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# Model-based estimation of market potential for Bio-SNG in the German biomethane market until 2030 within a system dynamics approach

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**Abstract.** One option for energy provision from renewables is the production and grid injection of synthetic natural gas from lignin-rich biomass like wood and straw. Bio-SNG (biological produced synthetic/substitute natural gas) is the product of the thermochemical production of methane via gasification and methanation of lignin-rich biomass. The first commercial bio-SNG plant went successfully into operation in the end of 2014, in Gothenburg (Sweden). Regarding the huge potential of lignin-rich biomass bio-SNG is expected to have a high potential for a sustainable and greenhouse gas reducing contribution in power, heat and fuel markets. Being a future technology with great advantages like storability and transportability within a gas grid but recently too high prices for market implementation, possible future market shares are uncertain because bio-SNG has to compete with anaerobic biomethane as well as fossil alternatives. With the combination of an extensive techno-economic evaluation for present and future costs of bio-SNG depending on the feedstock supply chain and economy of scale, Delphi-Survey and a quantitative market simulation we determined future market shares for biomethane and bio-SNG for Germany under varying scenarios like incentive schemes, economy of scale and feedstock prices. Results indicate that substantial governmental support in terms of either R&D effort to lower bio-SNG prices or direct subsidies for a further capacity development is necessary to achieve significant market shares for biogenic methane.

**Key words:** bio-SNG, System Dynamics, Bioenergy markets, biomethane.

## INTRODUCTION

Renewable Energy (RE) is a substantial part of Germanys Climate and Energy Strategy. Against the overall global trend, between 1990 and 2012 the share of Renewables increased whilst the overall energy consumption as well as the use of fossil energy carriers decreased in Germany, resulting in a 30% share of RE in Germanys power mix, a share of about 10% in the heat sector and a share of 5.4% in the mobility sector with solid, gaseous and liquid biomass ('Deutschland – Agentur für Erneuerbare Energien'). With a share of 100% in the fuels sector, 87% in the heat sector and 31% in the power sector, bioenergy is the most important RE in Germany (Thrän et al., 2015). One significant advantage of most bioenergy utilisations is the possibility to substitute fossil fuels in already existing infrastructures. Biomethane, a biogenic gas chemically equal to natural gas, can substitute fossil gas in all scopes of application. Thus, there is a tremendous potential for biomethane to substitute fossil gas (683 TWh $a^{-1}$ in 2014 (Erdgasverbrauch von Deutschland bis 2014 | Statistik). However, due to an imperfect market situation, in most cases energy out of biomass is more expensive than its fossil alternatives (Fisher & Rothkopf, 1991; Jaffe et al., 2005). Therefore governmental support is needed if it is the political will to decarbonize the energy system and increase the use of RE. The most recent amendment of the most important support scheme for biomethane, the Renewable Energy Source Act, reduces governmental compensations. This comes along with a transformation of the biomethane market from a compensation driven market to a market-driven one. It is uncertain how the market will develop in the mid-term under these new boundary conditions. Therefore a dynamic market model was developed to simulate mid-term market development under most recent and possible new boundary conditions for already market-implemented anaerobic biomethane and not yet market-implemented thermochemical biomethane, so-called bio-SNG. If one regards the needed efforts of Germany to reach the goal of a 40% reduction of GHG emissions compared to the 1990 level (further 749 million t $CO_{2eq}$) until 2030, biomethane can be a valuable contribution to reach this goal (European Environment Agency, 2014).

**Biomethane in a nutshell**

Biomethane is biogenic and renewable methane that can be produced on the one hand by anaerobic digestion (AD) of organic matter such as energy crops, manure, sewage, organic waste, and so on and on the other hand by gasification and methanation of lignin rich material such as forestry residues or energy crops (e.g. straw). Being chemically identical to natural gas it can use the already existing infrastructure and serve as a replacement in all natural gas applications. Depending on the value chain of biomethane production and the scope of application where natural gas is substituted large amounts of greenhouse gas emissions can be saved (Repele et al., 2013; Repele et al., 2014). In Germany renewable methane is primarily used in CHP plants (combined heat and power production) (Daniel-Gromke et al., 2013). Furthermore biomethane can be fed and buffered in the existing gas grid. Due to this easy storability and transportability it can be produced and consumed spatially separated and thus be an option for the upcoming task of energy plants to operate demand driven.

To start these actions support by energy and climate policies was necessary. In 2004 first stakeholders in Germany started with the production and trade of biomethane. Being a biogenic alternative to natural gas biomethane is about 2–3 times more expensive than natural gas (Dunkelberg et al., 2015). Amongst others this support led to a rapid installation of biomethane production plants and biomethane CHP plants.

However, because of the high interest on biomethane and its many advantages as fossil fuel substitute, i.e. the GHG emission saving potential, the storability, the existing industry sector but also the challenging market barriers make it worth to analyse the market structure and to derive scenario-driven forecasts on future market shares for biomethane. This is done by using a system dynamics market simulation model in combination with an extensive techno-economic analyses and involving experts via a Delphi-Survey.

