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MODELLING OF RENEWABLE GAS IN THE FUTURE ENERGY SYSTEM

Abstract

The Danish government has set ambitious targets regarding the future exploitation of renewable energy in the Danish energy system. In many respects, the prospective increase in renewable energy resources (RES) will substantially impact the entire future Danish energy system. Renewable gas is a fuel that can contribute to the sustainable transition towards an energy system independent of fossil fuels in the long-term.

This study investigates the role of renewable gas production in a renewable based Danish energy system. To facilitate the modelling of renewable gas, improvements of the structure in the spatiotemporal optimization model OptiFlow is carried out. The OptiFlow model is hard-linked to the existing energy system model Balmorel, allowing modelling the gas chain from up-stream renewable gas production, through storage facilities to end consumers. Balmorel is a bottom-up, deterministic, partial equilibrium model, which minimizes systems costs under perfect market conditions. The developments in OptiFlow enable modelling of various processing technologies, e.g. biological- and thermal- gasification as well as electrolysis technologies. The co-simulation of OptiFlow and Balmorel leads to the socio-economic optimal system, where investments and operations optimization is facilitated for the integrated electricity, district heating, and gas system.

The results of this study show that production of RE-gas is socio-economically attractive in all the investigated scenarios. Furthermore, the results show that RE-gas directly injected into the natural gas pipeline network is preferred. The analysis show that geographical allocation of resources has an impact on the results. Moreover, it was shown that hydrogen was not produced in periods with high electricity prices.

Keywords: Integrated energy system modelling; Gas system; Renewable gas; Balmorel model; OptiFlow model

Introduction

The Danish government has announced the ambitious long-term vision of achieving an energy system independent of fossil fuels by 2050. In many respects, the prospective increase in renewable energy resources (RES) will substantially impact the entire future Danish energy system, and in particular the gas system.

Today, gas is a key energy carrier in the Danish energy system, accounting for 20% of the total energy consumption; seasonal gas storages dimensioned to cover the consumption during approximately three winter months. Current Danish gas demand is primarily supplied by the large natural gas reserves in the North Sea, making Denmark self-sufficient with natural gas. In addition, local biogas is becoming economically attractive for both local use and grid injection accounting for 3% of the Danish gas consumption in 2016. The increasing trends of locally distributed renewable gas (RE-gas) production technologies entering the gas market add an interesting new dimension to the Danish gas supply.

The development of the gas system is important to investigate given the long-term energy policy targets, declining gas consumption, and limited natural gas resources in the North Sea - estimated to be depleted by 2040. To facilitate an effective and cost-efficient green transition, gas as a fuel and the gas infrastructure might play a key role. The sustainable transition of the Danish energy system has previously been studied using integrated energy assessment tools [1], [2], [3]. However, few studies have addressed future energy system scenarios with detailed focus on the gas system, integrated within the broader energy system [4], [5], [6], [7], [8]. The studies [7]–[12] points out the main potential benefits for future use of the gas infrastructure and utilisation of RE-gas i.e. 1) gas can be produced flexibly from renewable resources or VRE based electricity, 2) the existing gas infrastructure can allow seasonal storage of RE-gas, 3) RE-gas can be used in the transport sector, in industrial processes, and to generate electricity in peak load situations, 4) gas can be converted into liquid fuels. Thus, RE-gas can potentially play a prominent role in the future Danish energy system with high shares of variable renewable energy.

This study investigates the role of renewable gas production (biogas, synthetic natural gas (SNG), biomethane and hydrogen), RE-gas storage, and demand in a future renewable based Danish energy system. As the Danish energy system will undergo a radical transformation towards stronger sector integration, [11], [13], a holistic system perspective is needed to assess the future socio-economic value of RE-gas utilization. To facilitate the modelling of renewable gas, model developments in the spatiotemporal network optimization model, OptiFlow, is undertaken. Furthermore, OptiFlow is hard-linked to the energy system model Balmorel, allowing an integrated energy assessment of RE-gas production. This framework enables detailed modelling of the gas chain from up-stream renewable gas production through storage facilities and to end consumers. It accounts for the spatial and temporal system integration between gas, electricity, and district heating systems.

