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Published in:
Proceedings of the International Gas Union Research Conference 2017

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

IBP1178_17

CONCEPTUAL MODEL OF THE GAS SYSTEM AS AN INTEGRATED PART OF THE FUTURE DANISH ENERGY SYSTEM

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Abstract

Denmark has set the ambitious goal of achieving an energy system, which is independent of fossil fuels by 2050. This implies that the Danish energy system will experience a remarkable transformation in the future, heading towards energy production based on renewable energy sources (RES). Facing the challenging future, a smart integration of gas in the Danish energy system may – in an effective and cost-efficient way – contribute to a sustainable transition. The FutureGas research project addresses these issues considering a smart integration of gas, which includes a development of: 1) flexible production of power and heat to support integration of fluctuating renewables, 2) decentralised production and collection of renewable gases, 3) transmission and storage at national and international levels, 4) distribution of gas to transport, power and heat as well as to the industrial sector.
To investigate the transition of the Danish energy system, a system perspective is needed, which allows assessment of possible synergies across different sectors. Development of energy system models, which can facilitate integrated modelling of the entire energy system including the power, district heating, gas, and transport systems are therefore a central part of the project.
In this paper, a conceptual model of the gas system as an integrated part of the future energy system is developed. The conceptual model is developed to ensure that all important aspects of modelling the gas system are represented in a sufficiently detailed way to properly analyze the potential future interaction between the gas sector and the remaining energy system. The modelling framework will comprise a detailed representation of the power, district heating and gas systems, while sectors such as the transport and industry will be partially represented through exogenously specified demands. Specifically, the conceptual model of the future gas system includes production, conditioning, transmission, storage, trade and use. The conceptual model highlights the important variables and parameters as well as necessary restrictions. The conceptual model will at a later stage be implemented in the existing energy system optimization model Balmorel, which currently has a detailed representation of the electricity and district heating sectors as well as in the spatiotemporal optimization model OptiFlow.
The conceptual model will in the end, improve the current state of modelling integrated energy systems by combining the above-mentioned features with: 1) Investment optimization along with operation optimization. 2) High geographic resolution, which facilitates modelling the restrictions related to e.g. supply of district heating. 3) High temporal resolution. 4) Option to optimize with unit commitment. 5) Decommissioning of existing plants, making it possible to model the pathway towards future scenarios with high shares of RES.

1. Introduction

Denmark has set the ambitious goal of achieving an energy system, which is independent of fossil fuels by 2050. This implies that the Danish energy system will experience a remarkable transformation in the future, heading towards energy production based on renewable energy sources (RES). Facing the challenging future, a smart integration of gas in the Danish energy system may contribute to a sustainable transition in an effective and cost-efficient way as outlined in a number of studies (Dansk Energi, 2015; Energinet.dk, 2015a, 2015b; Energistyrelsen, 2014; Brian Vad Mathiesen et al., 2015; Meibom et al., 2013)

This analysis is a result of the FutureGas research project, which addresses these issues considering a smart integration of gas requiring development of: 1) flexible production of power and heat to support integration of

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fluctuating renewables, 2) decentralised production and collection of renewable gases, 3) transmission and storage at national and international levels, 4) distribution of gas to transport, power and heat as well as to the industrial sector.

The Danish energy system will in the future undergo a radical transformation towards a system with stronger couplings and interactions between energy vectors (Energistyrelsen, 2014; Geidl et al., 2007). Therefore, in order to assess the future value of the gas grid and utilization of renewable gasses (RE-gas), a holistic system perspective is needed (Wu et al., 2016).

In the context of energy systems research, several energy system analyses have been carried out for the future Danish energy system (Danish Commission of Climate Change Policy, 2010; Lund et al., 2011; Münster et al., 2012); but none have focused on detailed representations of gas grids and their potential role. Only a few energy system analyses have been made, which to a limited extent take into account the gas sector along with the electricity and heat systems (Bregnbæk and Stidsen, 2005; Energinet.dk, 2015a, 2015b, 2014; Jentsch et al., 2014)Therefore, research gaps exist both for methods and tools, which enable modelling and simulation of integrated energy systems (Brian Vad Mathiesen et al., 2015; Muditha Abeysekera et al., 2016) and which allows comprehensive assessments of the future Danish energy system including a detailed representation of the gas system.