**Biomethane market development and drivers in Germany**

Since 2004 the implementation of a biomethane market in Germany was promoted by a plurality of laws and regulations leading to a continuous expand of biogas plants, biogas upgrading plants and thus biomethane feed-in capacities (Fig. 1). The most important promoting law is the Renewable-Energy-Source-Act. It guarantees compensation for the production of renewable power for 20 years. Besides the application in CHP plants biomethane is a promising option for the fuel market, the heat market and the chemical industry (IEA Bioenergy, 2014). To this day the use for direct heat and transport are niche markets. With the possibility of grid feed-in biomethane could be traded within the EU, being liquefied it could be traded global. In this way a large-scale emission reduction could be achieved. Because of the recent version (2014) of the Renewable Energy Source Act support for further biomethane capacity expansion in Germany is no longer sufficient. This leads to a strong decrease of plant installations and capacity expansion.

Since the construction of the first biomethane plant in Germany in 2006 a constant biomethane plant installation was realized. Waves of plant installations occurred as a delayed reaction to supporting schemes that were highly profitable. However, big waves did not occur due to different delays in plant construction. The plant installation and biomethane producing capacity development is illustrated in Fig. 1.

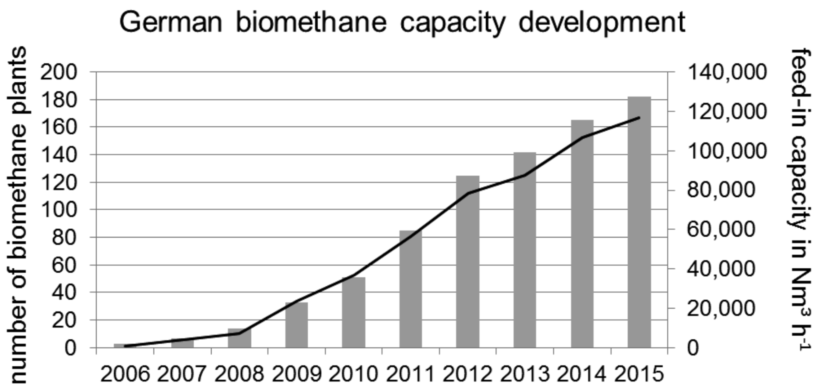


**Figure 1.** Development of biomethane capacity and plant installation in Germany (Deutsche Energie-Agentur GmbH, 2014).

Besides the above mentioned laws, regulations and support schemes further factors influenced the market development.

The competitive situation between biomethane and natural gas is determined by the price for natural gas and the profit you can make out of it. This permanent competitive situation in each scope of application is crucial for the investment decisions. The fix costs, i.e. for gas grid transport, the CHP unit, the staff or market effort can be assumed equal. But whereas natural gas can be purchased by fossil deposits, biomethane has to be produced by an expensive and complex biochemical or thermochemical conversion process out of biomass.

Another possibility to make profit out of biomethane is customers which are willing to pay a certain amount of money more for sustainable and renewable energy. This can be done via specific green power or green gas contracts. In the mobility sector pure biomethane or a mixture is available. Nevertheless this is only a niche market. Only a small fraction of potential customers are willed to pay a higher price for sustainable and climate-friendly energy.

**Production of Biomethane**

The here characterized biomethane can be produced via two conversion processes. The first one is biomethane produced via the biochemical process through digestion of biomass. The second one is the production via the thermochemical process of gasification and methanation. If produced through the thermochemical process the biomethane is often called bio-SNG (biological produced synthetic/substitute natural gas). In the following, biochemical produced methane is called biomethane and thermochemical produced methane is called bio-SNG.

The biomethane production via biochemical conversion is already a widely applied technology. The major process steps are (Kaltschmitt et al., 2009; Graf & Bajohr, 2011; FNR, 2014):

I. Pretreatment of substrate (e.g. crushing)
II. Anaerobic digestion
III. Raw biogas treatment
IV. Biogas upgrading.

Biomethane, respectively bio-SNG via the thermochemical conversion is yet barely applied in the market. A lot of research and demonstration is going on, but so far only one commercial plant is yet in operation (Kopyscinski et al., 2010). The first commercial plant has a bio-SNG capacity of 20 MW, is located in Gothenburg (Sweden) and went into operation in the end of 2014 (Goteborg Energi, 2014).

All thermochemical conversion plants and research concepts consists of the following process steps (Knoef, 2012; Seiffert & Rönsch, 2013):

I. Pretreatment of substrate (e.g. crushing, drying)
II. Gasification
III. Raw syngas treatment
IV. Methanation
V. Raw SNG upgrading.

**Current use and potentials of biomethane (biochemical and thermochemical)**

Considering economic and environmental aspects there is a reasonable potential for anaerobic biomethane in Germany of about 300 $MW_{el}$ (Scholwin et al., 2014). The bio-SNG plant in Gothenburg can be considered as the first one in commercial scale. So far there is no similar plant. However, there are research activities which concentrate on the gasification and/or methanation of lignin rich biomass to bio-SNG (e.g. in Austria (PSI, 2009), the Netherlands (ECN, 2011), Germany (Specht, 2006)).

Considering the bio-SNG potentials in Germany and Europe, there is not much data available. According to available biomass substrates there is a potential for bio-SNG out of woody biomass of around 66 and out of herbaceous biomass residues of around 6 bill. $m^3\ a^{-1}$ in Europe, according to (Thrän, 2012).