Following the introduction, Section 2 describes the framework utilized to model locally distributed renewable gas production as a part of the future integrated Danish energy systems. Section 3, describes the scenario framework along with the main data and assumptions. In Section 4, the scenario results obtained from co-simulating OptiFlow and Balmorel are presented and discussed. Finally, Section 5 provides conclusions and future work.

Modelling of renewable gas in integrated energy systems

To facilitate the modelling of renewable gas in the integrated Danish energy system, the spatiotemporal network optimization OptiFlow is hard-linked to the existing energy system model Balmorel.

Balmorel

Balmorel is an open-source energy system optimization model which currently includes the electricity and combined heat and power sectors. The model relies on a bottom-up modelling approach and is, furthermore, a deterministic, partial equilibrium model which assumes perfect competition. The objective of the model is to maximize social surplus and thereby provide the least-cost solution of the system, which includes operational costs and annualized investment costs of the power and district heating system.

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. Balmorel computes the conversion of primary energy to electricity and heat which, subsequently, are transferred to the end-user through the transmission and the distribution grid. The Balmorel model allows both exogenous and endogenous investment decisions.

The temporal resolution in Balmorel is user-defined and allow either hourly or time-aggregated simulations. Geographically, the Balmorel model used in this paper covers the Nordic countries and Germany. This study focuses on Denmark and thus the district heating system is modelled with a higher resolution, including 35 district heating areas in Denmark wherein heat demand is balanced, while modelling few district heating areas in the surrounding countries.

The Balmorel model is suitable for both long-term planning and for short-term operation e.g. of dispatchable power plants in both the power and the district heating sectors.

The Balmorel model has been developed in a series of research projects, however, this study employs the model version from the TOPWASTE project.

OptiFlow - and the link to Balmorel

OptiFlow is a spatiotemporal network optimization model, which was originally developed in the TOPWASTE project. The objective of OptiFlow is to maximize social welfare. The model is formulated as a general network model, allowing OptiFlow to optimize the networks that represent the energy chain for RE-gas production.

OptiFlow can be simulated as a stand-alone model, however, in this study, OptiFlow is co-simulated with Balmorel to represent the strong couplings between the RE-gas production and the energy system.

OptiFlow models RE-gasses as an integrated energy systems assessment include is facilitated with a high spatial resolution. The RE-gas modelling includes among others settings, endogenous investment decisions, modelling of RE-gas production technologies and storage facilities, and modelling of costs related to transport of resources which can influence the economic attractiveness of renewable gas production.

In this study, OptiFlow is used to model the energy chain from renewable energy resources, to transportation systems, technology processes, and finally the RE-gas flows to the final consumption. The OptiFlow-Balmorel hard-link is denoted as Buffer processes i.e. simultaneous exchanges between the models of: 1) monetary values through the objective function, 2) electricity and district heating generation and consumption through the electricity and heat balancing equations, 3) RE-gas with a quality of natural gas modelled using both the hard-linking to the electricity and heat balancing equations and a soft-link to the natural gas price market.

The Danish gas system is assumed to be maintained. Therefore, the modelling framework in OptiFlow allows RE-gas with natural gas quality to be injected into the 40 bar gas pipeline network.

Figure 1 illustrates a simplification of the RE-production network implemented in OptiFlow and the interplay with Balmorel.

In OptiFlow different plant types are allowed to be installed in specific areas. Thermal gasification plants producing bio-SNG with natural gas quality are geographically placed in central areas, while biogas production plants and thermal gasification plants producing syngas which can be used in gas engines for electricity and heat generation are located in smaller and medium size areas.

The transport of locally biomass resources might influence the economic feasibility of RE-gas producing technologies. Thus, transport by trucks of local Danish resources is modelled in OptiFlow.

Resources are transported to RE-gas production plant storage facilities on a weekly time scale. However, the RE-gas production from electrolysis and thermal gasification is modelled at an hourly time-step level to represent the variations in the electricity and district heating prices.

