refining margins fell from above to below the average margin of the competitor regions, even though they slightly increased

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in absolute terms. As the most important result, 90% of this loss of competitiveness is found to be attributable to energy operating costs, which in the EU rose relatively stronger than in the average competitor region. In absolute terms, during 2000 to 2012 energy costs per barrel increased almost four-fold in the EU, while on average less than two-fold in the competitor regions.

Moreover, the evolution of energy efficiency in the EU and in the competitor regions indicates that energy operating costs deteriorated because of the steep rise in unit energy costs in the EU. In fact, along with the spectacular four-fold increase of the crude oil price between 2000 and 2012, all forms of energy used in EU refineries (electricity, natural gas, fuel oil, etc.) experienced a similarly strong cost increase. This is perhaps not surprising given the relative scarcity of domestic energy resources in the EU, whereas Russia and the Middle East were able to resort to their own abundant oil and gas resources as a buffer, and the US to its newly developed non-conventional resources ('shale gas revolution').

Further data analysis suggests that the remaining 10% of the competitiveness deterioration which are not explained by the relative increase of EU energy costs are likely related to the relative decline of EU refineries' capacity utilization rates, a consequence mainly of the drastic 12% drop in domestic demand for oil products during 2000 to 2012, or even 26% if one excludes the mid-distillate products like diesel and jet fuel. Environmental and energy policies have likely contributed to this demand side effect, but its competitiveness impact (max 10%) remains of minor importance compared to the energy cost surge (90% of the total competitiveness loss).

From a broader perspective, our findings provide further support to recent arguments on the limits of energy efficiency improvements: they can alleviate regional energy price disparities only up to certain point, beyond which they cannot prevent a decline of competitiveness.

Gas Markets in the European Union: Testing Resilience

Henry Bartelet[a] and Machiel Mulder[b]

1. Background

In the European Union, the energy policy is built upon five closely related pillars: supply security, a fully integrated internal energy market, energy efficiency, emission reduction and research and innovation. In accordance with its ambition that Europe needs to have a secure, affordable and climate-friendly energy system, the European Commission wants to develop the European gas infrastructure in such a way that gas can flow without any technical or regulatory barriers between the regional gas markets. This policy is part of the 'Energy Union Package', which is meant to increase the so-called 'resilience' of the European gas market. In the context of natural gas, the Commission points to security of supply which should be enhanced through diversification of import routes and increasing the role of storages.

In this paper we analyze the resilience of the European gas markets over the past years. This paper contributes to the literature by providing a better explanation of the term resilience in relation to gas markets. This term, used by the European Commission regarding its energy policy, comes from ecological economics and has not been assessed yet in the literature dealing with energy markets. Unlike most papers, assessing only price responses to shocks, this paper analyzes the market mechanism of adjustment and how the physical balance is restored. This represents a novel point of view and provides a useful analysis for assessment of the European security of supply policy.

2. Method and data

This paper analyzes the five most extreme disturbances since the liberalization of the European gas market in order to assess whether the market proved to be resilient. In order to assess to what extent

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European gas markets are resilient, we analyze how the market has responded in a number of unexpected disturbances to the gas system over the past decade. During each of these events, the supply of gas to the market was heavily interrupted (see Table 1).

TABLE 1
Major disruptions in the European gas market since 2009

Period	Disturbance	Market	Size of disturbance	Weather (actual temperature below normal temperature)	Start date	End date
January 2009	Disruption gas transits Ukraine	NCG (GER)	60% compared to normal import levels	–10 degrees Celsius	January 6	January 20
February 2012	Disruption gas transits Ukraine	NCG (GER)	30% compared to normal import levels	–11 degrees Celsius	February 2	February 7
March 2013	Nyhamna plant outage (Norway)	NBP (UK)	10% compared to normal import levels	–8 degrees Celsius	March 3	Lasted a few days [c)]
March 2013	Interconnector outage	NBP (UK)	25% of recent UK demand levels [a)]	–4 degrees Celsius	March 22 (0700 GMT)	March 22 (1500 GMT)
December 2017	Baumgarten explosion	PSV (IT)	40% compared to normal import levels [b)]	+2 degrees Celsius	December 12	December 13