The purpose of this study is to contribute to the integrated energy systems modelling field by presenting a modelling framework enabling a further developing of an existing energy system model, by including a sufficiently detailed representation, which will capture the main potentials and challenges of the gas system as it is today and as it may develop in the future

2. Integrated Energy System Models

Energy system modelling is a powerful tool that can provide insight related to future trends in energy systems, supporting policy makers in the strategic decision for the world's transition towards a sustainable future (Di Leo et al., 2015; IEA, 2016; IPCC, 2014). Integrated energy system models allow holistic assessments of the whole energy system taking into account synergies between energy vectors (Lund et al., 2011). Energy vectors in future energy systems are increasingly interconnected through conversion technologies. In this respect, the gas system will be highly interconnected to other energy subsystems through e.g. co-generation plants (CHP) such as Combined Cycle Gas Turbines (CCGT) and through Power-to-Gas technologies (P2G). P2G allows VRE electricity generation to be used for RE-gas production which can be used directly or conditioned and injected into a gas pipeline network (Energinet.dk, 2015c; Meibom et al., 2013; Wu et al., 2016)

Generally, energy system models rely on different modelling approaches where some of the most important are listed below:

- General vs. partial vs. no equilibrium
- Top-down vs. bottom-up
- Myopic vs. perfect foresight
- Deterministic vs. stochastic
- Normative vs. explorative

Most energy system model are technology rich and relies on a bottom-up approach (Connolly et al., 2010). The models can be solved as a partly equilibrium model in energy related sectors e.g. Balmorel and TIMES-DK, or solved not using the equilibrium approach e.g. EnergyPLAN and STREAM (Connolly et al., 2010). The concepts of myopic or perfect foresight of the simulated periods is a general discussion, however, new approaches are developed allowing a rolling time horizon which represent e.g. certain policy decisions in specified years (Pfenninger et al., 2014). Future energy system with high penetrations of variable renewable energy (VRE) sources can be related with uncertainties of the energy production, however applying stochastic modelling approaches increases the computation time of the energy system models. By optimizing investment and operation in energy system model, both normative and explorative scenarios can be assessed.

As a consequense of the different modelling approaches, discrepancies in final scenario results are obtained (IPCC, 2014). Therefore, the interpretation and the communication of the results is extremely important.

Energy systems are very complex systems and can be described through a set of highly non-linear equations. However, in order to compute holistic energy systems models, these complex systems may be linearized. Furthermore, energy system models represent the energy system in a simplified and aggregated manner, which fits the purpose of long-term scenario assessments. To get a deeper insight into specific system dynamics more detailed systems models are developed e.g. gas pipeline network models and power system models (load-flow models).

Table 1. Recent reviews of energy, gas or electricity systems models

Publication	Focus
Energy system models	
(Connolly et al., 2010)	Energy system models
(IRENA, 2017)	Long-term modelling and tools to expand VRE power production
(Hall and Buckley, 2016)	Energy system models in the UK
(Pfenninger et al., 2014)	Energy system models
(Jebaraj and Iniyan, 2006)	Overview of energy models
(Bhattacharyya and Timilsina, 2010)	Review of energy system models
(Després et al., 2015)	Energy system models
Gas models	
(Busch, 2014)	Review of Natural gas models
(Ríos-Mercado and Borraz-Sánchez, 2015)	Optimization problems in natural gas transportation systems: A state-of-the-art review
(Hamedi et al., 2011)	Review of studies related to optimization of network design, flows, and operation
Integrated Gas and Electricity models	
(Bazmi and Zahedi, 2011)	Overview of power sector optimization models
(Ventosa et al., 2005)	Electricity market modelling
(Foley et al., 2010)	Electricity systems models

As seen in Table 1, most reviews were found for energy system models. These did however have limited focus on modelling of the gas system. Several reviews were found regarding modelling of gas systems, but only few were found which focus on integrated gas and power systems, and these all had the main focus on modelling og electricity systems, whereas the link to the district heating sector and biofuel production was negligible.

Within the energy systems models, various modelling frameworks are applied. The mathematical methods used to compute solutions for the energy system models can be distinguished by either optimization or simulation models. *Simulation* models are used to describe future energy system scenarios based on exogenously specified input data, while *optimization* models optimizes the system subjected to specified constraints by using mathematical programming. Energy system scenario models are suitable for assessment of explorative scenarios, while energy system optimization models are suitable for providing solutions for both normative and explorative scenarios (Nielsen and Karlsson, 2007; Pfenninger et al., 2014).

The number of energy system models is huge. However, within Denmark, few energy system models are used. The models vary from each other is various ways. In Table 2, the model type, geographical area, time resolution, and sectors included, are listed.

Table 2 provide an overview of the energy systems models on an overall level. The spatial and temporal resolutions are essential when investigating scenarios with high integration of VRE in energy systems (Hirth, 2013). As different tools have different focuses, they vary with regard to the level of aggregation. Balmorel may e.g. cover a large geographical area with a high spatial resolution e.g. several electricity regions in each country forming part of the Nordpool spot market and more than 20 district heating areas within Denmark. For comparison the two national models, TIMES-DK and EnergyPLAN include two electricity regions and uses electricity price profiles for surrounding countries, while the heating areas are 6 and 3, respectively. STREAM is the most aggregated of the energy systems models with only one electricity region and one district heating area.

The number of energy sectors included in the models and the level of detail in the models vary. All the models include a representation of the electricity and the district heating systems. The transport and industry sectors is represented in some of the models, however, the level of details of the sectors vary from a few exogenously specified demands in some models e.g. Balmorel, STREAM, to a more comprehensive modelling of the industry sector, including different temperature levels of energy services i.e. temperature required for a specific industry process e.g. in TIMES-DK, where three temperature levels are defined, 1) room heating, 2) below 150˚C, 3) over 150˚C.