**Aims and objectives**

It is the aim of this paper to show scenario-dependent possible market shares, market potentials and market behavior for bio-SNG in Germany. Therefore we analyzed the German biomethane and natural gas markets, being the markets where bio-SNG will have to compete in and transferred the results into a system dynamics market simulation model. Bio-SNG is integrated via a learning curve and market adoption concept. To validate and calibrate the model a techno-economic analysis and Delphi-Survey were conducted. Furthermore three different scenarios were implemented into the modeling approach. Thus, it is possible to derive possible future market shares for bio-SNG within the German biomethane and natural gas markets.

## MATERIALS AND METHODS

For the task of analysing the existing market structure as well as determining future market shares of biomethane and bio-SNG in the German biomethane market we decided to use the system dynamics methodology. Among a variety of approaches that are more or less capable for our demands the system dynamics methodology fits best. That`s because top-down approaches like input-output models or computable general equilibrium (CGE) models have a closer look at economic and inter-sectorial effects but lack mostly in providing technological details and development, assuming how technologies will evolve in the future, future cost-development and they violate the fundamental physical restrictions such as the conservation of matter and energy (Böhringer & Rutherford, 2006; Kretschmer & Peterson, 2010). Unlike top-down approaches, bottom-up models can describe technologies in detail, recent and prospective ones, they come usually as mathematical programming and can refer to technology changes, like efficiency standards and economy of scale. Though, bottom-up approaches are unsuitable to model economy-wide interactions and have drawbacks that come from the mathematical programming itself, i.e. the implementation of tax distortions or market failures (Painuly, 2001; Böhringer & Rutherford, 2008).

**System dynamics methodology**

Forecasts, especially for markets that were initiated by subsidies and now transferred to market-driven markets, can support decision makers. Where forecasting options are limited system dynamics (SD) is a methodology basing on the systems theory that provides decision support in dynamic and complex situations as well as capabilities to analyse, model and simulate them (Dace & Muizniece, 2015). It was first introduced by Jay W. Forrester in the 1950`s to support managers in complex business situations (Forrester, 1961). Having its foundation in business problems, SD was used in more and more disciplines to solve complex dynamic problems. The mathematical formulation of SD is made via a system of differential equations.

The basic tools of SD are causal loops diagrams, the construction of networks of stocks and flows and the analysis of the feedback structure. A special feature of SD is the high degree of learning while building the causal loops diagram and the simulation model. SD showed its suitability to fulfil modelling requirements in diverse scientific fields. In terms of energy markets SD models are predominantly used for the analysis of liberalized markets because of the advantage to model market mechanisms through differentiated mechanisms of action instead of following a single objective function that allows those models a differentiated image of real markets. One problem that can arise during model development with SD is the need of validation of the interdependencies and the necessity of calibration. So without a real reference system the development of a SD model is not possible. The suitability to model economic and environmental interactions and feedbacks is stated by (Berka & Dobrosi, 2004). Although SD provides the necessary tools for dynamical modelling of RE policies containing energy and climate policies only little research has been done on this topic (Aslani et al., 2014).

After solving the above mentioned calibration and validation task the analysis is mostly done via experimentation, exhaustive what-if-scenarios (Forrester, 1961; Morecroft, 1988) and automatic optimization via external software (Lane & Oliva, 1994.) by trial-and-error-simulation, parameter changing or on and off switching of loops and parameters (Al-Saleh & Mahroum, 2014).

One problem arising within model building approaches is uncertainty. A lot of research was carried out determining how to reduce uncertainty in model-building. A common approach is the combination of a quantitative modelling approach with qualitative approaches. To reduce uncertainty within the presented modelling approach we combined it with an extensive techno-economic analysis on future cost development for anaerobic and thermochemical produced biomethane that was evaluated by support of external experts via a Delphi-Survey. Details of the techno-economic analysis and the associated Delphi-Survey can be found in the supplementary data file.

**Model description for the biomethane market**

There are three major steps creating a SD model. The first step is the development of a conceptual model representing an abstraction of a real world problem and defining the boundaries of the model. It illustrates the fundamental principles and basic functionalities. Fig. 2 shows the conceptual model of the biomethane market simulation model (BiMaSiMo).

