

Coping with Uncertainties in the Electricity Sector—Methods for Decisions of Different Scope

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1. Motivations underlying the research

Decision-making in the energy sector and notably the power industry has to cope with multiple uncertain factors such as renewable forecasts, technology developments or demand growth. At the same time, there is a burgeoning stream of research over at least the last three decades trying to develop decision support models that explicitly deal with risk and uncertainty in the energy context. As many of these models are optimization models, the paper at hand focuses on this model category. Optimization models are especially used to analyze pathways for the decarbonization of the energy system at different scales – which implies time horizons of several decades and correspondingly large uncertainties. Against this background, the present contribution primarily aims to bridge the gap between the specialist literature and the general and political debate on uncertainties related to energy systems and their transformation with a focus on the power system as a key sector for decarbonization. The question to be addressed is thereby less of the order on how to do things right but rather on how to do the right things, i.e., what are adequate models for different types of decision problems.

2. A short account of the research performed

In the perspective of matching models with decision problems, we first provide a typology of decisions in the energy sector and also discuss different types of uncertainties. We thereby distinguish operational and investment decisions at the company level as well as political decisions on regulatory settings.

Based on these typologies, we then provide an overview of different methods to incorporate uncertainties in various decision support models. Stochastic optimization, chance-constrained programming and robust optimization are scrutinized along with other, less known methods like information gap decision theory (IGDT) or modeling-to-generate-alternatives (MGA). Also, simple deterministic equivalents, scenario and sensitivity analyses are considered when it comes to solving operational decision problems, investment decisions and policy choices regarding regulatory settings.

Uncertainties are particularly challenging in the latter context – yet the use of optimization approaches may be questioned on epistemic, empirical and methodological grounds. Nevertheless, improved conceptual framings are expected to be helpful to address the still largely unresolved challenges of energy policy and deep decarbonization. These deserve particular scrutiny as the corresponding choices embrace several decades and multiple decision makers in a multi-level governance context. A promising route to avoid the pitfall of “penny-switching” is thereby to investigate the use of quadratic optimization approaches as well as a coupling of optimization models with discrete choice models.

3. Main conclusions and policy implications of the work

After several decades of research both on the decarbonization of energy systems and on the appropriate modelling of uncertainties in the context of decision support models, there is obviously not one silver bullet nor one single solution that fits all problems. The long-time horizon for the system transformation together with the multiplicity of involved investors and policy makers gives rise to multiple uncertainties and makes decision support in the field challenging.

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A first step to cope with uncertainties is certainly to identify and assess them thoroughly. This may be done outside any optimization model used for decision support, by enumerating possible sources of uncertainty and estimating their range. By varying then parameters in the optimization model, the sensitivity of the reference model results with respect to changes in the assumptions may be identified.

A particular challenge to modelling is the intertwined decision making in a multi-level governance setting. Further research efforts may be devoted to developing transparent modelling approaches that enable an in-depth analysis of the interdependencies without imposing strong theoretical priors like in Nash equilibria. Dealing with decisions of other institutions as part of the structural uncertainties may be a way forward to identify “robust” or rather error-tolerant strategies for decarbonization in a multi-polar setting.

(Anti)Competitive effects of RES infeed in a transmission-constrained network

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1. Motivations underlying the research

In the process of the decarbonization of the power industry many countries are adding substantial capacities of wind and solar based power generation to their portfolio. While ownership of conventional capacities is often highly concentrated for historical reasons, in some countries renewable energy is mainly provided by small, independent producers. In such a setup, one might expect competitive pressure in the electric power industry to increase as renewable energy production grows. It is hoped that RES production might also curb the market power of conventional producers.

However, energy from renewable sources often has to be transported over long distances and current transmission systems are poorly designed for this task. In Europe, this is particularly true for wind power produced in coastal areas. In this paper we analyze the effects of regionally concentrated RES-infeed in a transmission-constrained network in which incumbent conventional producers have market power. Surprisingly we find that that an increase of RES infeed in a surplus region might lead to a decline in total generation and consumer surplus in the market if transmission capacities are insufficient. We also show that volatility might arise endogenously from strategic interaction. Conventional generation and nodal prices may be stochastic even if RES infeed, generation cost and demand are perfectly predictable and known to all market participants.

2. A short account of the research performed

We use a simple two nodes / one line network model of spatial Cournot competition. First we explain the intuition behind the potential for an anti-competitive effect of increased wind in-feed using simple graphs. We illustrate the switch from an equilibrium in which the market is fully integrated to an equilibrium in which transmission constraints are binding. The resulting fragmentation of the market allows the dominant conventional producers to exploit their local market power more aggressively. For certain parameter combinations, only equilibria in mixed strategies exist. In these cases even a deterministic environment yields stochastic conventional generation and prices. Then we calibrate the model with German data on consumption and transmission and numerically characterize pure and mixed strategy equilibria for various levels of wind in-feed. We find that for a large range of realistic parameters, wind in-feed in the surplus region has the potential to aggravate market power and decreases consumer welfare. Finally we discuss measures to mitigate this effect, such as maintaining enough competition among conventional producers and increasing transmission capacity.

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3. Main conclusions and policy implications of the work

Our main conclusion is that spatially concentrated RES indeed has a potential for anti-competitive effects if transmission capacities are sufficiently small and conventional generation is sufficiently concentrated. The effects on prices and consumer welfare can be substantial if large generators enjoy local market power. Even though the share of conventional generation in total generation declines as the importance of RES generation by new entrants increases, the need to maintain vigorous competition between large incumbents is increased.

Inland hard coal transportation costs in the European Union – A model based approach

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1. Motivations underlying the research

The European Union (EU) has committed itself to several climate and energy policy goals based on the Framework Convention on Climate Change and several self-imposed resolutions. Given these objectives, there is a trend away from lignite and hard coal towards renewable energies. However, despite these long-term goals, coal will remain a relevant energy carrier within the European electricity mix in the medium term.