Table 2. Relevant Danish energy system analysis tool characteristics. Based on (Connolly et al., 2010) but modifications are applied.

	Model type	Geographical area	Time resolution	Electricity	Heat	Transport	Industry	Detailed representation of gas network
BALMOREL	O	International	Hourly	Yes	Partly	Partly	Limited	-
TIMES-DK	O	International/ National	Time-slice	Yes	Yes	Yes	Yes	-
EnergyPLAN	S	National	Hourly	Yes	Yes	Yes	Partly	-
SIFRE/BID	O	International	Hourly	Yes	Yes	Partly	Partly	-
RAMSES	S	International	Hourly	Yes	Partly	Partly	Partly	-
STREAM	S	National	Hourly	Yes	Yes	Yes	Partly	-

Gas as an energy carrier is included in all models. However, the network specific characteristics are only represented in few models, and only in a very simplified way. This emphasizes the research gap and needs for integrated energy systems models that allow comprehensive assessments of the future Danish energy system, which include a detailed representation of the gas system (Brian Vad Mathiesen et al., 2015), (Muditha Abeysekera et al., 2016).

To get inspiration of how gas pipeline networks are modelled, different approaches presented in the literature will be discussed in the following section.

3. Important elements in gas modelling

The gas chain considered in this study includes the production of RE-gas, conditioning, transmission, distribution, storage, trade and final use. Optimizing the process chain related to the production of fossil-gasses i.e. Natural and Shale gas includes exploring, drilling, and extraction and a research area itself and are not further elucidated in this paper.

Heading towards a future Danish energy system, which relies on sustainable and renewable supply portfolios calls for a transition in the gas supply to higher penetrations of renewable based gas. In this paper, three renewable gasses are considered i.e. biogas, syngas, and hydrogen. Biogas is produced from the biological process anaerobic digestion, while syngas is produced from thermal gasification. Hydrogen is produced based on (renewable) electricity. The RE-gasses can achieve the quality of natural gas and thereby be used in the same gas consuming technologies. To achieve natural gas quality, biogas can be upgraded by removing CO_2, while biogas and syngas can achieve natural gas quality through methanisation process i.e. by adding hydrogen. A small amount of ‘raw’ RE-gasses can also be injected into the gas pipeline network.

Gas can be transported in various conditions i.e. as gas, as liquefied natural (renewable) gas (LNG) or as compressed natural (renewable) gas (CNG). Metrics for the economic attractiveness of converting gas into other conditions can be found in (Ríos-Mercado and Borraz-Sánchez, 2015). However, this study will focus on the transportation of gas through the pipeline gas network, which includes storage facilities, both for short- and long-term.

The different types of models used for representing the gas system can be divided into two categories; 1) economic and market models and 2) technical gas network flow models. Both categories provide valuable knowledge about the gas network, however, in all cases a basic understanding of the fundamental gas flow dynamics, which are described through partial differential (highly non-linear) equations, is crucial, both when investigating gas only models or when integrating with other energy vectors e.g. in energy systems models.

Based on physical principles, the flow of gas is described through equations among others including the law of conservation of mass, Darcy’s law and equations of state. Furthermore, in order to compute compressible gas flows in long pipeline networks, novel equations are developed such as Weymouth equation, the Panhandle A and B equations. In (Osiadacz, 1987) and (Crane Co., 1982), a complete overview of fundamental gas flow theory is provided.

The gas pipeline network is complex, and the list of challenges related to solving optimization problems in the gas transportation systems is long. In (Ríos-Mercado and Borraz-Sánchez, 2015) Ríos-Mercado and Borraz-Sánchez review research works related to solving essential elements in the gas pipeline network i.e. physical flows through pipelines, compressor stations, valves and regulators, line-packing, seasonal storage facilities, storages of gas in form of e.g. LNG or fuels, gas quality satisfaction (pooling) (i.e. Wobbe index, gas gravity, heating value), and pipeline capacities. In addition to the elements, an appropriate representation of *gas flows* and *pressure levels* can be obtained relying on fundamental flow equations, described in e.g. (Osiadacz, 1987) and (Crane Co., 1982).

Gas pipeline networks are described through equations according to the state of the system i.e. *steady-state* or *transient*. A steady-state gas flow process describes a system where the gas flow and pressure are constant for individual locations in the system over time, while the process variables are time depended in a transient system.

Optimization problems in gas models can be solved using different mathematical solution methods i.e. linear problems (LP) or non-linear problems (NLP), which are solved using either continuous variables, integer variables (I) or a mix of continuous and integer variables (MI). Combining different methods results in six types of mathematical model solution methods i.e. LP, NLP, ILP, INLP, MILP, and MINLP, where LP and MILP is the most common in energy systems models.

