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Synthetic Natural Gas produced with carbon dioxide from geothermal energy generation in Iceland and used in Switzerland

A Life Cycle Assessment

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1-21-2021

Life Cycle Assessment of Synthetic Natural Gas[1] produced with CO_2 from geothermal energy generation in Iceland and used in Switzerland

Final report on LCA activities

January 21, 2021

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[1] "Synthetic Natural Gas" (SNG) is the generic term used for methane generated via power-to-gas processes. In the following, "Liquefied Green Gas" (LGG) will be used as equivalent term.

Table of Contents

1. Summary

Production of synthetic natural gas (SNG) by means of methanation of hydrogen and CO_2 represents an option for indirect electrification of heating systems and transport vehicles, if hydrogen is produced via electrolysis. Potential environmental benefits of such an indirect electrification and substitution of currently dominating fossil fuels must be quantified from a life-cycle perspective, taking into account the entire production, supply, and use phase of the SNG in comparison to alternatives based on fossil fuels.

Previous analysis has demonstrated that from both the economic and environmental perspectives, low-cost and low-carbon electricity for electrolysis is among the key factors for an economic and environmentally sound SNG production in practice. Furthermore, an appropriate source of CO_2 is required. Considering these boundary conditions, Iceland – with its ample resource of low-cost and low-carbon electricity from hydropower and with geothermal power stations representing appropriate point sources for CO_2 supply – seems to be an ideal location for SNG production. Such SNG can be transported to Switzerland and used as fuel there, substituting natural gas (or heating oil and petrol) in the residential and transport sectors. The current Swiss regulation for imported biofuels requires the demonstration of environmental benefits compared to fossil alternatives from a life-cycle perspective to profit from tax reductions. Similar regulations for SNG are not yet in place, but can be expected to become relevant in the future.

There are concrete plans for production of SNG in Iceland and subsequent import to Switzerland from a Swiss-based project consortium. The Technology Assessment group at PSI has been commissioned by this consortium to perform a Life Cycle Assessment (LCA) of their project in order to evaluate the legitimacy of Icelandic SNG production using local hydropower and CO_2 from the geothermal power plant Hellisheiði followed by SNG transport to and use in Switzerland as heating or transport fuel from the environmental perspective. Primary goal of this LCA was the quantification of life-cycle Greenhouse Gas (GHG) emissions and of the "overall environmental impact" applying the method of "Ecological Scarcity" (2013). Both these LCA indicators are mandatory elements applying for tax exemptions – certain reduction levels compared to fossil alternatives have to be demonstrated in order to be eligible for biofuel imports today. It is assumed that similar regulations can be expected for SNG, even if its carbon content is not of biogenic origin.

The LCA reveals that – under the given boundary conditions in Iceland with hydropower as low-carbon electricity source – the key issues determining the benefits of SNG in terms of reduction of GHG emissions compared to natural gas are the following:

- the LCA approach chosen for quantifying environmental burdens of CO_2 captured and used as feedstock for SNG production;
- the accounting for CO_2 emissions due to SNG consumption (i.e. combustion).

Applying a so-called "substitution approach" for the quantification of product-specific GHG emissions of SNG, as currently recommended by relevant LCA guidelines, and attributing CO_2 emissions due to SNG combustion entirely to geothermal energy production, SNG used as heating and passenger vehicle fuel allows for a reduction of life-cycle GHG emissions of more than 70% and almost 50%, respectively, compared to the use of natural gas in Switzerland. From an overall system perspective (including geothermal electricity generation and SNG consumption), reduction of life-cycle GHG emissions due to SNG substituting natural gas can amount to not more than 50%, since the CO_2 released by the geothermal plant represents an additional flow of CO_2 into the atmosphere. Due to indirect emissions along the SNG chain, reductions of GHG emissions are lower in practice: 37% and 27% can be achieved with SNG as heating and vehicle fuel, respectively.

The way how CO_2 emissions from combustion of synthetic fuels such as SNG must be accounted for in practice, and to which processes they need to be attributed will be determined by the regulating

authorities, potential integration of the transport and residential sectors into the EU ETS, and potentially also by contracts between CO_2 supplier and user, i.e. SNG producer.