The long-term goal of an energy system dominated by renewable energies requires businesses and politicians to make numerous decisions. Energy system models try to reflect and predict reality with its key relationships and thus provide a basis to support decision-making. Yet, energy system models have limitations due to necessary assumptions and simplifications. To assess the potential technical, economic, ecological and social impacts of policy measures, high accuracy and thus high-resolution input data is required. Depending on the problem, this also applies to geographical data. For fuel prices however, this is usually not the case. Many energy system models only differentiate fuel prices between countries, but not within a country. Location-specific costs, such as transport costs, are therefore not taken into account. For hard coal power plants, among the main cost drivers of fuel supply are the transport costs of steam coal from import harbors to the power plant sites. These costs consist either of freight rates of the barges, charges for transport by train, or a combination of both. In addition, transshipment costs during transport may arise.

Therefore, we aim at determining country-specific regional transport costs for hard coal to power plant sites in the European Union. Another goal of this work is to answer the question of whether the differences in transport costs for hard coal within a country are large enough to change the merit order and whether there are differences between countries in the European Union.

2. A short account of the research performed

For this purpose, a model for the EU has been developed which determines the country-specific regional transport costs for hard coal from the import harbors to the respective power plant sites. The geographical resolution of this work is at the municipal level of each country, in which each municipality is characterized by specific costs, depending on distance from import harbor and means of transport. In total, transport costs were modelled for 119,978 municipalities. The model results are presented and discussed for Germany, France, Italy and Spain. In addition, the effects of a low water scenario for Germany are examined, as it occurred in Central Europe in autumn 2018.

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3. Main conclusions and policy implications of the work

The model results show a clear ranking of the most favorable locations in terms of transport costs for hard coal, starting with locations at the open sea. In this case, no onward transportation by inland waterway vessels or train is needed. As the costs of shipping coal from its producing countries to Europe also depend on the size of the ships used, an additional aspect is the question of which ship sizes can unload at the specific harbor. The second-best choice are all inland locations near riverbanks since inland waterway vessels can be unloaded directly at the power plant site too, but a ship-to-ship handling is needed in advance which increases costs. Furthermore, inland waterway vessels are more expensive than seagoing vessels due to their smaller load quantities. All other locations remote from both sea and river access are the most expensive sites because transport by train or truck are the only options to transport coal to the respective power plant sites. The latter is extremely expensive, which is why it is an exceptional case and not part of the model. It can be concluded that the geography of a country has a major impact on transport costs.

Although the impact of transport costs is small compared to fuel prices and CO₂ prices, they are large enough to change the merit order. Variable costs of hard coal-fired power plants are close, so that even small differences can change their position in the merit order. Transport costs thus mainly exert an influence on the competition between coal-fired generation units. A comparison between the standard and a low water scenario in Germany shows that median transport costs to existing power plant units increase about 29 percent if waterway vessels can only load half of their usual cargo. Not all power plants are affected equally because some have alternative supply options.

Our model results are particularly suitable as input for energy system models simulating European power plant dispatch. Further work can assess if an integration of transport costs results in a better reflection and prediction of reality.

The Impact of Renewable Energy Forecasts on Intraday Electricity Prices

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Motivations underlying the research

Over the coming years, the shift to renewable power is set to be one of significant structural changes in the German energy system. Being actively facilitated and supported by the German government, the shift will lead, among others, to an expansion of the share of wind and solar power in the German energy mix. Due to the fact that energy harnessed by wind turbines or photovoltaic panels is intermittent, having precise wind and solar power forecasts is important. Therefore, the focus of the present study will be placed on analyzing forecast errors in wind and solar power forecasts.

We study these forecast errors in the context of the German electricity market. Besides a day-ahead market, electricity can be traded in a continuous intraday market in Germany. The day-ahead and intraday market have two features relevant for the present study. First, both of them take place before the moment of physical delivery of electricity. Second, intraday market takes place closer (in temporary terms) to the moment of delivery.

These two features have two important implications. First, prices in both day-ahead and intraday markets are based on wind and solar power supply forecasts. Second, these forecasts are usually closer to actual values at the moment of physical delivery (i.e. are more precise) in the intraday market. As a consequence, the influence of forecast errors on intraday prices drops (meaning that prices become closer to the actual fundamental equilibrium) the closer trading occurs to the point of actual electricity delivery. Our study proves that this influence is non-linear.

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Moreover, there is a second, more technical, contribution that our study makes. This contribution is a wholesale auction-curves- and optimization-based non-linear econometric model which we develop. This model extends the family of relatively unelaborated empirical-wholesale-curves-based models. In its core, the model shifts day-ahead supply curves to approximate the corresponding intraday supply curves and calculate intraday prices.

A short account of the research performed

To carry out our results, we focus on the German-Austrian EPEX SPOT market and study the period between 01.01.2016 and 31.12.2017. We use prices from the day-ahead market as well as hourly weighted average intraday prices usually referred to as VWAP by the EPEX SPOT. From the EPEX SPOT we also have the data as to the wholesale empirical supply and demand curves. We obtain the data regarding the forecasted and actual wind and solar power supply from ENTSO-E Transparency.

As opposed to our linear and non-linear benchmarks, our main econometric models are not built on the analysis of the day-ahead and intraday price time series. Instead, the main models are based on manipulations with empirical wholesale supply and demand curves. The models first transform demand curves into their inelastic analogues to simplify the study and then shifts the wholesale day-ahead supply curves to approximate the corresponding intraday supply curves. The magnitudes and the directions of the shifts are determined by (a) errors in wind and solar power forecasts and (b) absolute amounts of wind and solar power generated at the moment of delivery. To optimally select the shift size, a non-linear optimization technique is applied. In other words, we add or subtract the adjusted forecast errors from the day-ahead supply. As a result, the day-ahead wholesale supply curves are shifted horizontally. The shifted day-ahead supply curves are thus our approximations of the intraday supply curves. Naturally, the intersections of the shifted day-ahead supply curves with the demand curves coincide with the intraday prices.