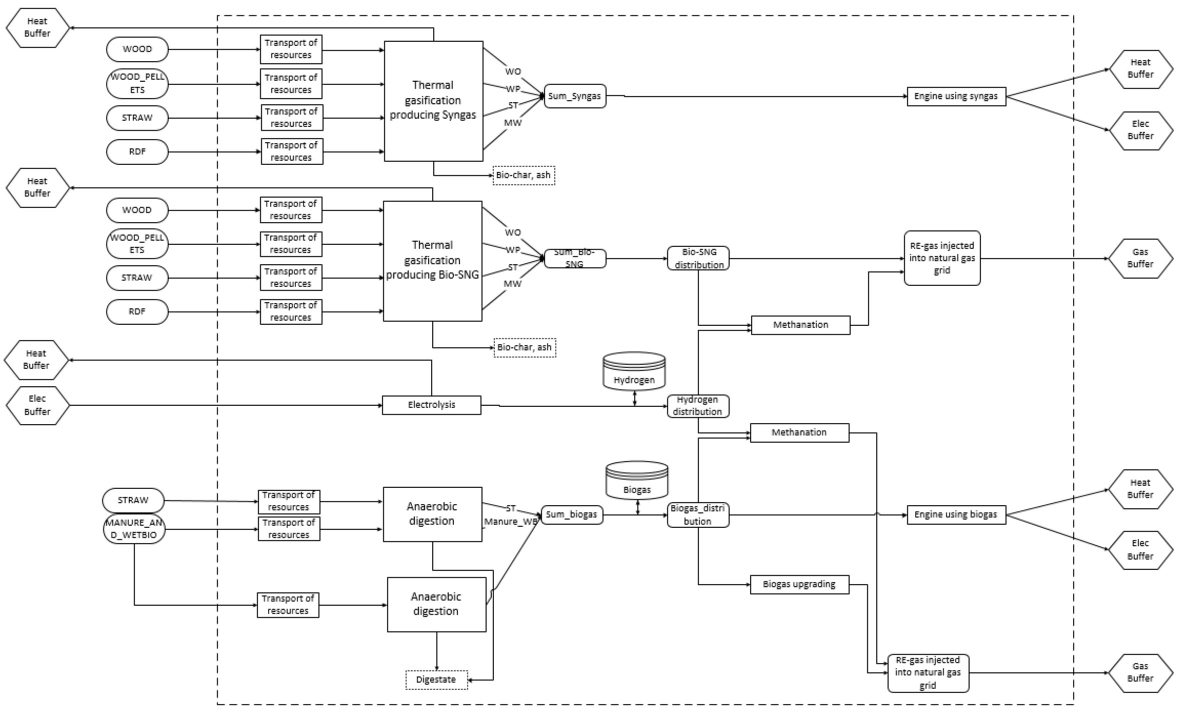

Figure 1
The network implemented in OptiFlow.

Main scenario and data assumptions

In this study, the co-simulation of OptiFlow and Balmorel leads to the socio-economic optimal system, given specified demands, fuel potentials, and fuel prices. A base scenario is conducted with the input parameters presented in this section. However, two sensitivity scenarios are conducted to investigate effects on the RE-gas production by varying the price of natural gas while keeping the CO_2 price constant.

Demands

The electricity and district heating demands by 2050 are extracted from the Nordic Energy Technology Perspective (NETP) [14]. The electricity demands are specified according to the electricity regions, while district heating demands are distributed based on the areas.

Potentials

The national resources available for RE-gas productions are taken from [15] and are listed in Table 1.

Table 1: National fuel potentials for energy purposes

Fuel potentials for RE-gas production in Denmark		
Manure, wet biomass	70	PJ
Straw	13	PJ
Refuse derived fuel (RDF)	5	PJ
Wood	No restrictions import is allowed	
Wood Pellets		

The national resources are implemented in OptiFlow according to the geographic area for the harvesting of resources e.g. manure and wetbio resources are spatially allocated in the 35 areas in OptiFlow based on [16].

Fuel prices

Fuel prices and CO_2 prices are adopted from the Carbon-Neutral Scenario in NETP [14], which corresponds to the 2˚C scenario in the Energy Technology Perspective (ETP) conducted by IEA [17]. The prices represent a sustainable future dominated by renewable based energy production. The green energy transition is motivated by the high CO_2 prices, representing the marginal abatement cost. In this future system, the demand for fossil-fuels is low, resulting in low fossil-fuel prices. The CO_2 and fuel prices used in this study are shown in Table 2.