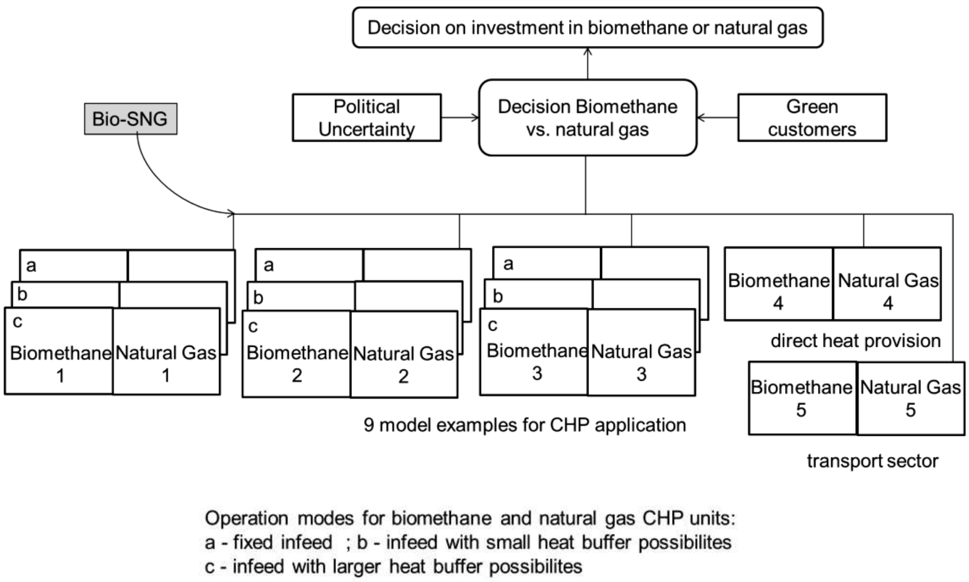


**Figure 2.** Conceptual model for BiMaSiMo.

The model is separated into the different possible applications of biogenic methane, in the same way to natural gas. For the application in CHP units the model consists of three possible applications, where biomethane and natural gas are used (hospital, swimming pool and district heating) with three different operation modes each (fixed infeed, infeed with small heat buffering possibilities and infeed with larger heat buffering possibilities and thus more flexibility). Along with the nine applications for the heat and power provision the applications for direct heat provision and in the fuel sector were modelled in a similar competitive manner. For each application a detailed sub-model was created to best possible illustrate the costs and revenues for each year in the time horizon 2000–2030. In this way the model is able to show the difference between costs and revenues for each application of biomethane respectively natural gas. In combination with a dynamic pay-off calculation it is possible to model the investment decisions. Those are affected by customers that are willing to pay a higher price for so called green products and by political uncertainty. Based on an investment rate calibrated by historical data it is possible to derive information on future investment decisions depending on future support schemes.

A detailed description of the causal loop diagrams, the stock and flow diagrams, system boundaries, and so on of BiMaSiMo can be found in (Horschig & Szarka, 2015) and the supplementary data file. Because of the already mentioned competitive situation between biogenic methane and natural gas, BiMaSiMo includes a model of the German natural gas flows, to calculate how much fossil gas can be substituted in which scope of application. Based on a large database at the German biomass research centre (DBFZ Deutsches Biomasseforschungszentrum) and the prior extensive techno-economic analyses a detailed model building process was possible, including a price formation mechanism for feedstock prices. For the biochemical conversion pathway extensive data is available and was implemented in the model. The thermochemical conversion pathway to bio-SNG for the future price and capacity development of this conversion pathway is implemented via learning curves.

Historical data of anaerobic biomethane plant installation and capacity expansion was used to calibrate the anaerobic biomethane SD model. The techno-economic analysis was used to calibrate the learning curve and market adoption model. Furthermore the price formation of biomethane is modelled separately to meet the requirements of its complexity. The availability of feedstock in form of biogas plants, which can be upgraded to biomethane plants, is limited to 10% of the installed biogas plant capacity due to calculations of (Scholwin et al., 2014). The decisions between biomethane and an alternative energy source as well as the different biomethane utilizations are based on two assumptions:

I. There is a strictly profit-based decision in which the purchaser of a certain amount of energy decides for the energy source he can receive the most payback for.
II. There is an individual and environment-based decision where there is a certain willingness to pay a higher price for a climate friendly product by direct gas consumers.

Subsequently the conceptual model was transformed to a causal-loop-diagram (CLD). In the next step the CLD is transferred into a stock and flow Diagram (SFD). SFD`s have a richer visual language than CLD`s. Variables and connections between them are defined with differential equations and therefore can be simulated. The SFD in

Fig. 3 shows the learning curve and market adoption sub-model for bio-SNG because this is not mentioned in the above mentioned reference for BiMaSiMo.