Main conclusions and policy implications of the work

First, the results showed that our main models, although being unconventional, can be used successfully to model intraday prices. The benefit of our models would be their straightforward interpretability because we can easily see the impact of each considered parameter on the shift size of a supply curve. Second, we demonstrated non-linear impact of forecast errors in wind and solar forecasts on intraday electricity prices. As our study indicated, the non-linear shape of the merit order curve and the sector of this curve in which the equilibrium price is realized are possible reasons for the non-linear impact. Third, we conduct an auxiliary study to show that forecast errors also impact volatility of intraday prices in a non-linear manner. The auxiliary study also allows us to conclude that the rising amount of wind or solar power capacities in fact increases the volatility of intraday prices.

Furthermore, our results allow us to derive 6 main policy implications. First, we show that locations of new wind and solar power plants must be selected to minimize correlations between the outputs of the already existing and new capacities. Second, we argue for more diversity of renewable power supply sources. Third, we show that it is efficient to expand cross-border transmission infrastructure to avoid country-specific bottlenecks. Fourth, greater investments into quality of renewable energy forecasts are beneficial. Fifth, that flexible generation and better demand side management will ease the non-linear impact of forecast errors. Finally, efficient and transparent renewable energy curtailment management can further improve the stability of energy systems.

The Role of Energy Poverty on Economic Growth in Sub-Saharan African Countries

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1. Motivation underlying the research

Access to energy is one of the essential inputs for socio-economic development (Johansson & Goldemberg, 2002; Davidson & Sokona, 2002). Access to energy is also one component of the wider

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range of problematic issues faced by those living in poverty. Economic poverty is defined as insufficient income to acquire basic goods and services; within this definition, energy poverty is defined as the exclusion of people from basic access to energy that is energy poverty. In addition, the particular and important role of electricity to the countries' economic growth has been extensively discussed in the energy literature. The literature has not reached clear consensus on nexus between electricity and economic growth but Payne (2010) summarizes the four hypotheses assumed and confirmed: growth (electricity consumption $EC \rightarrow$ economic growth EG); conservation hypothesis ($EG \rightarrow EC$); neutrality ($EC \neq EG$); and feedback ($EC \leftrightarrow EG$).

In the sub-Saharan African region, it is a priority for reliable and affordable energy to be widely available which is critical to the development of this region. This region is important as sub-Saharan African region accounts for 13% of the world's population, yet only 4% of its energy demand. This is evident from sub-Saharan Africa's rapid economic growth contributing to energy use rising by 45%, since 2000 (IEA, 2014). A major objective of development policy in sub-Saharan African countries is also alleviating poverty. Ideally, alleviating poverty is to create an environment of inclusive growth which achieves an efficient allocation of resources is vital. One of the channels to reduce the population's poverty is through provision of access to energy and other services.

Hence, the primary aim of this paper is to examine empirically the role of energy poverty to boosting economic growth in the sub-Saharan African region, within the context of the importance of electricity consumption to ignite growth and development. Specifically, this paper examines the hypothesis that energy poverty is a positive contributor to economic growth in the context of developing countries with a focus on fourteen sub-Saharan African countries (Benin, Botswana, Cameroon, Congo – Republic, Eswatini, Kenya, Mauritius, Mozambique, Namibia, Nigeria, Senegal, South Africa, Tanzania and Togo) for the period from 1990 to 2016. This research is relevant given that many sub-Saharan African countries are in a unique position of shifting investments in the energy sector as traditional forms of energy production are being replaced by modern sustainable energy options.

2. A short account of the research performed

The theoretical framework of this study is based on one side on the discussion of the definition of energy poverty and the concept that economic growth and development depend on the "quality" of the population. Based on this the estimated economic model is as follows:

Where GDP is Gross Domestic Product per capita; ACESSELEC is the percentage of population with access to electricity used as a proxy for energy poverty with an expected positive relationship with the dependent variable; URBANIZATION is %share of people living in urban areas; POPULATION is the annual population growth; EDUCATION is the total enrolments in primary education of country in period as a measure of economic growth.

A Generalized Method of Moments (GMM) regression was used to estimate Eq1. due to its ability to control for econometric issues such a cross-sectional dependence of countries and multi-collinearity among variables, and hence the results might be dissimilar to those of the fixed effects estimation.

In all regressions where the control variables were introduced one by one, all the access to electricity coefficients are positive and statistically significant against GDP growth. This suggests that a reduction in energy poverty is beneficial to economic growth: the coefficient ranges between 0.095 and 0.120. When factoring all the control variables for the need of robust testing, an increase by 1% in access to electricity leads to an increase of 0.120% in the annual growth rate, *ceteris paribus*.

3. Main conclusions and policy implications of the work

Access to electricity proved to be a robust macroeconomic determinant of growth, which highlights its important role in determining economic activity in the region. What is of importance is the multiple benefits that the economy will receive at a later stage from an increase in people with access to electricity. These associated benefits are the effects on the quality of education, gender equality, health and poverty reduction socio-economic development for that household.