Table 2: Fuel and CO_2 prices

Fuel prices		
Natural Gas	6.98	€/GJ
Coal	2.35	€/GJ
Fueloil	11.67	€/GJ
Gas oil	14.25	€/GJ
Oil	16.40	€/GJ
Straw	8.92	€/GJ
Wood chips	9.91	€/GJ
Wood pellets	11.71	€/GJ
Nuclear - Uranium	1.94	€/GJ
CO_2 price	135.8	€/ton CO_2

Technologies related to RE-gas:

The technologies assessed in this study includes anaerobic digestion, thermal gasification, electrolysis, upgrading technologies, catalytic methanation of CO_2, and storage facilities.

Anaerobic digestion

In this study, biogas produced by anaerobic digestion can use two types of resources i.e. a mixture of manure and wet biomass, and straw. The methane percentage of the biogas is assumed to be 65%. The biogas can be upgraded to biomethane by removal of CO_2. Moreover, methane can be produced by catalytic methanation of the pure CO_2.

The by-product from the anaerobic digestion is digestate. In this study, no value is assigned to the digestate, nor to the increased recycling of nutrients and fibers from straw used in anaerobic digestion.

Thermal gasification

In this study, the thermal gasification plants can use four resources: wood, straw, wood pellets, and refuse derived fuel (RDF). The study distinguishes between the two types of RE-gasses produced by the thermal gasification plants such as syngas, which can be used in combined heat and power production and bio-SNG, which can be injected into the gas grid. To produce bio-SNG from syngas, CO_2 is removed, and a water-gas shift reaction is used.

In the thermal gasification plants, excess heat is produced. This study assumes this excess heat to be used for district heating. Moreover, by-products from the process i.e. ash and bio-char, contains carbon and nutrients which can be recycled to the earth. As for the digestate, this study does not assign a value to the by-product from thermal gasification.

Electrolyses and methanation of CO_2:

Hydrogen can be produced by electrolysis using electricity as input. Flexible production of hydrogen can potentially play a key role in the future Danish energy system [18], however, in this study, hydrogen is only modelled to be used for the catalytic methanation of CO_2. According to [15], by using the catalytic methanation technology on biogas, 1.5 times more biomethane can be produced, while 2 times the bio-SNG can be produced when using the technology in combination with syngas.

Techno-economic data for RE-production technologies

The techno-economic data for RE-gas production technologies are taken from [15] and is presented in Table 3. The lifetime of the biogas upgrading technology is assumed to be 15 years, while the lifetime of the other technologies is estimated to be 20 years.

Table 3
Techno-economic parameters for RE-gas production technologies.

	Investment costs (M€/GJ/h)	Fixed O&M costs (k€/GJ/h)	Variable O&M costs (€/GJ/h)	Fuel efficiency (RE-gas output)	Output heat
AD	0.401	-	12.9	40%	-
AD – mix fuel	0.297	-	14.2	47.%	-
Biogas upgrading	0.117	2.9	-	100%	-
TG -SYNGAS	0.294	5.7	0.7	85%	5%
TG – Bio-SNG	0.424	11.6	0.7	70%	20%
Electrolyzers	0.099	3.0	-	79%	-
Catalytic methanation of CO_2	0.137	6.8	-	200% for syngas 150% for biogas	17%

AD: Anaerobic digestion; **TG:** Thermal gasification

Results

This section presents the scenario results obtained by co-simulating OptiFlow and Balmorel.

RE-gas production is strongly coupled with the electricity and district heating sectors. Gas can therefore serve as an energy carrier that will strength the couplings between energy vectors in future energy systems. Therefore, RE-gas productions are assessed using a holistic energy system perspective.

Electricity and district heating systems

The simulation year in this study is 2050. It is an underlying assumption that no existing generation capacity is installed in the system, meaning that the energy system is built up based on technology costs in 2050. With the high marginal CO_2 abatement cost in 2050, this leads to a renewable-based energy system. By 2050, the integrated Nordic and German electricity system is dominated by variable renewable energy (VRE) sources, with 50% wind and 11% solar PV. The well-functioning Nordic electricity market enables the 29% Nordic hydropower to be efficiently used for balancing variations in electricity production. The remaining 10% of the electricity generation mix is covered by thermal capacity.

