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A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model

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ABSTRACT

Bottom-up energy models can support strategic decision-making and can help to manage an efficient transition to a low-carbon energy system. The manufacturing industry accounted for about 19% of EU-wide greenhouse gas emissions in 2014, which underlines the importance of this sector for model-based decarbonisation assessments.

This paper describes the methodology of the FORECAST model. FORECAST is a bottom-up simulation model used to develop long-term scenarios for the future energy demand of industry, services and household sectors. In this study, we discuss the model in the light of developing transition scenarios for the decarbonisation of the industry sector. In doing so, we focus on the model's structure and simulation algorithms, and provide illustrative results.

The FORECAST model includes a broad range of mitigation options combined with a high level of technological detail. Technology diffusion and stock turnover are explicitly considered to allow insights into transition pathways. The model further includes different policy levers to improve its applicability as a policy support tool. The model is designed to cover the entire industry sector from major energy-intensive processes to the numerous less energy-intensive sub-sectors and applications.

The concluding discussion suggests future research directions to improve the contribution industry sector models can make to supporting the industrial energy transition.

1. Introduction

Energy system models are used as tools to support strategic decision-making in the transition to a low-carbon energy system. While a huge number of diverse models are used today [14], traditionally, energy systems modelling concentrated on the supply side and feature a lower level of technological detail for energy demand sectors. Recently, more diverse simulation-based modelling frameworks have been used that are based on modular approaches with more detailed demand representation [49].

This paper describes the methodology of the FORECAST model. The model develops long-term scenarios for the evolution of energy demand and greenhouse gas (GHG) emissions in the industrial, services and residential sectors of individual countries until 2050. In this paper, we focus on the industry sector module of FORECAST.[1]

The industry sector accounted for about 19% of EU-wide greenhouse gas emissions in 2014. Globally, the importance of the industry sector was even higher, with a 30% share of global GHG emissions in 2010 [20,21]. Compared to other sectors, industry is difficult to decarbonise due to process-specific GHG emissions (e.g. for cement and lime production), high temperature heat demand, feedstock needs and technically required coal use (e.g. oxygen steel production) as well as high technical diversity and international competition.

The chapter on industry in the fifth IPCC assessment report concludes that simply improving energy efficiency will not be sufficient to reduce the absolute global emissions from industry [20,21]. On the contrary, a broad set of mitigation options is needed including fuel and feedstock switching, carbon capture and storage (CCS), material use efficiency, recycling, the re-use of materials and products, product service efficiency and demand reductions. In the following, we briefly review current industry sector models with a particular focus on the types of mitigation options considered.

Bottom-up[2] industry sector models follow different approaches including accounting, simulation and optimisation methods [25]. Some

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[1] When we refer to FORECAST in the following text, we always only mean the industry-related module of FORECAST.

[2] E.g. Ref. [49]: "Bottom-up models are based on a detailed description of the technical components of the energy system".

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model-based scenario analyses address the industry sector as a whole [19], while many others focus on individual sub-sectors like steel [44,46] or cement [47] or selected technologies [54,19]; for example, assess long-term GHG reduction scenarios for the UK industry using the TIMES model and consider interactions with the entire UK energy system. The UK model considers incremental energy efficiency improvements for processes but also radical process innovations, fuel switching and CCS. The IEA ETP global scenarios also use an optimisation framework (TIMES) for industry, and focus on individual processes in energy-intensive industries [45]. The model considers energy efficiency, new production processes, fuel and feedstock switching and CCS. The ETP's most ambitious mitigation scenario also considers (exogenous) assumptions about material efficiency along the product value chain. A sector-specific model focusing on steel and cement is presented by Ref. [59]. They model the competition between alternative production technologies, the fuels used, CCS and recycling, with exogenous assumptions about energy efficiency improvements.

The PRIMES model has been used for a variety of scenarios to inform EU decision-making and follows a simulation approach for the industry sector. It considers industry's investment behaviour. Mitigation options include energy efficiency, process switches, fuel and feedstock switches and CCS [13,16]. The US's NEMS model is a simulation model with a high level of technology detail including explicit process flows for energy-intensive industries and less detailed modelling of investment decisions [58]. In NEMS, energy efficiency improvement is a combined result of energy price changes and autonomous improvement. A very detailed bottom-up model used for the Dutch industry sector is described by Ref. [15]. It includes a detailed simulation of micro-economic investment decisions and allows a variety of policy parameters. In terms of mitigation options, it focuses on energy efficiency, fuel switching and combined heat and power, in particular. A similarly detailed approach is followed by the Canadian CIMS model [43].