This study's findings are added to the recent literature on electrification that states access to electricity is a positive contributor to the livelihoods of households in a variety of ways. The fourteen sub-Saharan African countries' experience is informative because it exemplifies the importance of access to energy, particularly in developing and relatively poor countries. It signals to government in these regions that priority should be given to policies that intend to increase the access of electricity to households within their country. As per Gonzalez- Eguino (2015) quoting a report by IEA, "the cost of providing universal access to energy by 2030 would require annual investment of \$35 billion, i.e. much less than the amount provided annually in subsidies to fossil fuels". Hence, significant investment and allocation of resources is essential. In the current constrained economic conditions, the net benefit of such investment should be estimated: the cost of the investment in providing access to energy infrastructure vis-à-vis the economic benefit associated with the improvement of living standards and essentially economic development. In this study, we have provided some quantitative evidence for the impact that access to electricity can potentially have to economic growth.

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Clean Cooking: Why is Adoption Slow Despite Large Health and Environmental Benefits?

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1. Motivations underlying the research

More than 40 percent of the global population still depends on traditional biomass, such as fuelwood, agricultural residues and animal wastes, for cooking and home heating. In Sub-Saharan Africa, the traditional biomass supplies more than 80% of the total energy requirement for household cooking. Half of the total energy demand for household cooking in South Asia is also supplied by traditional biomass. More than 90% of low-income households around the world rely on traditional biomass for cooking and home heating. The widespread use of traditional biomass causes major health and environmental problems. The indoor air pollution generated from the use of traditional biomass for household cooking causes more than four million premature deaths each year; most of which are of children and women. Burning of biomass for household cooking is one of the major sources of deforestation in the developing world. It also contributes to climate change through the emissions of CO₂ and black carbon, the precursors of global warming, and the reduction of carbon sinks through deforestation and forest degradation. One of the key solutions to this problem is the adoption of clean cooking either through the use of improved or efficient cookstoves or switching over to cleaner modern fuels. However, the adoption of clean cooking is very slow, despite the global efforts of promoting clean cooking over the last four decades. This paper discusses, based on rich literature, the main factors responsible for the slow

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adoption of clean cooking. It also offers some innovative approaches to accelerate clean cooking policies and programs in developing countries.

2. A short account of the research performed

We conducted a systematic review of existing empirical studies that investigate the relationship between the adoption of clean cooking and the potential factors that influence the rate of adoption. We use several search engines, such as ScienceDirect, Google Scholar, Scopus, JSTOR and ISI Web of Science databases, for finding the relevant studies. We also use individual websites of several international organizations (e.g., World Bank, Regional Development Banks, UN Agencies, International non-governmental organizations) that provide the knowledge and financial services for the promotion of clean cooking. The methodology used and key findings from all relevant studies are presented. The review does not only synthesize the findings from the literature but also critically evaluates the merits of the findings.

3. The main conclusions and policy implications

The slow adoption of clean cooking can be attributed to various supply- and demand- side factors. Key supply-side factors include lack of infrastructure associated with the supply of modern fuels and clean cookstoves, and lack of technological innovation of clean cookstoves that are locally adaptive. The main demand-side factors include households' limited access to information and awareness, limited household income or affordability, and behavioral factors. Cultural inertia also played a role in the adoption of clean and improved cooking solutions. Further, households are often not motivated towards clean cooking solutions because a system that values convenience, cleanliness and cooking time saved is lacking.

The study suggests a number of policy interventions. A policy addressing the behavior factor is the most critical to increasing the deployment of clean cooking. Behavioral factors, such as lack of motivation and ignorance towards the benefits of clean cooking, have played a big role in the failure of many clean cooking initiatives in the past. Unless the households understand the benefits (e.g., health, environmental and time saving), and appreciate the social values (e.g., cleanness, comfort and leisure) of clean cooking, they would not adopt it even if it is made freely available. Prioritizing social marketing to address these behavioral barriers and creating ownership through the engagement of local stakeholders would help for sustainable adoption of clean cooking. Also important is involving local entrepreneurs for manufacturing and marketing of clean cookstoves. Donor-driven improved cookstove programs would not sustain long after donor supports expires if the local capacity for repair and maintenance is not built and proper incentives are not created for local markets.

A policy that encourages strong and effective awareness campaigns of clean cooking that involves women and children is critical for the success of clean cooking programs. Enhancing the engagement of women in clean cooking adoption decision is very important. Increased private sector participation, together with creating a space for market-driven implementation of clean cooking, would be a way for sustainable adoption of clean cooking in developing countries.

Policies that enhance local employment and increase the income of poor households is the key to the success of clean cooking programs. As long as households have zero opportunity costs (i.e., they have free time in the absence of any productive activities), they will go to natural forests or public lands to collect fuelwood and dung, no matter how cheaper would be the clean cooking alternatives. While a policy to make clean cooking affordable for low-income households is important, how to implement it is questionable. Existing subsidies to cleaner fuels benefitted more to rich households. Subsidies, if any, should be carefully designed to channel to targeted low-income households. Also important is further research on in-depth analysis of key barriers, particularly behavioral barriers, and come up with innovative solutions to reduce these barriers.

Ownership Unbundling of Electricity Distribution Networks

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In the past three decades, electricity markets around the world have been radically transformed. Power utilities have dramatically diverged from their origins as integrated monopoly utilities. Many of the changes have been initiated by significant institutional reforms, such as horizontal and vertical unbundling of integrated utilities, the introduction of independent regulators and incentive-based regulatory frameworks, and the privatisation of publicly-owned energy assets. At the same time, the way power is produced, managed, and consumed is changing, with increasing amounts of decentralised and distributed intermittent renewable sources. Network operators are transforming into network data platforms, increasingly leveraging data collected from the grid for e.g. predictive maintenance and customer services.

Separating electricity distribution and transmission networks from generation, trading, and supply, has been a key component of the reforms over the past decades. The most common form of separation in OECD countries has been to create legally separate entities that own and operate the networks, with an external and independent regulator. The more extreme form of separation is to require ownership unbundling and to prohibit the networks to be (majority) owned by players with competitive power market activities. Although there are several examples of voluntary ownership separation of the Distribution System Operator (DSO), there have only been two countries to have forced this in their markets: New Zealand (1998) and the Netherlands (2009). In both cases the aim was to improve competition, increase network quality, and reduce costs by increasing efficiency.