The generation mix in the both the Danish and in the integrated Nordic and German system is only presented for a Base scenario since the energy system configuration is not varying significantly between the three future scenarios.

Figure 2 presents the configuration of the Danish electricity and district heating production by 2050. The figure illustrates a scenario, where the Danish electricity generation portfolio is dominated by wind and solar PV, and the district heating sector is electrified and is using the Danish waste resources.

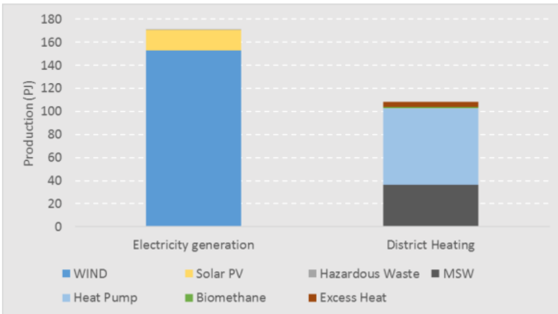

Figure 2
Danish electricity and district heat production

In this future scenario, with high penetrations of VRE generation, electricity prices tend to be volatile. The average electricity price in the scenarios is 48 €/MWh, with 1 €/MWh difference between West- and East of Denmark. More volatile electricity prices provide the incentive for flexible power-to-gas technologies to produce hydrogen in time periods with low electricity prices.

RE-gas production

The results related to RE-gas production obtained by co-simulating OptiFlow and Balmorel is presented in Figure 3.

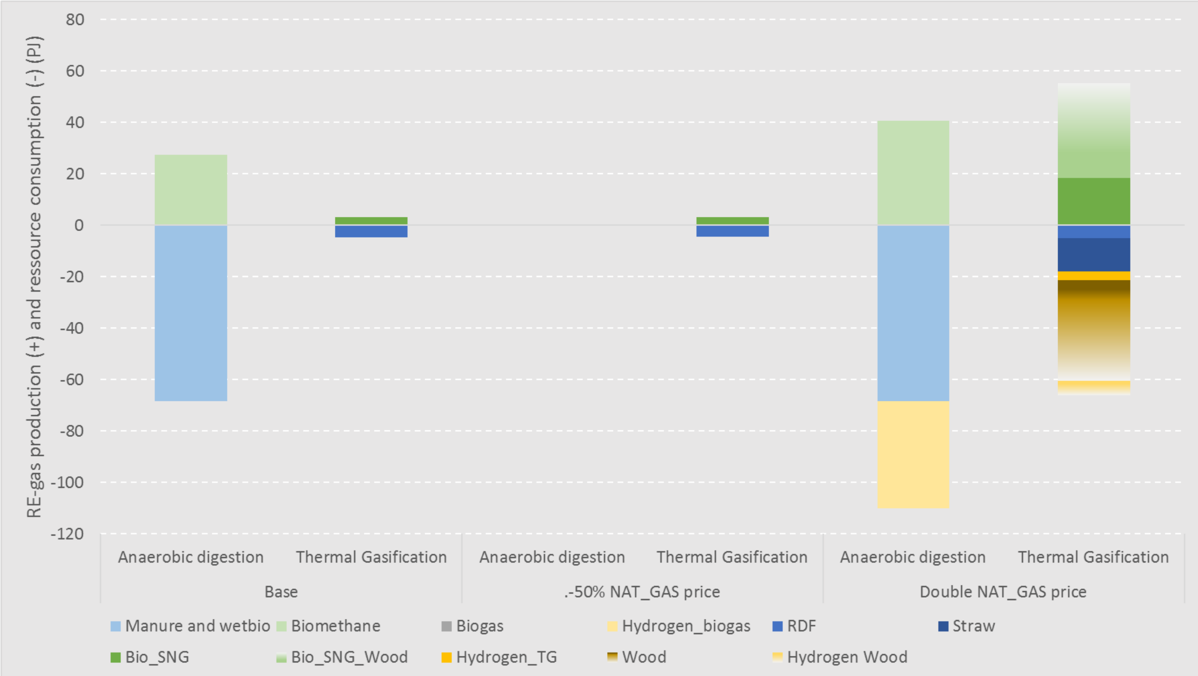

Figure 3
Danish RE-gas production (+) and fuel consumption (-) by 2050 in the three future scenarios.