Note: The weather variable is an average of the daily average temperatures during the disruption period. For German shocks in Munich, for UK in Southend-On-Sea and for Italy in Barona, Milan. Source: https://www.wunderground.com/weather
Sources: a) https://www.platts.com/latest-news/natural-gas/london/wrap-uk-gas-market-spikes-on-interconnector-outage–6282481; b) https://www.rt.com/business/413375-russia-gas-europe-lng-dependence/; c) http://www.mondovisione.com/_assets/files/Platts-International-Gas-Report-April–8-Edition.pdf

3. Results and conclusions

Analyzing the market response to the extreme disturbances in the European gas market since 2009, we cannot falsify the hypothesis that the liberalized European gas market is resilient. Even during the extreme disturbances in the recent past, the market has been able to provide an adequate response to restore the supply and demand balance. Following an extreme disturbance, the gas market provided a price signal to reflect the new supply and demand situation (shortage of gas) and following the price signal, market players responded accordingly by sourcing additional sources of gas to the market and by decreasing demand.

We conclude that European policy making for gas markets should focus on strengthening interconnections within the European market and leave the security and diversity of supply issue primarily to the market.

The Value of Saving Oil in Saudi Arabia

Jorge Blazquez,[a] Lester C. Hunt,[b] Baltasar Manzano,[c] and Axel Pierru[d]

Saudi Arabia is taking measures to reduce its high energy consumption, one of the world's largest in per capita terms. In 2016, the country substantially increased its domestic prices of gasoline and electricity, increasing them again in 2018 in an attempt to further align these prices with international market

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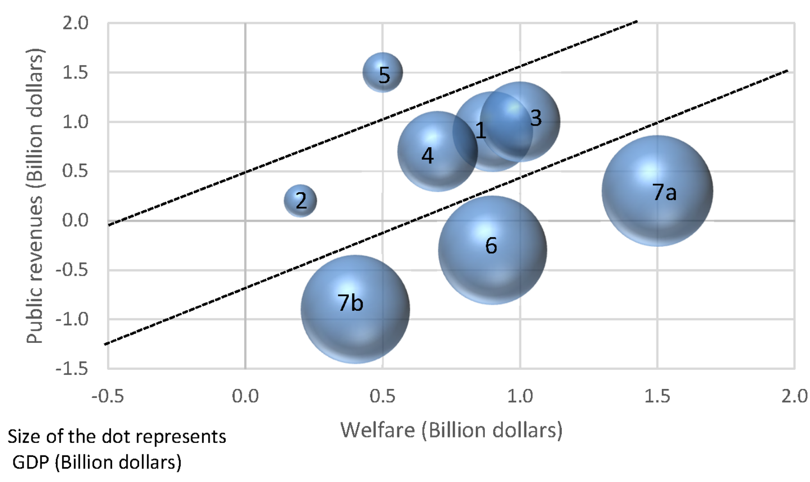
prices. In this context, a relevant policy question is, what is the value of saving a barrel of oil in Saudi Arabia? The instinctive answer is that it is the difference between the international market price and the domestic price. However, this answer is insufficient in calculating the value of oil saved from domestic consumption for the following reasons: First, domestic agents buy oil at a price set by the government that is below the international market price, which leaves room for improving economic efficiency by saving oil. Second, the rest of the world's demand for Saudi oil is not perfectly elastic, which impacts the revenues from exporting the oil saved. Third, there are various ways to reduce the domestic consumption of oil.

This study analyses different policies that aim to reduce the domestic consumption of oil in the long run and, thus, increase oil exports in a general equilibrium model calibrated for Saudi Arabia. The policies considered in this study are:

Policy 1: Increasing the production of oil.
Policy 2: Increasing the share of natural gas used for electricity generation through LNG imports.
Policy 3: Increasing the efficiency of natural gas power plants.
Policy 4: Deploying renewable technology.
Policy 5: Increasing the administered price of domestic oil.
Policy 6 Increasing the efficiency of electricity in energy services.
Policy 7a and 7b: Increasing the efficiency of oil and oil products in energy services.