The discussion over the advantages and disadvantages of mandated ownership separation of DSOs is topical given the changes to the role of distribution networks in the energy transition. Whereas the role of networks was clear at the start of deregulation, the challenges posed by the energy transition and the opportunities offered by digitisation, provides additional arguments to examine the value of ownership unbundling, relative to legal unbundling with additional policy measures, at the DSO level in more detail.

From a policymaking perspective the question is whether the benefits of DSO ownership unbundling outweigh the costs, both in the short term and in the long term, relative to a situation with legal unbundling and additional policy measures. This requires understanding the current market structure and dynamics, and importantly, forming a view of how the energy system will develop given the energy transition and further digitalisation.

According to proponents, distribution ownership unbundling leads to (i) increased retail competition, (ii) improved quality of networks and security of supply, (iii) increased market transparency, and (iv) improved efficiency and lower costs. According to opponents, ownership unbundling leads to (i) consolidation among incumbents, (ii) reduced coordination between networks and generation/ supply, (iii) less investment in generation and networks, and (iii) high one-off transaction costs and structural costs.

The optimal scale and scope of a firm is highly firm-specific, both the type of industry and history are significant in determining optimal scale and scope at any given time. The wide range of scales and scopes observed in firms demonstrates this. Forcing simultaneous ownership unbundling of different activities can subsequently result in horizontal consolidation of separated activities, raising the possibility of increased concentration and reduced competition in the long run. There is very little evidence for the stability of forced separations and that they lead to a reduction of long-run prices, in the presence of such horizontal mergers. It is also not clear if ownership unbundling addresses the possible need to better align managerial incentives across the different activities. The latter is particularly relevant in markets with significant customer autonomy and high customer switching rates, high distributed renewable penetration, and advanced digitised network operators.

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We reviewed 60 papers relevant to ownership unbundling of electricity transmission and distribution over the period 1990 to today, of which 23 discuss the effects of (ownership) separation of distribution networks. We have developed a framework for assessing the degree of consensus on forced distribution ownership unbundling, looking at their overall ownership unbundling assessment and with respect to their assessment of the effect of unbundling on competition, quality, and costs. The majority of papers – both theoretical and empirical – are either *not in favour* or *inconclusive* on the benefits of distribution network ownership unbundling. Along the competition and quality dimensions, the papers are relatively equally spread between *in favour*, *inconclusive*, and *not in favour*. However, with respect to costs, there are a significant number of papers *not in favour*.

To examine the impact of ownership separation we collected data from New Zealand and the Netherlands to test whether competition and quality improved, and whether costs fell. To examine the effects on retail competition we collected data on: (i) Retail market concentration (HHI index), (ii) Concentration ratio of the top 3 retail players (CR3), (iii) Retail margins, and (iv) Switching rates between retailers. To examine the effects on network quality we collected data on: (i) Outage duration (SAIDI), and (ii) Outage frequency (SAIFI). To examine the effects on costs we collected data on (i) One-off costs, and (ii) structural costs/ efficiency.

The empirical evidence for New Zealand demonstrates that the benefits do not appear to outweigh the costs by a wide enough margin to justify interfering in the ownership structure of companies. On the positive side, ownership unbundling in New Zealand led to substantial cost reductions and increases in quality of service. On the negative side overall competition was reduced, tariffs rose as cost reductions were not passed on the end-users, and there were substantial one-off transactions costs involved. In recent years, the rules on ownership unbundling have been relaxed to allow distribution companies to own and operate generation and be active in retail – under certain conditions.

The data for the Netherlands do not show a significant impact of ownership unbundling on quality or competition. There is no difference *pre-* and *post-*unbundling. However, there were clear one-off and structural costs involved with unbundling. Thus on balance, the expected benefits have largely not materialised, whereas the costs of unbundling, have materialised and are significant. Additionally, as the Netherlands implemented this form of unbundling unilaterally, many foreign players – with network assets – are active in retail and other commercial activities (approximately 60 percent of retail customers are served by a company that owns networks outside the Netherlands). Thus, creating an un-level playing field nationally as well as on a European level, rather than levelling the playing field. If network companies could have been sold, they too may well have passed into the foreign ownership of bundled international companies.

With the emergence of distribution network platforms, data hubs, and increasingly active DSOs, enforcing an organisational form, even disregarding the negative theoretical and empirical evidence, seems outdated. From a policy perspective, it is thus advisable to consider other policy measures to improve competition in retail, improve the quality of the network and drive down monopoly network costs. Measures that could be considered, in addition to current legal unbundling, are (i) strengthening the regulatory framework and the regulator, (ii) decreasing or removing barriers to entry for retail activities, (iii) further ring-fencing of distribution activities, and (iv) improving transparency for end-users. The latter is one of the key focus areas for the European Commission and leading regulators, such as the UK's, Ofgem.