4. Conceptual Model

To investigate the transition of the Danish energy system, a system perspective is needed which allows assessment of possible synergies across different sectors. A research gap exists with regard to methods and tools that enable modelling and simulation of integrated energy systems (Brian Vad Mathiesen et al., 2015; Muditha Abeysekera et al., 2016). Therefore, developments of energy system models, which can facilitate integrated modelling of the entire energy system including the power, district heating, gas, and transport systems are of high importance for the integrated energy system modelling field.

In the FutureGas research project, the conceptual model for the gas systems will be applied to an existing energy system model, which has the important characteristics, which was discussed in the section of integrated energy systems models:

- Bottom-up modelling
- Optimization– investments and operation
- Normative and explorative assessment
- High spatial and temporal resolution
- Economic perspective – partial equilibrium model – using economic dispatch
- Possibility to link to gas technical detailed models - in order to validate results and elucidate technical challenges

Among the reviewed energy system models, Balmorel fulfills the above requirements for model characteristics and thus will be used as a base model for implementing the conceptual model of the gas system.

Balmorel is an energy system optimization model, which currently includes both the electricity and district heating sectors. Balmorel is a bottom-up model, which assumes perfect competetive markets. Furthermore, the model is a deterministic partial equilibrium model, with the objective of maximizing social surplus by minimizing system costs.

The Balmorel model entails a comprehensive representation of technical components in the current energy system e.g. electricity and heat generation technologies and transmission capacities, and furthermore, computes the conversion of primary energy to electricity and district heat which, subsequently, are transferred to the end-user through the transmission and the distribution grid. Balmorel allows both exogenous and endogenous investment decisions and has previously been used for both long-term investments planning and for the planning of short-term operation.

The model is mostly run in a LP mode, however, a MILP version exists, which allows modelling of with integers e.g. unit commitment. To model the gas system MILP will be applied.

The conceptual model framework will improve the Balmorel model by modelling the future gas system, which includes production and conditioning of RE gases, as well as, transmission, storage, trade and use of all gases considered.

To illustrate the model developments contributions to the existing Balmorel model, Figure 1(top) show a diagram of the current Balmorel model, and Figure 1(bottom) show the Balmorel model after implementation of the conceptual model.

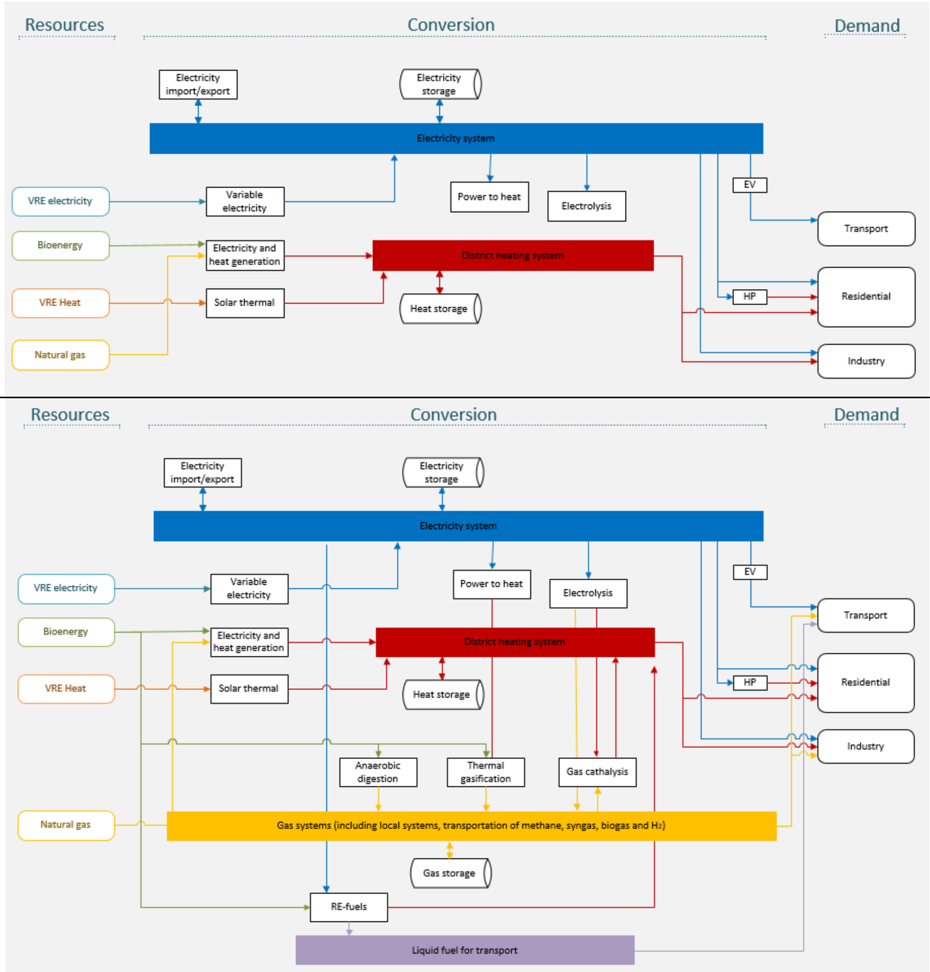

Figure 1. A conceptual model for the integrated energy system in Balmorel. Current modelling framework in Balmorel (top), improved modelling framework including modelling of the gas system (bottom).