The present LCA confirms that the type of electricity supply for electrolysis is among the determining factors for the life-cycle GHG emission performance of SNG. However, electricity in Iceland is in general associated with very low GHG emissions and therefore, the differences between specific options (hydropower versus electricity from the Icelandic grid) regarding life-cycle GHG emissions are minor. Contributions from SNG transport from Iceland to Switzerland to overall GHG emissions are small for all the different transport options investigated. Table 1 summarizes the LCA results in terms of reduction of life-cycle GHG emissions by SNG application compared to fossil fuel boilers and passenger vehicles.

Table 1: Reductions of life-cycle greenhouse gas emissions by SNG production in Iceland, supply to and use in Switzerland compared to conventional alternatives in percent, depending on the type of electricity used for SNG production and the LCA approach chosen. (a) case in which CO_2 emissions due to SNG combustion are entirely attributed to the geothermal plant as CO_2 supplier. "w/o car&road infra" refers to a calculation, in which production and maintenance of cars and roads are not taken into account, since this might be required by a regulation.

Electricity used for SNG production	**Hydropower Iceland**		**Power grid mix Iceland**	
CCU-fuel LCA approach	system expansion	substitution (a)	system expansion	substitution (a)
SNG boiler, compared to:				
NG boiler	37	74	33	65
oil boiler	44	79	40	72
SNG vehicle, compared to:				
NG vehicle	27	47	23	41
petrol vehicle	34	55	31	50
SNG vehicle (w/o car&road infra), compared to:				
NG vehicle (w/o car&road infra)	33	71	29	61
petrol vehicle (w/o car&road infra)	41	77	37	70

Regarding LCA results according to the method of ecological scarcity (supposed to represent "overall" environmental burdens), the key factor is that CO_2 captured and supplied to methanation must contain negligible amounts of Sulphur, since the catalyst used in methanation has very low tolerance of sulfur contamination. Therefore, CO_2 capture and supply must go hand in hand with gas cleaning and a substantial reduction of H_2S emissions to (almost) zero. Consequently, this reduction of H_2S emissions is due to SNG production and accounted for as environmental benefit (with negative ecological scarcity scores). This benefit is higher than all other environmental burdens generated along the SNG production, supply and use chain, meaning that applying the ecological scarcity method to the SNG system analyzed suggests an overall environmental benefit of implementing the SNG chain (in absolute terms, not only compared fossil fuel reference systems). This result, however, must be interpreted with caution, since the ecological scarcity method is Swiss-specific and its application to environmental issues in Iceland questionable: H_2S emissions contribute to acidification, to which agriculture is a main contributor in Switzerland; related boundary conditions in Iceland are likely to be completely different.

Due to the current uncertainties in the regulatory environment, this analysis cannot provide conclusive, quantitative answers regarding the reduction of GHG emission due to SNG production in Iceland and use in Switzerland compared to natural gas. However, the analysis reveals that the envisaged SNG production and supply chain exhibits a large potential for reduction of GHG emissions and is not associated with substantial negative environmental side-effects. Thus, under the given boundary conditions, SNG from Iceland represents a viable, clean fuel that can contribute to a decarbonization of the Swiss economy, if natural gas is still foreseen as a fuel to be used in the future.

However, the analysis suggests that uncertainties in the regulatory environment with their major impact on the GHG emission reductions accounted for, which can have substantial economic impacts, need to be eliminated before the implementation of an SNG production facility in Iceland and the import of SNG to Switzerland.

2. Acknowledgement

The authors thank the entire project consortium for the efficient project management, for sharing knowledge and data, and for providing constructive feedback to the LCA throughout the entire project period. Furthermore, the feedback of the external reviewer is acknowledged – revisions based on the review comments helped to improve the quality of this report substantially.

Moreover, supplementary funding of the work provided by PSI’s ESI-platform is acknowledged.

3. Preface

The Technology Assessment group at PSI has been assigned to perform a Life Cycle Assessment (LCA) of Synthetic Natural Gas (SNG) production in Iceland by Nordur Power AG, which aims at establishing an SNG production facility there with the intention to import this SNG to Switzerland as "renewable-based fuel".[2] This LCA is one part of the so-called "IMPEGA" project; in parallel to LCA, the logistics and economics as well as the regulatory environment are investigated by other project partners.