Electricity Markets in the Resource-Rich Countries of the MENA: Adapting for the Transition Era

Rabmatallah Poudineh,^a Anupama Sen,^b and Bassam Fattouh^c

1. Motivations underlying the research

The Middle East and North Africa's (MENA) resource-rich economies are pursuing two parallel strategies in their electricity sectors: (i) increasing and integrating renewables into their power generation mix to mitigate the impact of rising domestic oil and gas demand on their economies and boost hydrocarbon export capacities; and (ii) undertaking power sector reforms to attract investment in generation capacity and networks, remove subsidies, and improve operational efficiency. These goals imply that the design of reforms needs to be carried out with a view to a rising share of non-dispatchable resources. The lack of an integrated approach to simultaneously address these two strategies is likely to lead to several misalignments between renewables and various components of future electricity markets, as the share of intermittent resources increases in the generation mix. The key challenge is that the 'ultimate model' capable of reconciling these two goals is as yet unknown, and is still evolving, due to uncertainties around the development of technologies, institutions, and consumer preferences. Failure to find the right model is likely to frustrate reform efforts and governments may find themselves in need of making significant changes to the electricity market at later stages. For example, inadequate tariff structure design, following the removal of subsidies, could lead to difficulty in recovering the power systems' fixed costs, and also to the regressive distribution of costs among ratepayers. Furthermore, introducing significant renewables without a proportionate increase in power system flexibility (both in generation and in the grid) typically leads to curtailment and/or lower system reliability. Moreover, integrating demand-side resources faces a significant hurdle when ownership and operation of the national electricity grid are not decoupled. The tension between liberalization and decarbonization in pioneering electricity markets, such as in the EU, has arisen partly because renewables were imposed upon a market designed for conventional fossil fuel electricity. Resource-rich MENA countries, by contrast, could design their electricity markets around the incorporation of renewables at the outset and tap into years of international experience gained through trial and error.

2. A short account of the research performed

We argue that resource-rich MENA countries can move towards adopting a transition model of electricity markets, the individual elements of which can be adapted to suit either *centralized* or *decentralized* future electricity sector outcomes. Such a model needs to:

- combine the effective features of various successful designs;
- balance the roles of the market versus the government;
- be compatible with the current technology mix and institutions in the region;
- allow for the further development of renewables;
- be flexible enough to adapt to future developments in the electricity sector;
- encourage efficiency and security of supply; and
- promote consumer preference.

We focus on major resource-rich MENA economies which are locked into a cycle of dependency on fossil fuels, due to two primary interconnected factors: rising domestic hydrocarbon consumption on the back of under-priced and plentiful fossil fuel reserves (oil/gas); and, rising dependence on oil and gas export revenues to finance domestic economic activities and maintain rent distribution. We identify six

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resource-rich countries which form the focus of the analysis in the paper: Algeria, Kuwait, Iran, Qatar, Saudi Arabia and United Arab Emirates (UAE). We review the current status of renewables in these countries as well as their future renewable targets, and we identify and describe five key features related to the region's electricity sector that will affect not only the design of instruments to achieve renewable targets but also future developments of these countries' power sectors. These include: the organisation of the electricity sector around vertically-integrated structures, slow progress of electricity reform implementation despite ambitious legislation, strong state presence in the electricity sector, highly subsidised tariffs, and mismatch between end user load profile and renewable resources generation profile due to high inefficiency of consumption. Against this context, we assess the state-of-the-art in electricity reform in the six countries. We then outline the key components of our transition model for the wholesale market, retail market, and network regulation, considering governments' objectives and the specific contexts of the countries in the region.

3. The main conclusions, application and policy implications

We show that resource-rich MENA countries can adopt market structures that avoid the risk of market breakdown under fully liberalized electricity systems with a high share of non-dispatchable resources. On wholesale market design, we argue that a hybrid structure of short-term coordination (through energy-only spot markets) combined with fixed-price long-term contracts is proved to be the way forward for resource-rich MENA countries during the transition period, particularly given the contexts within which they operate (for example, the rapid demand growth and the difficulty of obtaining sufficient revenues from customers along with rigid governance structures). This can be in the form of mandated requirements for electricity suppliers to purchase certain percentages of their final demand in the forward market in advance of the delivery. Alternatively, it can be a capacity market in which long term capacity contracts are allocated in an auction with a central agency as the counterparty. For the network segment, these countries can adopt an innovation-oriented regulatory model, in order to balance between efficient utilisation of existing resources versus building more networks. Such an approach also allows these countries to benefit significantly from regional integration of their power markets and electricity trade. The retail market can be opened to competition for large consumers, but for small users it can be regulated without the government distorting retail prices through subsidies. The structure of final electricity prices must not lead to inequitable distribution of system fixed costs or encourage grid defection. Finally, the advent of prosumers, along with fall in the cost of batteries and advances in information and communication technology, may open up a new path for consumer involvement in the electricity sector. It also may provide a new design for restructuring the power sector in the form of prosumer-network-prosumer as an alternative or complement to the traditional liberalization model of wholesale-network-retail. Finally, there is no one path to market liberalization for MENA hydrocarbon economies, as combinations of technological advances, consumer preference, and institutional changes can offer alternative or complementary approaches to the 'classical' model of power sector reform.

Different Cost Perspectives for Renewable Energy Support: Assessment of Technology-neutral and Discriminatory Auctions

Jan Kreiss,^a Karl-Martin Ehrhart,^b Marie-Christin Haufe,^b Emilie Rosenlund Soysal^c

Motivation

Auctions are the prevalent instrument for promoting renewable energy sources worldwide. Auctions enable the controlled deployment of renewable energy sources while reducing costs. However, there are different views on efficiency, relevant costs, auction targets, and their implications on the auction design.

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Technology-neutral auctions are open to all RE technologies and do not discriminate (positively or negatively) among participants, whereas discriminatory auctions treat different classes of participants differently. Non-discriminatory technology-neutral auctions theoretically result in an outcome that minimizes the generation costs of RE sources. This, however, may conflict with other targets, particularly with the internalization of integration costs and the minimization of the support costs through a reduction of the producer rent.

We show that technology-neutral auctions are not a panacea. We analyze two types of discriminatory design elements that improve the expected auction outcome with respect to specific auction targets. By applying theoretical concepts to auctions for renewable energy support, we highlight how discriminatory auctions can prevent windfall profits and how to include an overall economic perspective in the auction design. We illustrate our results with real-world examples.