A relevant consideration is whether any oil saved would be exported immediately or left in the ground for future extraction and production. Our analysis focuses on the long-term impacts and for this reason, we assume that any barrels of oil saved are exported. However, we recognize that adjusting the level of production to current and future market conditions is critical for maximizing the value of Saudi oil. The figure below summarizes the results of our analysis of these different policies in terms of the impact on welfare, public revenues, and GDP.



The analysis therefore suggests that:

- Policies designed to curb oil consumption have positive impacts in terms of households' welfare and on Saudi carbon emissions. The cost of the policies and their impact on productivity are also critical.
- The fall in the international price due to the increase in oil exports reduces the potential welfare gain from these policies.
- Policies aimed at increasing energy efficiency have limited scalability, and, consequently, the potential positive impacts at macroeconomic scales are relatively small.

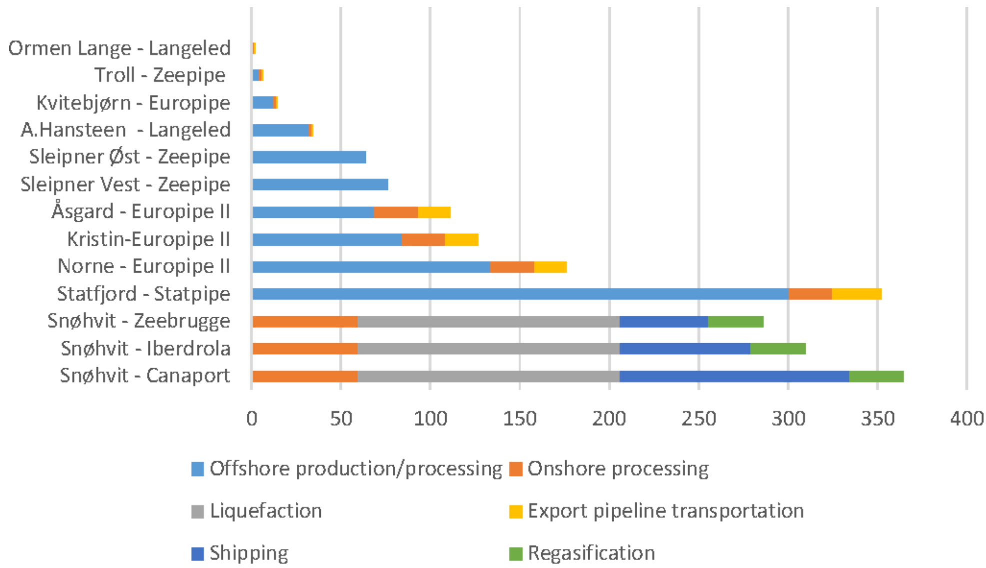


FIGURE 1
CO_2 emission intensity (kg/Sm3o.e.)

- Shifting power generation from oil to natural gas has a positive impact on the Saudi economy even if the natural gas is imported.
- The gross welfare gains of energy efficiency projects, either in the use of electricity or in transportation, are higher than those aimed at replacing the use of oil for power generation with natural gas or renewables. However, energy efficiency projects tend to be more expensive than initiatives to reduce oil in power generation.
- Welfare gains for all the policies studied range between a minimum of \$6 and \$56 per barrel of oil saved. These policies reduce the level of domestic CO_2 emissions by around 370 kg per barrel saved, excluding the policy that increases the share of natural gas in the generation mix.

Although our analysis considers the individual implementation of each policy, the government could carry out a number of programs simultaneously. The implementation of any of the policies changes the domestic consumption of oil across different activities and sectors, altering the potential benefits of the other policies. Consequently, further work is needed on the optimal combination of policies.