Figure 3 illustrate that RE-gas is produced in all scenarios, as RDF is socio-economically attractive to be used in the thermal gasification plant due to alternative costs of treating the waste fraction. Furthermore, the results show the general trend of producing RE-gas which can be injected into the natural gas pipeline network.

In the Base scenario, the models result in socio-economic optimal system where biogas is produced from the mixture of manure and wetbio while RDF is used for thermal gasification. Using the mixture of manure and wetbio in the anaerobic digestion process is marginally more economically attractive than adding straw in the process, under the given scenario assumptions. However, investigating the dual variables, the results show that using the mixture of manure and wetbio combined with straw is also economically attractive in the Base scenario. Valuing the by-product from the anaerobic digestion where straw is added to the process could potentially influence the results further.

Reducing the price of natural gas by 50% leads to a system where only RDF is used in the gasifier. However, increasing the natural gas price by 200% leads to a situation where the system benefits from producing more RE-gas.

In the double natural gas price scenario, RE-gas with natural gas quality is produced. Furthermore, the catalytic methanation technology is used to produce additional methane by adding hydrogen to both biogas and syngas.

In this scenario, it is socio-economically attractive to use RDF, straw, and wood in the thermal gasification plants. The results show that resources are transported between the areas. The reason for this split is found in the spatial allocation of resources along with the constraint of installing bio-SNG producing plants in the central areas, while the other plants are located outside the central areas.

In Figure 3, utilization of wood is presented by the color gradient, illustrating that the resources of wood are unconstrained and can supply the Danish demand for gas in a socio-economically efficient way.

Moreover, Figure 3 show a high utilization of hydrogen in the methanation of the CO_2. The results furthermore show that hydrogen is produced continuously in most of the simulated time periods. Hydrogen is however not produced in periods with high electricity prices.

Conclusion

This study investigated the role of renewable gas production in a future renewable based Danish energy system. As the Danish energy system will undergo a radical transformation towards a system with stronger couplings and interactions between energy vectors in the future, a holistic system perspective is used to assess the future socio-economic value of RE-gas production. To facilitate the modelling of renewable gas, model developments in the spatiotemporal network optimization model, OptiFlow, were implemented. Furthermore, OptiFlow was hard-linked to the energy system model Balmorel, allowing an integrated energy assessment of RE-gas production.

This modelling framework allowed a detailed modelling of the gas chain from up-stream renewable gas production, through storage facilities to end consumers, taking into account the spatial and temporal system integration between the gas, electricity, and district heating system.

The results of the co-simulation of OptiFlow and Balmorel represents the socio-economic optimal system, where investments and operations optimization is undertaken for the integrated energy system. The results show that production of RE-gas is socio-economically attractive in all the investigated scenarios. Furthermore, the results show that RE-gas directly injected into the natural gas pipeline network is preferred.

In the high natural gas price scenarios, the catalytic methanation technology is used to produce additional methane. The modelling approach applied in this study, allowed the investigation of RE-gas production with a high temporal and spatial resolution. This was used to show that the deployment of the chosen technologies for producing RE-gas varies according to the resource allocation, and to show the effect of electricity price on hydrogen production.

Future work

A natural extension of this study would be to perform a comprehensive systems analysis including more energy scenarios to assess the influence of RE-gas production and utilization in systems with different VRE penetrations. The flexible production of hydrogen as well as the use of gas in fast responding power plants could potentially influence the utilization of the electricity transmission lines and could be a part of a future analysis. As briefly showed in this paper, RE-gas production is related to the allocation of biomass resources. Thus, a future study could address the crucial question of where the bioenergy resources are used in a most cost-efficient way in the integrated energy system, taking into account the spatial allocation of resources.

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