Other models focus on individual mitigation options or sub-sectors. Examples include assessments of energy efficiency potentials and technologies for steel [10] (Fischedick_et_al_2014) [3,55,57]; and cement [11,30,34,61,63] and chemicals and refineries [35,39] or the cross-cutting potentials of electrification [38]. These assessments are characterised by a very high level of technology detail, often considering individual plants. However, they focus less on endogenous modelling of the transition path or the impact of policy instruments, and more on constructing technology scenarios.

Only a few models consider material use efficiency as a mitigation option [28,45]. If considered at all, this is mostly handled exogenously in the scenario definition, e.g. in the form of reduced industrial production.

Concerning the availability of models to capture the entire set of mitigation options, the IPCC report concludes that: "*The crude representation of materials, products, and demand in scenarios limits the evaluation of the relative importance of material efficiency, product-service efficiency, and demand reduction options.*" [20,21]; p. 744), although these aspects might become more relevant for policy making [62]. Similarly, in a review of 5 integrated assessment models (IAMs) [48], state that "[…] recycling, lightweighting, and other material efficiency strategies should be part of technology-rich IAMs, which would allow them to assess a wider spectrum of emissions mitigation strategies than is currently the case". According to Pauliuk et al., such mitigation options are currently not included in IAMs and most IAMs have a relatively aggregated representation of industrial energy demand. However, a recent publication does take the first steps in this direction and includes more demand-side mitigation options thus reducing the reliance on CCS, for example [60].

The brief literature overview above supports the IPCC's conclusion, particularly for models that aim to cover entire industry sectors. For such models, the high heterogeneity of production technologies and energy uses presents a huge challenge. Some models feature a high level of technology detail, or policy parameters, or consider a transition path or costs, but very few consider all these aspects in an integrated approach. Models with a very high level of technology detail are often less comprehensive in their consideration of policy instruments.

We aim to address this gap by presenting the industry sector bottom-up model FORECAST. The model can address a wide range of research questions, but the main focus of this paper is on the model's ability to calculate comprehensive transition scenarios for the entire industry sector of individual countries by considering a broad scope of mitigation options.

The following description of the FORECAST model focuses on its structure and main simulation algorithms as of December 2017. Due to the model's broad scope and long history in applied policy support, it is only possible to provide an overview of the model in this article. We refer the reader to other publications for more detailed descriptions of individual sub-models or applications to individual research questions.

This paper continues with a brief summary of the model's development and application history and a general overview of its structure. A more detailed discussion of the six individual sub-models follows, and a brief summary of model interfaces and add-ons, before the description of an illustrative case study. Finally, we draw general conclusions and make recommendations. We illustrate the individual sections with exemplary results from different studies. The article is accompanied by supplementary online material that completes the model description with tables on technology structure and input parameters.

2. Model history

The FORECAST model has been undergoing development for more than 10 years. A brief overview of important industry-related studies also provides insights into the typical research questions addressed by the model. Early studies looked at energy efficiency potentials and costs in Germany's basic materials industries [22,24,25] as well as in the EU as a whole [17]. The model has been extended continuously from its origins as an accounting model focusing on technology scenarios into a simulation model capable of assessing the impact of policies. Such studies included assessments of energy efficiency policies and their contribution to EU-targets in 2020 and 2030 for the European Commission [27] as well as long-term climate policy scenarios for the German Environment Agency (Schlomann_et_al_2011). Links with macro-economic models and considering the circular economy have been other topics in the model's development [33]. Recent applications have widened the scope of the model to include fuel switching for process heating and space heating, allowing the assessment of the entire heating and cooling demand and supply [6]. With an even broader scope and embedded in an overall energy system transition study [50], the model has also been used to develop a decarbonisation pathway for the entire industry sector in Germany [23]. This study is presented in the illustrative example in section 6.

While the FORECAST model has also been used for international studies (e.g. the cement industry in Taiwan [34], or Brazil), most applications have a clear focus on Germany and the EU. Most of the studies looked at the years 2030 and 2050. In principle, however, short-term analyses and ex-post analyses are also possible. One example of an ex-post analysis is the development of end-use energy balances for the EU heating and cooling sector [51].

3. Model overview

The FORECAST model is designed as a tool that can be used to support strategic decisions. Its main objective is to develop scenarios for the long-term development of energy demand and greenhouse gas emissions for the industry, services and household sectors of entire countries. The industry sector module of FORECAST considers a broad range of mitigation options combined with a high level of technological detail. Technology diffusion and stock turnover are explicitly