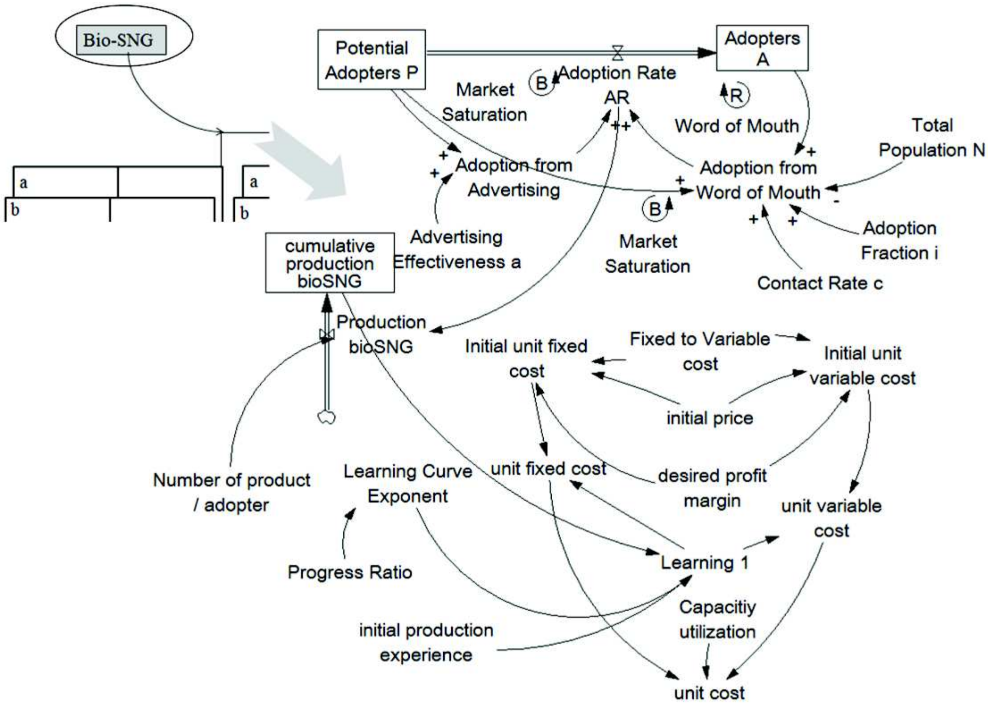


**Figure 3.** SFD of bio-SNG submodel (according to Sterman, 2009).

**Techno-economic evaluation**

During a related project a comprehensive techno-economic evaluation of biochemical and thermochemical conversion technologies for biomass to biomethane was carried out. In total, 66 biochemical conversion alternatives and 33 thermochemical conversion alternatives were evaluated. The alternatives are based on different biomass feedstocks (e.g. maize, manure, straw, residual wood), different scale (1.4–16 $MW_{BioCH4}$ (AD) and 13–524 $MW_{BioCH4}$ (SNG)) and different upgrading respective gasification and methanation technologies. The alternatives were evaluated by a multi-criteria analysis.

The results of the techno-economic analyses and the Delphi-Survey show that a further reduction of the usual biomethane prices through learning processes is minimal. One reason can be seen in the cut-off of compensations for bioenergy in general and the associated decrease of funds for research and development (R&D) efforts. Being a promising future technology bio-SNG is still part of many R&D efforts and market implementation projects. With the techno-economic analyses and through further R&D activities future bio-SNG prices between 5–18.25 €ct $kWh^{-1}$ can be realised. These depend mainly on the plant concept and the feedstock mix.

**Scenario definition**

Assumptions within BiMaSiMo for feedstock price development, cost development for anaerobic biomethane and gas demand are equal for all scenarios. There is no significant increase of the natural gas price (3.26 €ct $kWh^{-1}$ until 2030) and the trade with carbon emissions stays on the current level as well as the price per ton $CO_2$ (6€ $t^{-1}$ $CO_2$ (European Emission Allowances (EUA); Böhringer & Lange, 2013)). The scenarios are defined to reflect the best market possibilities in the CHP, heat and transport sector, where biogenic methane can be an alternative to fossil methane.

The *base scenario* is defined by encompassing compensation reductions for the production and use of biogenic gas in the power, heat and transport sector and thus, affects biomethane as well as bio-SNG. Whereas there are several options for the decarbonisation of the power sector, the heat sector is often called a sleeping giant. The *green heat scenario* is defined by an additional payment for green heat produced in environmental beneficial combined heat and power plants from 2016 on. The model will determine the minimum threshold for the green heat support to incite further biomethane capacity installation. This scenario shows the possibilities to partly decarbonize the heat sector with a domestic biogenic gas that can be used in all applications of natural gas. The third scenario is called *green transport scenario*. This scenario is defined by a substitution of natural gas transport through biomethane.

Each of the three scenarios is simulated with the current average anaerobic biomethane price (7.16 €ct $kWh^{-1}$) and possible future bio-SNG prices of 5, 5.5 and 6 €ct $kWh^{-1}$) derived from the techno-economic analysis and the presented learning-curve and market adoption sub-model.

**Greenhouse gas emission reduction**

Values for greenhouse gas emissions (GHG) for biomethane and its fossil references are derived from (Majer, 2011) and multiplied by the amount of substituted natural gas in the particular application. Of course, GHG emission values are highly dependent on assumptions. Therefore the here presented values are more a direction than a precise value.

## RESULTS AND DISCUSSION

The results of the simulation of the *base scenario* show that there is nearly no further capacity development of anaerobic or thermochemical biomethane until 2030, except for bio-SNG with a price of 5 €ct $kWh^{-1}$. This agrees with market development predictions of (Deutsche Energie-Agentur GmbH, 2014). The main reasons for that are the insufficient support schemes that are not compensating the price difference between natural gas and biomethane. The support schemes that are in force since 2004 guarantee compensation for 20 years. According to current stand, after expiration of these compensations the biomethane plants will be taken from the grid. The model assumes that after 20 years all plant components have to be renewed and therefore new incentives are necessary for an ongoing biomethane production. The current adaptions of the main support schemes are not sufficient and consequently the biomethane plants installed in 2004 will be the first to be taken from the grid resulting in a decrease in feed-in capacity. With a future bio-SNG price of 5 €ct $kWh^{-1}$ an additional amount of 3,600 TJ $a^{-1}$ (≈ 10,540 $Nm^3$ $h^{-1}$, 1 TWh $a^{-1}$) fossil energy could be substituted by bio-SNG. This would be natural gas in CHP plants. Environmentally seen in terms of GHG emission reduction this is the most beneficial use of biomethane.