Short account of the research performed

We combine theoretic methods with practical examples and experiences from past auctions. We theoretically analyze different forms of discrimination and several discriminatory instruments to evaluate auction design options against the underlying economic principles for the future promotion of RE sources. That is, game-theoretic principles of auction theory and their application to renewable energy support are combined in an in-depth analysis.

In our analysis, we also take the trade-offs between different cost perspectives into account. The implementation of discriminatory elements in auctions allows pursuing targets of the internalization of integration costs and the minimization of the support costs. We consider two forms of discrimination, which both can reduce the total costs for the consumers, however, also may generate inefficiencies with respect to the minimization of generation costs.

We address the conflicting views on relevant costs and discriminatory auction design elements by providing a consistent definition of costs related to RE deployment. Here, the separation of the cost components is imperative for our analysis. Further, we present the variety of policy objectives for the RE support and relate these to the cost definitions. Based on these definitions, we analyze how the two approaches of discrimination, quality-based and cost-based discrimination, perform with respect to the policy objectives. We show that both approaches are suitable for the auctioneer to reduce consumers' overall costs, which is an argument for policy makers to take discriminatory design options into account.

Conclusions and policy implications

The reduction of greenhouse gas emission through the expansion of RE sources is undisputed, and auctions are becoming the prevalent mechanism for determining the support of RE sources. The current trend indicates more open auctions in which bidders from different technologies and/or from different countries participate.

Although non-discriminatory technology-neutral auctions minimize the generation costs theoretically, we illustrate the trade-offs associated with discriminatory auctions. Depending on the targets and available information, discriminatory auctions may be a reasonable choice because, for example, they can reduce the auctioneer's expenses for supporting RE sources.

The first type of discrimination differentiates between the bidders based on the different characteristics of their projects. This approach considers the implications on the overall system costs. The applicability depends on the available information. For a full implementation, the integration costs of every RE project are required. Nevertheless, even with less information, it can be implemented successfully and even be combined with other forms of discrimination. It has been proven in practice that it is difficult to retrieve the desired information, yet that discrimination mainly results in favorable outcomes.

The second type of discrimination involves reducing the producer rent by differentiating between the bidders based on their different cost structures. Discriminating against low-cost bidders in favor of high-cost bidders reduces the support level through absorbing the different profits of the different bidders and, thus, reduces the producer rent, resulting in a lower support level. It requires less information

and allows for three theoretically equivalent implementations, which, however, are different from a practical and political perspective.

Concluding, the theoretical concepts of discrimination can be transferred to RE auctions, where they can have a positive impact on the essential expansion of RE sources with the lowest overall system costs. Although there are differences between the theoretically optimal concepts and the practice, examples show that the concepts can be implemented successfully.

Different Cost Perspectives for Renewable Energy Support: Assessment of Technology-neutral and Discriminatory Auctions

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Towards Electricity Markets' Integration and Investment in Transmission Capacity: East African Community Power Markets

Geoffrey Aori Mabea^a and Rafael Emmanuel Macatangay^b

Investments in transmission capacity bring opportunities to promote the interconnection of electricity markets, enable the delivery of renewable energy, and increase aggregate economic welfare. The efficient operation of electricity markets across jurisdictions depends crucially on the configuration of the transmission system, enhancing the prospects for power trading. For the nascent electricity markets of East Africa Community (EAC) member countries, the availability of transmission capacity interconnecting them is a key determinant of power market integration, the international trade of electricity, and the pursuit of an energy union in East Africa. It is thus vital to analyse the optimality of transmission capacity expansion.

This paper seeks to assess the impact of transmission capacity expansion on a prospective EAC electricity market. It performs a simulation of the transmission investments expected to yield the highest economic welfare across multiple jurisdictions in the EAC. The current plans for transmission investments in the EAC provide a practical starting point. We first analyse the status quo, and then consider

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different scenarios, simulating the economic implications of integrating the various electricity markets in the EAC. The assessment proceeds with a step-by-step addition of both in-country networks and cross-border interconnectors and culminates in the selection of the expansion plan yielding the highest economic welfare.

The simulation model performs an economic dispatch using an optimal power flow, and applies a nodal pricing framework to a set of electricity markets that are currently unintegrated. The results show that the aggregate loss in economic welfare due to inadequate transmission capacity could be \$0.3 million/hour, and that a capacity of at least 200MW for all transmission lines captures the economic welfare gains from trade. This paper offers fresh insights on how the estimation of nodal prices across yet to be integrated electricity markets constitutes an important step towards the creation of a robust power pool. The five EAC electricity markets are currently unintegrated, but could benefit tremendously from cross-border power trading. The coupling of EAC electricity markets increases the operational efficiency of their power systems and facilitates the penetration of renewable energy generation across jurisdictions.

Comparing Regulatory Designs for the Transmission of Offshore Wind Energy

Yann Girard,^{a} Claudia Kemfert,^b and Julius Stoll^a*

Offshore wind energy plays an important role to meet global targets for renewable energy. For offshore wind energy to be successful, the total cost of offshore wind electricity produced needs to be low. This not only requires a cost-effective development and operation of the offshore wind farms themselves but also of the offshore transmission assets that transport the produced electricity ashore. An efficient regulatory design is crucial for this.

This paper compares different regulatory designs in order to determine what policy leads to the most cost-effective development and operation of offshore transmission assets. We argue that the regulatory design impacts cost-effectiveness in two aspects.

First, the market design shapes the degree of integration between the offshore transmission asset and the offshore wind farm. When the local transmission system operator (TSO) or a third party build the offshore transmission asset, development and operation of the transmission and wind farm take place separately, creating additional coordination efforts. However, when development and operation of the offshore transmission asset are bundled in the hands of the offshore wind farm developer, coordination improves.

Second, the market design affects competition. When regulation requires a competitive tender to determine the development and operation of the offshore transmission asset, all bidders are in direct competition. Alternatively, in a monopolistic market environment, only the local TSO is obliged to ensure development and operation of the offshore transmission asset.