Implementing the conceptual model in Balmorel adds an additional dimension to the model. Thereby a more holistic perspective of the integrated energy system can be used to assess future energy scenarios.
The improved model allows couplings between the gas, power, and district heating networks, as illustrated in Figure 1.

The model developments furthermore include:

- Modelling gas flow with different pressure levels
- Modelling of gas storage, both short-term (line-pack) and long-term (seasonal) storage
- Representing gas losses and leakages
- Modelling collection of local biomass resources
- Modelling renewable gas production and upgrading and methanization of renewable gas to achieve natural gas quality
- Modelling P2G technologies and gas heat pumps
- Representing different gas qualities
- Modelling the potential demand from industry, transport and individual heating

Furthermore, important competing technologies, such as electric vehicles for transport, or heat pumps for individual heating will be included to assess the future role of gas fairly.
The framework, details, and assumptions for implementing the conceptual model in the Balmorel are described in the following. Balmorel is programmed in the General Algebraic Modelling System (GAMS), which is a high-level modelling language suitable for mathematical programming problems.

The presented modelling framework describes a simplified representation of the gas system compared to high detailed gas technical focused systems models. However, the improved Balmorel model will be soft-linked to the gas-system model allowing insight into physical gas constrains. Furthermore, by soft-linking Balmorel with a gas-system model, results from Balmorel will be evaluated and validated.

2.1. Gas Flow Modelling

The gas flow in the pipeline network will be derived from fundamental gas flow theory, as described in (Osiadacz, 1987). As highlighted in the literature review, different approaches for modelling the gas flow in pipeline networks are applied. However, in this model, gas flows are modelled according to the approach presented in (Bregnbæk and Stidsen, 2005) and (Bregnbæk, 2007).

The general model is described through a linear mass-flow balance equation and non-linear equations for momentum over the pipes through a relationship between upstream pressure, flow rate, and downstream pressure. A quasi steady-state model is formulated encompassing the linear mass-balance equation using piecewise-linearization of the non-linear equations. Additional binary variables indicating flow directions are introduced resulting in a mixed-inter programming problem. Utilizing a heuristic approach, the mixed-integer programming problem is solved as a linear programming problem.

2.2. Modelling of storage

Currently, in Denmark, two storage facilities are installed enabling seasonal storage of gas. The total capacity is equivalent to three winter months of Danish gas consumption. This important component in the gas network is modelled in Balmorel as a storage facility, where the level in the storage at time t has to equal the level at time t-1.

The operation of the gas pipeline network allows short-term storage of gas in the pipelines, also known as line-packing. This is an essential element in the daily operation enabling flexibility in the short-term balancing of gas supply and demand. Even though some studies argues that steady-state cannot describe the actual dynamic of the gas system including the line-pack (Clegg and Mancarella, 2016; Pambour et al., 2016), the line-pack will be modelled in a simplified way in this model according to the approach presented in (Midthun, 2007).

2.3. Modelling renewable gas production

Modelling of renewable gas production (biogas from anaerobe digestion, syngas from thermal gasification, biomethane from upgrading and methanization technologies, and hydrogen) is increasingly important to include in energy system analysis, as the Danish system is heading towards independencies of fossil fuels.

To facilitate the modelling of renewable gas and collection of local bioenergy resources, model developments in the spatiotemporal network optimization model, OptiFlow is facilitated according to the approach presented in (Bramstoft et al., 2017). The OptiFlow model is hard-linked with Balmorel, allowing modelling the gas chain from transport of local biomass resource to renewable gas production, through storage facilities to end consumers. The developments in OptiFlow will enable modelling of various bioenergy inputs for different processing technologies, e.g. biological- and thermal- gasification as well as electrolysis technologies.

2.4. P2G technologies and gas heat pumps

Additional modelled technologies, which physically couple energy vectors, include electrolysers and gas heat pumps. Electrolysis is a promising technology in the sustainable transition and is thus modelled in Balmorel: To specify a hydrogen demand, electrolysis which is modelled according to (Karlsson and Meibom, 2008), the modelling encompasses: production and storage of hydrogen, injection of limited quantities (10%) into the gas pipeline network as well as use in fuel cells for power production following the properties of a backpressure plant. Hydrogen is also used for production of renewable gases and biofuels.

Gas heat pumps could potentially play a role in the future (GrønEnergi and Ea Energy Analyses, 2016). In Balmorel, gas heat pumps will be modelled according the framework addressed in (GrønEnergi and Ea Energy Analyses, 2016).