The Environmental Footprint of Gas Transportation: LNG vs. Pipeline

Katerina Shaton,[a] Arild Hervik,[b] and Harald M. Hjelle[c]

1. Motivations underlying the research

End-use combustion generates the majority (80–90%) of the CO_2 emissions from the natural gas value chain and has received due attention in academic research and political discussion. In this paper,

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we focus on the environmental footprint of the rest of the value chain: extraction, processing and transportation.

The main objective of this paper is to estimate and compare the environmental footprints of pipeline and LNG gas upstream value chains. The analysis is based on the real data from the fields, processing and transportation facilities on the Norwegian Continental Shelf (NCS). We estimate the unit emissions of CO_2 (carbon dioxide), NO_x (nitrogen oxides), nmVOCs (non-methane volatile organic compounds) and CH_4 (methane) associated with the extraction, processing and transportation of natural gas.

2. A short account of the research performed

In order to perform a reasonable comparison, we consider ten pipeline chains, which represent the variety of the value chain configurations on the NCS. We consider fields of different size and age connected to each of the three major gas processing plants; two fields with offshore processing; and also fields connected to the main electricity grid onshore and the fields using feed gas to generate electricity. There is only one large-scale LNG chain on the NCS. As the estimates are sensitive to the distance over which the LNG is shipped, we consider three alternative destinations.

The total emission intensities of pipeline and LNG chains are estimated by adding up emission intensities on all segments of the defined parts of the chains. The emissions relating to extraction include those by mobile units used to drill production wells. Exploration (seismic surveys by special ships, exploration drilling by drilling rigs) and support activities provided by supply vessels and helicopters and emissions relating to the storage and loading of oil and NGL/condensate are excluded from the analysis.

Figure 1 shows the CO_2 emission intensities of the considered chains. The footprint of the pipeline chains varies from 2.4 kg/Sm3o.e. for the Ormen Lange chain to 352.4 kg/Sm^3o.e. for the Statfjord chain. The largest contributor to the CO_2 footprint of the pipeline chains is the offshore segment, which is due to gas-based energy production. Turbines account for about 90% of the total emissions of the fields not connected to the main electricity grid onshore. The footprint of the LNG chain varies from 286.2 kg/Sm^3o.e. for the shortest route to 364.7 kg/Sm^3o.e. for the longest route. The main emissions contributors are power generation for liquefaction and fuel combustion for sea shipping.

3. Main conclusions and policy implications of the work

The results of this comparative study corroborate the general findings of other studies that pipeline transportation chains environmentally outperform LNG-based chains, as LNG chains comprise extra processing steps. The most important observation is the variability of the environmental performance of different technological solutions and the corresponding emission intensities. This limits the usability of average estimates and restricts the scope for drawing general conclusions regarding pipeline transportation emission intensities. In cases where the fields are geographically close to the shore and electricity is available from the main grid, pipeline transportation is indeed 'green'. In other cases, long distances and the need to generate power offshore make pipeline transportation significantly more CO_2 emission-intensive. Due to technological specificity, LNG chains are significantly more CH_4- and nmVOC-intensive than pipeline chains. With regard to NOx emissions, there is no clear advantage of the considered pipelines over LNG chains.

A direct comparison of pipeline and LNG transportation may not by reasonable in cases where LNG is transported over long distances where pipeline transportation is impossible. However, the choice between a possibility of receiving pipeline gas and importing LNG over long-distances should be also evaluated from the perspective of its environmental impact.

The evaluation and analysis of emissions to air from gas production and transportation chains should also contribute to decision-making regarding new major infrastructure development, especially in remote areas like the Barents Sea. In light of the increasing environmental concerns and stricter environmental policies of many gas-consuming countries, infrastructure development decisions of gas producers may affects their competitive positions in the markets.