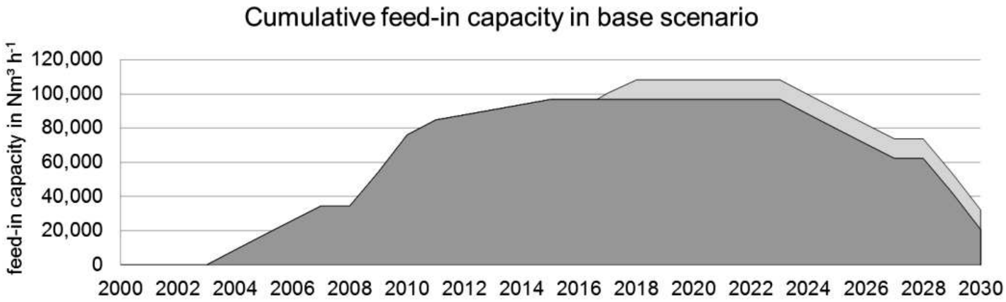


**Figure 4.** Results of base scenario simulations

Results of the *green heat scenario* show that with the current price for biomethane the additional payment for green heat must be at least 13 €ct kWh$^{-1}$ to incite further capacity installation. Decreasing prices for biomethane will lower the necessary threshold, of course. Possible future prices for bio-SNG need a threshold (additional payment) of 6 €ct kWh$^{-1}$ of green heat (bio-SNG price of 6 €ct kWh$^{-1}$) and 4 €ct kWh$^{-1}$of green heat (bio-SNG price of 5.5 €ct kWh$^{-1}$). As shown in Figure 4 a bio-SNG price of 5 €ct kWh$^{-1}$does not need additional support to incite further capacity installation. Implementing at least the threshold for a green heat support would incite a new capacity installation of around 2,400 TJ a$^{-1}$ (≈ 7,027 Nm³ h$^{-1}$, 0.66 TWh a$^{-1}$). This is strictly tied to the assumption that the compensation for green power stays on its current level due to the fact that green energy from combined heat and power plants can receive compensation for the produced power and additional revenues from the sales of the arising heat.

Results of the *green transport scenario* show that with the current price for biomethane the additional support must be at least 6 €ct kWh$^{-1}$. This threshold is necessary to compensate the different profit opportunities of natural gas and biomethane in the current transport sector. In this way fuel stations could sell exclusively 100% biomethane instead of mixtures with natural gas. In doing so an annual natural gas demand of around 10,000 TJ a$^{-1}$ (≈ 30,000 Nm³ h$^{-1}$, 2.77 TWh a$^{-1}$) could be substituted by biomethane in the transport sector only. Analog to the results of the green heat scenario the threshold gets lowered with decreasing bio-SNG prices. A bio-SNG price of 6 €ct kWh$^{-1}$has a threshold of 5 €ct kWh$^{-1}$, a bio-SNG price of 5.5 €ct kWh$^{-1}$has a threshold of 4 €ct kWh$^{-1}$ and a bio-SNG price of 5 €ct kWh$^{-1}$ has a threshold of 3.8 €ct kWh$^{-1}$.

The assumed future bio-SNG prices of 5, 5.5 and 6 €ct kWh$^{-1}$can be realized by only few bio-SNG plant concepts and with ongoing R&D effort. It has to be mentioned that the different influencing variables in the system dynamics model have a different power of influence. The variables biomethane price, future bio-SNG price and natural gas price significantly influence the simulation results.

According to calculations of (Rönsch, 2010) a representative bio-SNG plant concept emits 17.9g $CO_{2eq}/MJ_{SNG}$ GHG (≈ 64,5g $CO_{2eq}$ $kWh^{-1}$). Details of this concept can be found in the supplementary data file. Compared to fossil references for possible applications of bio-SNG in the power, heat and transport sector significant GHG savings can be achieved. The fossil references are 393g $CO_{2eq}$ $kWh^{-1}$ for CHP plants (average from power provision through usual power mix and heat provision by natural gas), 180g $CO_{2eq}$ $kWh^{-1}$ for direct heat provision by natural gas and 249g $CO_{2eq}$ $kWh^{-1}$ for transport with natural gas. The base scenario simulation derived a further bio-SNG capacity development of 3,600 TJ $a^{-1}$ (≈ 10,540 $Nm^3$ $h^{-1}$, 1 TWh $a^{-1}$) in the CHP sector, when a bio-SNG price of 5 €ct $kWh^{-1}$ is getting realized. This is equivalent to an emission saving of 328 kt $CO_{2eq}$ $a^{-1}$. Simulation results for the green heat scenario derived a possible capacity development for bio-SNG in the heat sector of 2,400 TJ $a^{-1}$ (≈ 7,027 $Nm^3$ $h^{-1}$, 0.66 TWh $a^{-1}$). This is equivalent to an emission saving of 76 kt $CO_{2eq}$ $a^{-1}$. The natural gas based transport in Germany could be decarbonized with 10,000 TJ $a^{-1}$ (≈30,000 $Nm^3$ $h^{-1}$, 2.77 TWh $a^{-1}$) out of bio-SNG. This is equivalent to an emission saving of 510 kt $CO_{2eq}$ $a^{-1}$. Of course, the above mentioned GHG saving values are more road signs then precise predictions. Nevertheless they show that especially investments in a further use of bio-SNG in the CHP and transport sector can achieve high GHG emission savings. In times of debates on nitrogen oxide emissions from inner-city diesel transport the substitution with biogenic gas like bio-SNG and biomethane can contribute to a decrease of nitrogen oxide emissions and thus increase air quality.