2.5. Representing gas qualities

The problem of representing different gas qualities is also known as the pooling problem where gas with different qualities enters the same pipeline network. The gas quality is calculated according to different parameters i.e. Wobbe index, methane number, gas gravity, heating value. However, in this modelling framework, a simplified approach for representing and ensuring an adequate gas quality is applied. Based on previous studies e.g. (Abeysekera et al., 2016, 2014; Guandalini et al., 2015; Kvist, 2011; Pellegrino et al., 2017), a maximum limit (e.g. 10%) of alternative gas injection in the natural gas grid is specified. The modelling of gas qualities will be coherent with the modelling framework applied for gas transportation and line pack.

2.6. Modelling industry

Currently, gas is heavily used in industries, however, in a future sustainable energy sector, some gas demands might be substituted by other energy carriers e.g. electricity or district heating. In particular, low-temperature energy services in industries will likely shift to other energy carriers, while gas may still be used in industries, which require high process temperatures due to the physical properties of gas. Thus, in the improved Balmorel model, the industry sector will be modelled according to different temperature levels of energy services i.e. temperature required for a specific industry process. The modelling framework applied for the industry is presented in (Wiese and Baldini, 2017).

2.7. Modelling transport sector

The modelling framework for the transport sector is as follows: The demands for transport fuels are determined in the energy system model TIMES-DK. OptiFlow will be developed to model the network of biofuel production and subsequently hard-linked to Balmorel. Finally, the co-simulation of OptiFlow and Balmorel is soft-linked to TIMES-DK, with the purpose of transferring different demands for fuels in the transport sector. In this way, the co-simulation of OptiFlow and Balmorel leads to the socio-economic optimal system, given specified transport demands from TIMES-DK.

2.8. Geographical resolution

The spatial resolution is important when modelling locally distributed RE-gas production facilities as well as district heating. The geographical resolution should represent a sufficiently detailed picture of the Danish gas system including future challenges. The spatial resolution will be determined by the potentials for renewable gas production, population and heat density, and according to the existing gas infrastructure.

5. The Value of the Conceptual Model

The developed conceptual model in this paper will (when it is implemented in Balmorel) improve the current state of modelling integrated energy systems by combining the above-mentioned features with: *1) Integrated modelling with strong representation of the electricity and district heating sectors with the industry and transport sectors*, which may become the main consumers of gas in the future. In comparison, many of the analyses of power to gas only represent gas as a fuel used by the electricity sector e.g. (Belderbos et al., 2015; de Boer et al., 2014; Jentsch et al., 2014; Palzer and Henning, 2014; Varone and Ferrari, 2015). *2) Modelling of the surrounding electricity and gas markets*, thereby facilitating modelling of competing flexibility measures. Many system analyses focus on one country with no representation of the surrounding markets or maximum a representation through a power price interface e.g. (Belderbos et al., 2015; Daniëls et al., 2014; Sterner, 2009). The transmission of gas through Denmark may however play an important role in terms of contributing to the economy of maintaining the gas grid. *3) Investment optimization along with operation optimization.* Most models focus only on operation optimization e.g. (Daniëls et al., 2014; Sterner, 2009), but in a future where energy systems become increasingly integrated, it becomes difficult to foresee optimal investment decisions without tools which facilitate optimization of investments. *4) High geographic resolution*, which facilitates modelling the restrictions related to distribution of gas and district heating as well as availability of local biomass resources. In comparison, most models have one or a few areas within the modelled system e.g. (Belderbos et al., 2015; Daniëls et al., 2014; B. V. Mathiesen et al., 2015; Palzer and Henning, 2014; Sterner, 2009; Vandewalle et al., 2014; Varone and Ferrari, 2015). *5) Option to optimize with unit commitment*, unlike e.g. (Daniëls et al., 2014; Jentsch et al., 2014; B. V. Mathiesen et al., 2015; Palzer and Henning, 2014; Sterner, 2009; Varone and Ferrari, 2015) *6) Decommissioning of existing plants*, making it possible to model the stepwise transition towards future scenarios with high shares of RE. Frequently, the existing system is completely replaced with new plants in an analysis of a future energy system. One example of this is (Palzer and Henning, 2014).

This study thereby contributes to the integrated energy systems modelling field by presenting a modelling framework enabling a holistic modelling of the integrated energy system and allowing comprehensive assessments of the future Danish energy system and the transition towards it, including a detailed representation of the gas system.

6. References

Abeysekera, M., Rees, M., Wu, J., 2014. Simulation and analysis of low pressure gas networks with decentralized fuel injection. Energy Proceedia 61, 402–406. doi:10.1016/j.egypro.2014.11.1135

Abeysekera, M., Wu, J., Jenkins, N., Rees, M., 2016. Steady state analysis of gas networks with distributed injection of alternative gas. Applied Energy 164, 991–1002. doi:10.1016/j.apenergy.2015.05.099

Bazmi, A.A., Zahedi, G., 2011. Sustainable energy systems: Role of optimization modeling techniques in power generation and supply - A review. Renewable and Sustainable Energy Reviews 15, 3480–3500. doi:10.1016/j.rser.2011.05.003

Belderbos, A., Delarue, E., D'haeseleer, W., 2015. Possible role of Power-to-Gas in future energy systems 1–5. doi:10.1109/EEM.2015.7216744

Bhattacharyya, S.C., Timilsina, G.R., 2010. A review of energy system models. International Journal of Energy Sector Management 4, 494–518. doi:10.1108/17506221011092742

Bramstoft, R., Græsted Jensen, I., Pizarro Alonso, A., Münster, M., Ravn, H., 2017. Modelling of Renewable Gas in the Future Energy System. International Gas Union Research Conference, Rio 2017 1–10.