Levelized Cost of Consumed Electricity

Tunç Durmaz[a] *and Aude Pommeret*[b]

1. Motivations underlying the research

Profitability of renewables energies is in general appraised through the concept of levelized cost of electricity (LCOE). It is usually computed as a discounted average cost that ignores the intermittency of the generated electricity. Nevertheless, ignoring intermittency and reasoning on average values gives a disproportionate advantage to renewable sources and can lead to taking wrong decisions. The same problem applies to the grid parity which is another tool used to assess renewables' profitability. Indeed, using such methodologies, the Energy Information Administration reports that solar photovoltaic (PV) has already obtained grid parity in several places. However, the LCOEs obtained cannot be compared directly with those of carbonized electricity sources as solar PV electricity generation is intermittent and cannot be used in isolation.

This study attempts to fill this gap by proposing a new method to compute the average cost of renewables that accounts for intermittency and flexibility options provided by smart meters and batteries. As our focus is on residential electricity consumers, we introduce a new metric: levelized cost of consumed electricity (LCOCE). Under various scenarios, we calculate the LCOCE using an economic model that allows a household (a residential electricity consumer) to optimize its electricity consumption as well as grid feed-ins and electricity stored given varying electricity tariffs, weather conditions (solar irradiance), and devices used.

Our approach is novel because it accounts for (i) location-specific (United Kingdom (UK) and Hong Kong (HK)) and dwelling-specific (flat and house) behaviour of the household that optimizes its electricity consumption; (ii) uncertainty in solar irradiation both within the day and seasons; (iii) variations in tariff rates; and (iv) cost of acquisition and installation of flexible smart devices in the smart grid, including smart meters, batteries, and so on.

2. A short account of the research performed

Computation of LCOCE necessitates three different types of data: (i) discount rate, relative risk aversion coefficient, and system lifetime; (ii) investment, maintenance and operation costs; and (iii) data on electricity generation and consumption. To obtain 'optimal' electricity generation and consumption decisions, we construct an optimization model and calibrate it on two sets of data: observed data on a UK house and simulated data on an apartment in a high-rise building in HK. We consider two different types of dwelling as a single house is more representative of Welsh homes while a flat in a high-rise building is the typical type of dwelling in HK. We also consider different solar PV installations depending on the location as we seek to appraise the cost of the most standard one for each type of dwelling. Following this, we derive the optimal electricity consumption, solar generation, storage and purchases (sales) from (to) the grid for the UK and HK cases.

The two cases that we apply the LCOCE approach to clearly demonstrate the two opposed consequences of intermittency for the cost of the electricity consumption that are accounted for in the LCOCE, but not in the LCOE. For HK, the additional cost of the backup (storage, smart meter, and electricity purchase) that needs to be used when no electricity is generated explains why the LCOCE is higher than the LCOE (as the LCOE of solar electricity does not account for such backups) for systems *that include solar panels*. On the contrary, in the UK, the opportunity to sell the excess power to the grid, that is accounted for in the LCOCE (and not in the LCOE), generates a sufficiently large gain to prevail

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on the previous effect, except when there is storage. The different conclusions for each country are driven by the low electricity tariff in HK which limits the gains from selling excess electricity to the grid.

3. Main conclusions and policy implications of the work

This paper makes a clear point about the proper calculation of the cost of solar PV panels that can be complemented with devices, such as a smart meter and a battery, at the household level. Our method makes several improvements in that it accounts for the intermittency at daily and seasonal levels, electricity tariff variations, optimal household electricity consumption behaviour as well as the cost of complementary technologies such as smart meters and batteries.

We observe that accounting for intermittency reduces the cost of solar consumption for the dwelling in the UK while it increases it for the high-rise building apartment in HK. These outcomes stress the importance of computing costs depending on the location, which implies not only specific weather conditions, but also specific types of dwelling, consumption habits, as well as electricity tariffs.

With the rising generation of solar power at the household level and the rising use of batteries and smart meters, a more accurate measure of a weighted average cost of electricity consumption is crucial for analysing the economic value of investing in smart grids, and, accordingly, for expanding smart communities. A more accurate calculation of the weighted average cost of electricity consumption is also informative for policymakers when deciding on policies to promote further investment in home renewable energy systems. In particular, computing the LCOCEs for specific types of systems can allow them to determine a more accurate amount of financial support for the households.