The results of the base scenario show that without further incentive schemes and funding for ongoing R&D-effort there won`t be a market penetration of bio-SNG in Germany. It has to be mentioned that our approach has limitations, of course. The model is strictly limited to the German biomethane market and trade of biomass, feedstock or the end product biomethane is not yet considered. Furthermore effects of an increased biomethane production from other bioenergy carriers are not considered like feedstock competitions. Also, due to a lack of already installed bio-SNG plants the applied bio-SNG data is mainly based on simulation and modelling, which leads to uncertainties in subsequently calculations.

## CONCLUSIONS

A system dynamics model was developed to assess the potential market share of bio-SNG in Germany until 2030. Simulation results show that a capacity development of bio-SNG in the CHP sector at current support is only possible with low bio-SNG prices of 5 €ct $kWh^{-1}$. The heat sector needs support of at least 13 €ct $kWh^{-1}$ at current support levels to foster the substitution of natural gas with biogenic methane. Lower bio-SNG prices will decrease the needed support. Results of the green transport scenario derived the necessity of an additional support of at least 6 €ct $kWh^{-1}$ at current level of support. The results of our simulation show that a further decarbonisation of natural gas supply chains in the CHP, heat and transport sector can only be achieved with additional support and further R&D effort to decrease current bio-SNG production costs. In this way it is possible to directly formulate policy proposals for decision support. Additionally the focus can be shifted respectively expended. Instead of a pure energetic focus the high potential of biomethane respective bio-SNG in the chemical sector can be included. This would also push the current evaluation to a more overall evaluation. It could involve the consideration of further technology concepts as well as an adjustment of evaluation area and period, e.g. for whole EU till 2050. However, for a comprehensive decision support the simulation model needs to be extended and further research is necessary.

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## REFERENCES

Al-Saleh, Y. & Mahroum, S. 2014. A critical review of the interplay between policy instruments and business models: greening the built environment a case in point. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2014.08.042

Aslani, A., Helo, P. & Naaranoja, M. 2014. Role of renewable energy policies in energy dependency in Finland: System dynamics approach. *Applied Energy* **113**, 758–765.

Berka, V. ja Dobrosi, L. 2004. High level handling of system dynamics models in rural development planning, in: Iron Curtain International Symposium. Wolfbauer, J., Kürzl, H. (ed), Budapest,Hungary. pp. 79–84.

Böhringer, C. & Lange, A. 2013. European Union's Emissions Trading System, in: Encyclopedia of Energy, Natural Resource, and Environmental Economics. *Elsevier*, pp. 155–160.

Böhringer, C. & Rutherford, T.F. 2008. Combining bottom-up and top-down. *Energy Economics* **30**, 574–596.

Böhringer, C. & Rutherford, T.F. 2006. Combining Top-Down and Bottom-Up in Energy Policy Analysis: A Decomposition Approach. *SSRN Electronic Journal*. doi:10.2139/ssrn.878433

Dace, E. & Muizniece, I. 2015. Modeling greenhouse gas emissions from the forestry sector – the case of Latvia. *Agronomy Research* **13**, 464–176.

Daniel-Gromke, J., Denysenko, V., Barchmann, T., Reinelt, T. & Trommler, M. 2013. *Aufbereitung von Biogas zu Biomethan und dessen Nutzung – Status quo und Perspektiven*. in: Dezentrale Energieversorgung. TK Verlag, p. 468.

Deutsche Energie-Agentur GmbH. 2014. Industry barometer biomethane. data, facts and trends of biogas feed-in. [WWW Document] URL http://www.dena.de/fileadmin/user_upload/Projekte/Erneuerbare/Bilder/Branchenbarometer_Biomethan_I_2014.pdf. (in German).

Deutschland – Agency for renewable energy [WWW Document], URL http://www.unendlich-viel-energie.de/themen/politik/deutschland (accessed 6.23.15). (in German)

Dunkelberg, E., Salecki, S., Weiß, J., Rothe, S. & Böning, G. 2015. Biomethane in the energy system – ecological and economic evaluation of upgrading technologies and utilisation options. Publication series of the institute of ecological and economic research 207/15, Berlin (in German).

ECN. 2011. MILENA – Status of Development. Online-Abfrage. Energy Research Centre of the Netherlands (ECN), Petten.

Erdgasverbrauch von Deutschland bis 2014 | Statistik [WWW Document], n.d. Statista. URL http://de.statista.com/statistik/daten/studie/41033/umfrage/deutschland---erdgasverbrauch-in-milliarden-kubikmeter/ (accessed 12.18.15).