Our study examines two comparable countries with contrary regulatory approaches. Therefore, we calculate the cost of offshore transmission assets in Germany and the United Kingdom. Germany follows a monopolistic approach, in which development and operation of the wind farm and the transmission asset are separated. By contrast, the UK follows a competitive and largely integrated approach.

We collected a new data set using cost information from national authorities, TSOs, and other sources of offshore transmission assets built so far. We find that German offshore transmission assets are significantly more expensive. This result is robust even after considering differences in distance, technology choice, capacity utilization, environmental regulation, and financing conditions. The cost difference is not explained by a higher security of supply in Germany. The cost in Germany are further amplified by the offshore liability levy, a financial compensation scheme paid by the TSO to the wind

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farm operators for delayed commissioning of transmission assets. We argue that the cost difference between offshore transmission assets in the UK and Germany primarily measures the cost impact of the different regulatory approaches.

Eyes on the price: Which power generation technologies set the market price?

Eike Blume-Werry,^a Thomas Faber,^b Lion Hirth,^c Claus Huber,^d and Martin Everts^e

Wholesale power markets follow the principle of short-run electricity markets where the market clearing price is determined by the intersection of supply and demand at any given hour. In theory, the resulting hourly day-ahead market price is equal to the marginal costs of the last (marginal) unit in the merit order necessary to satisfy the demand. Given that this marginal unit sets the price for all power generation units operating during that particular hour, one can label it as ‘price setting’.

In the literature, it is frequently stated that in most central European markets, gas- and/or coal-fired power plants are usually the marginal price-setting units, which is why we refer to it as conventional wisdom. The nature of European power plant portfolios with significant coal- and gas-fired generation capacities (and their marginal pricing) comprise the basis for this conventional wisdom - as do causal relationships between coal and/or gas prices and wholesale power prices that a number of scholars have researched. However, there is, to our knowledge, no academic literature that looks in detail into the actual price setting on European markets and the extent to which coal- and gas-fired power plants are indeed commonly price-setting.

This paper aims to fill this gap and investigate price setting on European power wholesale markets using a fundamental electricity market model. From the hourly calculations of European power markets, one can derive the marginal price-setting technology for any given hour. Taking a whole year as a time-frame, it is possible to analyse how the hours of a year are structured and what share different generation technologies take in providing the marginal price-setting units. The core objective is to broaden knowledge of price setting on European power markets, and obtain a more nuanced picture of what technologies set market prices. Given that the European power market is integrated and significant cross-border flows are occurring, the analysis looks at 20 integrated central European power markets. This helps to understand interdependencies and in what ways larger markets dominate price setting elsewhere.

In view of ongoing public debates on CO₂ price floors and the announcement of the Dutch government that one be introduced, this paper analyses how different CO₂ price floors affect the price setting as part of a sensitivity analysis. This sheds light on the question of how carbon price floors influence marginal price setting and if a given price floor will result in a shift from coal to gas as a dominant price-setting technology.

A key observation is that, with respect to the marginal price-setting units, the modelling results indicate a higher level of interconnectivity than one might assume. Large countries tend to dominate the price setting—presumably quite simply due to the large number of power plants and their differentiated marginal costs. Hence, electricity markets and wholesale power prices of comparably small countries are significantly influenced by the energy policies of their larger neighbours. Indeed, modelling results show that in terms of price setting, foreign energy policies can have a larger influence on a given state’s electricity market than domestic policies.

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Looking at the technologies one notes that for the large majority (>90%) of total hours in all countries, reservoirs, pumped-hydro, nuclear, gas-, coal- and lignite-fired power plants provide the marginal price-setting units. Other technologies such as stochastic renewables or other fossil plants play an almost negligible role in terms of price setting. Altogether, the modelling results show that gas-fired power plants provide the price-setting units for almost a third of the total hours, and thus for more hours than any other generation technology. Coal- and lignite-fired power plants follow, and together provide the price-setting units for over a quarter of the total hours (whereby lignite-fired power plants take a larger share than coal-fired ones). A notable point is that reservoirs and pumped-hydro power plants are also price setting for another quarter of the total hours. Nuclear power plants set the price for just below 10 percent of the hours, a share similar to that of renewables, including run-of-river power plants. On an individual country basis, the picture of price-setting technologies can look very different depending on countries'—and surrounding, connected countries'—generation portfolios.

Scenarios with different carbon price floors show that the general structure of the price setting remains largely unaffected by the researched carbon price changes; yet a more substantial impact on wholesale power prices, fuel switching, CO₂ emissions and import/export balances can be observed. We find that the proposed Dutch carbon price floor would lead to rising Dutch imports and ergo reduced Dutch emissions, but with little to no emission reductions on a wider European level. A theoretical multilateral carbon price floor of the countries of the Pentalateral Energy Forum would result in rising wholesale prices and reduced emissions that are, unlike in the scenario of the Dutch carbon price floor, not fully offset by rising emissions elsewhere.

Altogether the research shows that large countries tend to have a strong influence on price setting in smaller neighbouring countries, as long as there are sizeable interconnector capacities. National policy measures such as coal phase-outs or carbon price floors thus have substantial effects across national borders. Generally, we find a price-setting pattern that is more complex and nuanced than the conventional wisdom suggests, and that power generation technologies other than coal- and gas-fired power plants provide the marginal price-setting units more often than one may assume. This should be taken into account upon discussion on the price setting on electricity wholesale markets.

Last but not least, it is shown that whilst carbon price floors have little effect in terms of switching the price-setting technology, they can—if executed on a multilateral basis—trigger substantial emission reductions at a wider European level. The proposed unilateral Dutch carbon price floor would in contrast only shift production and emissions abroad.