Bregnbæk, L., 2007. The Balmorel Model Structure : The Gas add-on Module.

Bregnbæk, L., Stidsen, T.K., 2005. Natural Gas Supply in Denmark - A Model of Natural Gas Transmission and the Liberalized Gas Market A Masters Thesis submitted to the department of Informatics and Mathematical Modeling at the Technical University of Denmark.

Busch, L.K., 2014. Review of Natural Gas Models 0–32.

Clegg, S., Mancarella, P., 2016. Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems. IEEE Transactions on Sustainable Energy 7, 718–731. doi:10.1109/TSTE.2015.2497329

Connolly, D., Lund, H., Mathiesen, B. V., Leahy, M., 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy 87, 1059–1082. doi:10.1016/j.apenergy.2009.09.026

Crane Co., 1982. Flow Of Fluids Through Valve, Fittings and Pipe. Technical Paper No. 410 M.

Daniëls, B., Seebregts, A., Joode, J., Smekens, K., Van Stralen, J., Dalla Longa, F., Schoots, K., Grond, L., Holstein, J., 2014. Exploring the role for power-to-gas in the future Dutch energy system.

Danish Commission of Climate Change Policy, 2010. Grøn energi.

Dansk Energi, 2015. Gassystemets fremtid og udfasning af naturgas Analyse nr, 1–61.

de Boer, H.S., Grond, L., Moll, H., Benders, R., 2014. The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels. Energy 72, 360–370. doi:10.1016/j.energy.2014.05.047

Després, J., Hadjsaid, N., Criqui, P., Noirot, I., 2015. Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. Energy 80, 486–495. doi:10.1016/j.energy.2014.12.005

Di Leo, S., Pietrapertosa, F., Loperte, S., Salvia, M., Cosmi, C., 2015. Energy systems modelling to support key strategic decisions in energy and climate change at regional scale. Renewable and Sustainable Energy Reviews 42, 394–414. doi:10.1016/j.rser.2014.10.031

Energinet.dk, 2015a. Energikoncept 2030 - Sammenfatning 20. doi:10.1017/CBO9781107415324.004

Energinet.dk, 2015b. Gassens rolle i omstillingen.

Energinet.dk, 2015c. Energikoncept 2030 - Baggrundsrapport.

Energinet.dk, 2014. Strategisk energiplanlægning - Danmark 2025, 2035 og 2050 1–12.

Energistyrelsen, 2014. Gasinfrastrukturen - Den fremtidige anvendelse af gasinfrastrukturen.

Foley, A.M., Ó Gallachóir, B.P., Hur, J., Baldick, R., McKeogh, E.J., 2010. A strategic review of electricity systems models. Energy 35, 4522–4530. doi:10.1016/j.energy.2010.03.057

Geidl, M., Koeppel, G., Favre-Perrod, P., Klöckl, B., Andersson, G., Fröhlich, K., 2007. Energy hubs for the future. IEEE Power and Energy Magazine 5, 24–30. doi:10.1109/MPAE.2007.264850

GrønEnergi and Ea Energy Analyses, 2016. Energiforsyning 2030 - Baggrundsrapport.

Guandalini, G., Colbertaldo, P., Campanari, S., 2015. Dynamic modeling of natural gas quality within transport pipelines in presence of hydrogen injections. Applied Energy 185, 1712–1723. doi:10.1016/j.apenergy.2016.03.006

Hall, L.M.H., Buckley, A.R., 2016. A review of energy systems models in the UK: Prevalent usage and categorisation. Applied Energy 169, 607–628. doi:10.1016/j.apenergy.2016.02.044

Hamedi, M., Farahani, R.Z., Esmaeilian, G., 2011. Optimization in Natural Gas Network Planning, Logistics Operations and Management. Elsevier Inc. doi:10.1016/B978-0-12-385202-1.00019-0

Hirth, L., 2013. The market value of variable renewables. The effect of solar wind power variability on their relative price. Energy Economics 38, 218–236. doi:10.1016/j.eneco.2013.02.004

IEA, 2016. Nordic Energy Technology Perspectives 2016. Energy Technology Policy Division 269. doi:10.1787/9789264257665-en

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)].

IRENA, 2017. Planning for the Long-Term Modelling and Tools To Expand.