European Emission Allowances (EUA) [WWW Document], n.d. URL https://www.eex.com/de/marktdaten/umweltprodukte/spotmarkt/european-emission-allowances#!/2016/03/30 (accessed 3.30.16).

European Environment Agency. 2014. Annual European Union greenhouse gas inventory 1990–2012 and inventory report 2014.

Fisher, A.C. & Rothkopf, M.H.. 1991. Market failure and energy policy: a rationale for selective conservation. *Energy Policy* **17**, 397–406.
FNR. 2014. Leitfaden Biogasaufbereitung und -einspeisung. Fachagentur Nachwachsende Rohstoffe e.V. (FNR), Gülzow.
Forrester, J. 1961. *Industrial Dynamics*. Productivity Press,Cambridge, MA. 482pp.
Goteborg Energi. 2014. GoBiGas – Goteborg Energi [WWW Document], URL http://www.goteborgenergi.se/English/Projects/GoBiGas_Gothenburg_Biomass_Gasification_Project
Graf, F. &, Bajohr, S. 2011. biogas – production, upgrading, feed-in. Oldenbourg Industrieverlag GmbH, München. (published in German)
Horschig, T. & Szarka, N. 2015. The German biomethane market – A policy evaluation approach using System Dynamics. Proceedings of the 33rd International Conference of the System Dynamics Society, Cambridge, Massachusetts,USA.
IEA Bioenergy. 2014. Biomethane – Status and Factors Affecting Market Development and Trade.
Jaffe, A.B., Newell, R.G. & Stavins, R.N. 2005. A tale of two market failures: Technology and environmental policy. Ecological *Economics* **54**, 164–174.
Kaltschmitt, M., Hartmann, H. & Hofbauer, H. 2009. Energy from biomass: Fundamentals, technologies and procedures, Second Edition, Springer, Berlin (in German).
Knoef, H., 2012. Handbook Biomass Gasification Second Edition, BTG Biomass Technology Group BV, Enschede, Netherlands.
Kopyscinski, J., Schildhauer, T.J. & Biollaz, S.M.A. 2010. Production of synthetic natural gas (SNG) from coal and dry biomass – A technology review from 1950 to 2009. *Fuel* **89**, 1763–1783.
Kretschmer, B. & Peterson, S. 2010. Integrating bioenergy into computable general equilibrium models – A survey. *Energy Economics* **32**, 673–686.
Lane, D.C. & Oliva, R. 1994. The greater whole: Towards a synthesis of system dynamics and soft systems methodology. *European Journal of Operational Research* **107**, 214–235.
Majer, S. 2011. Results of ecological evaluation of biogas/biomethane from exemplary biogas plants, Biogas Council e.V. Berlin (in German).
Morecroft, J.D.W. 1988. System dynamics and microworlds for policymakers. *European Jorunal of Operational Research* **59**, 9–27.
Painuly, J. 2001. Barriers to renewable energy penetration; a framework for analysis. Renewable *Energy* **24**, 73–89.
PSI. 2009. The SNG Technology Platform in Güssing, A Status report of Bio-SNG project. Paul Scherrer Institut, Villigen, Schweiz.
Repele, M., Paturska, A., Valters, K. & Bazbauers, G. 2014. Life cycle assessment of biomethane supply system based on natural gas infrastructure. *Agronomy Research* **12**(3), 999–1006.
Repele, M., Dudko, M., Rusanova, J., Valters, K. & Bazbauers, G. 2013. Environmental aspects of substituting bio-synthetic natural gas for natural gas in the brick industry. *Agronomy Research* **11**(2), 367–372.
Rönsch, S. 2010. Technical analysis of thermo-chemical Bio-SNG production. Annual meeting of the technical committee 'energy process engineering' and 'gas cleaning'. Dortmund, Germany.
Scholwin, F., Grope, J., Schüch, A., Daniel-Gromke, J., Beil, M. &, Holzhammer, U. 2014. Actual state of biomethane use – costs – climate impact – utilisation pathways – comparison of combined heat and power production of biogas, biomethane and natural gas. Federal Ministry for Economic Affairs and Energy, Berlin, Germany.
Seiffert, M. & Rönsch, S. 2013. Biosynthetic Natural Gas, in: Encyclopedia of Sustainability Science and Technology: Springer Verlag, Berlin-Heidelberg, Germany.

Specht, M. 2006. Handout – The AER-Process. Cluster initiative 'Energy-North-East-Brandenburg'. Center for Solar Energy- and Hydrogen-Research Baden-Wuerttemberg (ZSW), Stuttgart (in German).

Sterman, J.D. 2009. Business dynamics: systems thinking and modeling for a complex world, Irwin/McGraw-Hill, Boston. pp. 982

Thrän, D. 2012. European biomethane potentials., Workshop Biomethane Trade. DBFZ, Brussels.

Thrän, D., Hennig, C., Rensberg, N., Denysenko, V., Fritsche, U. & Eppler, U. 2015. IEA Bioenergy Task 40: Country Report Germany 2014. IINAS – International Institute for Sustainability Analysis and Strategy GmbH, Darmstadt/Leipzig.