Jebaraj, S., Iniyan, S., 2006. A review of energy models. Renewable and Sustainable Energy Reviews 10, 281–311. doi:10.1016/j.rser.2004.09.004

Jentsch, M., Trost, T., Sterner, M., 2014. Optimal use of Power-to-Gas energy storage systems in an 85% renewable energy scenario. Energy Procedia 46, 254–261. doi:10.1016/j.egypro.2014.01.180

Karlsson, K., Meibom, P., 2008. Optimal investment paths for future renewable based energy systems-Using the optimisation model Balmorel. International Journal of Hydrogen Energy 33, 1777–1787. doi:10.1016/j.ijhydene.2008.01.031

Kvist, T., 2011. Establishment of a biogas grid and interaction between a biogas grid and a natural gas grid.

Lund, H., Hvelplund, F., Vad Mathiesen, B., Aalborg Univ. Dept. of Development and Planning., 2011. Coherent energy and environmental system analysis. A strategic research project financed by The Danish Council for Strategic Research Programme Commission on Sustainable Energy and Environment.

Mathiesen, B.V., Drysdale, D., Chozas, J.F., Ridjan, I., Connolly, D., Lund, H., 2015. A Review of Smart Energy Projects and Smart Energy State-of-the-Art.

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Ostergaard, P.A., Möller, B., Nielsen, S., Ridjan, I., KarnOe, P., Sperling, K., Hvelplund, F.K., 2015. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy 145, 139–154. doi:10.1016/j.apenergy.2015.01.075

Meibom, P., Hilger, K.B., Madsen, H., Vinther, D., 2013. Energy comes together in Denmark: The key to a future fossil-free Danish power system. IEEE Power and Energy Magazine 11, 46–55. doi:10.1109/MPE.2013.2268751

Midthun, K.T., 2007. Optimization models for liberalized natural gas markets.

Muditha Abeysekera, A., Wu, J., Jenkins, N., 2016. HubNet Position Paper Series Integrated energy systems: An overview of benefits, analysis methods, research gaps and opportunities Title Integrated energy systems: An overview of benefits, analysis, research gaps and opportunities.

Münster, M., Morthorst, P.E., Larsen, H. V., Bregnbæk, L., Werling, J., Lindboe, H.H., Ravn, H., 2012. The role of district heating in the future Danish energy system. Energy 48, 47–55. doi:10.1016/j.energy.2012.06.011

Nielsen, S.K., Karlsson, K., 2007. Energy scenarios: A review of methods, uses and suggestions for improvement. International Journal of Global Energy Issues 27, 302–322. doi:10.1504/IJGEI.2007.014350

Osiadacz, A., 1987. Simulation and analysis of gas networks. Gas Engineering - Mathematical models, E. & F.N. Spon Ltd.

Palzer, A., Henning, H.M., 2014. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part II: Results. Renewable and Sustainable Energy Reviews 30, 1019–1034. doi:10.1016/j.rser.2013.11.032

Pambour, K.A., Erdener, B.C., Bolado-Lavin, R., Dijkema, G.P.J., 2016. Development of a Simulation Framework for Analyzing Security of Supply in Integrated Gas and Electric Power Systems 1–32. doi:10.20944/preprints201611.0109.v1

Pellegrino, S., Lanzini, A., Leone, P., 2017. Greening the gas network - The need for modelling the distributed injection of alternative fuels. Renewable and Sustainable Energy Reviews 70, 266–286. doi:10.1016/j.rser.2016.11.243

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews 33, 74–86. doi:10.1016/j.rser.2014.02.003

Ríos-Mercado, R.Z., Borraz-Sánchez, C., 2015. Optimization problems in natural gas transportation systems: A state-of-the-art review. Applied Energy 147, 536–555. doi:10.1016/j.apenergy.2015.03.017

Sterner, M., 2009. Bioenergy and renewable power methane in integrated 100% renewable energy systems. Renewable Energy and Energy Efficiency.

Vandewalle, J., Bruninx, K., D'haeseleer, W., 2014. A mixed-integer linear operational model of a coupled electricity , natural gas and carbon energy system with power to gas.

Varone, A., Ferrari, M., 2015. Power to liquid and power to gas: An option for the German Energiewende. Renewable and Sustainable Energy Reviews 45, 207–218. doi:10.1016/j.rser.2015.01.049

Ventosa, M., Baíllo, Á́., Ramos, A., Rivier, M., 2005. Electricity market modeling trends. Energy Policy 33, 897–913. doi:10.1016/j.enpol.2003.10.013

Wiese, F., Baldini, M., 2017. Pathways to Carbon Neutral Industrial Sectors: Integrated Modelling Approach with High Level of Detail for End-use Processes, in: 12th. Conference on Sustainable Development of Energy, Water, and Environment Systems, Dubrovnik 2017. p. 2017.

Wu, J., Yan, J., Jia, H., Hatziargyriou, N., Djilali, N., Sun, H., 2016. Integrated Energy Systems. Applied Energy 167, 155–157. doi:10.1016/j.apenergy.2016.02.075