Despite of being commissioned by Nordur Power AG, the LCA has been carried out as independent research, and has been reviewed by an external party. The content reflects the authors' state of knowledge as of December 2020 – this concerns technical issues such as the characteristics, performance and available data regarding the planned SNG production facility in Iceland (consisting of the geothermal energy generation plant with CO_2 capture and treatment, electrolysis, and methanation) to be used for the LCA, transport options for the SNG from Iceland to Switzerland, and potential use cases. This also concerns the rather policy- and business-related aspects relevant in the LCA context, namely the contracts specifying electricity supply of the SNG production facility as well as the CO_2 supply from the geothermal plant to the methanation.

There is an ongoing discussion whether the CO_2 released by the geothermal plant might in the future entirely be captured and geologically stored. As a result, it would not be available for SNG production. The present LCA is, however, performed under the hypothesis that CO_2 for methanation, captured from the geothermal power plant, will be available throughout the entire lifetime of the methanation unit. The SNG production facility will only be established, if CO_2 availability is guaranteed by specific contracts.

Carbon dioxide for SNG production is going to be supplied by the geothermal power plant Hellisheiði. Currently, its operator ON Power is running an exhaust treatment plant at the Hellisheiði geothermal power plant, so called SulFix II station, since the gas stream from the geothermal boreholes contains water and steam, dissolved minerals and different gases like CO_2, H_2S, H_2, CH_4, etc. After a separation of the liquid and gaseous state, the gas part is diverted to the power stations where the electricity is produced. Non-condensable gases in the exhaust stream are treated, by separating hydrogen sulphide (H_2S) and CO_2 from the other exhausts. Thereafter these gas components are re-injected deep into the bedrock at the plant site. Based on the experience with the pilot gas separation station SulFix and CarbFix gas injection projects, the industrial scale SulFix II station was built in 2014. Today, SulFix II dissolves around 77% of the H_2S along with 23% of CO_2 from the power plant. The H_2S concentration in the exhaust stream has been reduced to a level below 2%. The realization of an SNG production plant using the remaining CO_2 will support ON Power's long-term strategic goal to further minimize Sulphur and carbon dioxide emissions from the geothermal power plant. For this purpose, the capacity of SulFix II shall be extended and the (further cleaned) waste gas utilized for the production of SNG.

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[2] The term "renewable-based fuel" might be slightly misleading in the context of SNG production subject to this analysis. While the energy consumed for SNG production can be renewable, the CO_2 used for SNG production – supplied from a geothermal power plant – cannot be considered as "renewable". There is no generally applied terminology, such CO_2 is often considered as "geogenic", or "fossil". For the sake of simplicity, this analysis used the term "fossil CO_2 emissions" for CO_2 originating from geothermal power, equivalent to "geogenic".

4. Methodology

4.1. Goal and scope

Goal of this analysis is the quantification of the environmental impacts (with a strong focus on impacts on climate change, i.e. greenhouse gas (GHG) emissions, and in addition overall impacts applying the method of ecological scarcity) associated with the production of synthetic natural gas (SNG) in Iceland with CO_2 captured at the geothermal power station Hellisheiði and subsequent transport to and use in Switzerland; either as vehicle fuel in compressed natural gas (CNG) vehicles, or heating fuel in natural gas boilers. These burdens need to be compared with those of the conventional alternative natural gas in order to quantify environmental benefits and potential trade-offs from a life cycle perspective. For this purpose, Life Cycle Assessment (LCA) is performed and as such the analysis is intended to be used for comparative assertion.

The results of the LCA will provide information to the Nordur Power SNG AG regarding the environmental viability of their project, especially in the context of potential tax exemptions importing SNG as "renewable-based fuel" to Switzerland – therefore the focus on life-cycle GHG emissions and LCA results according to the method of ecological scarcity; these LCA results are mandatory elements for tax exemption applications. Furthermore, the Association of the Swiss Natural Gas Industry will use the results of the present study as a basis for development of similar projects for import of "renewable-based" gases to Switzerland. This report is also supposed to be released to the public.

Synthetic natural gas is generated by methanation of hydrogen and CO_2. In the product system subject to this analysis, hydrogen is generated via electrolysis and CO_2 is supplied by capturing it from the geothermal power plant Hellisheiði in Iceland. The resulting methane is compressed, liquefied and transported to Switzerland, where it is supposed to be re-gasified and used as "renewable-based fuel" or "recycled carbon fuel" either by vehicles of for heat generation (Figure 1).

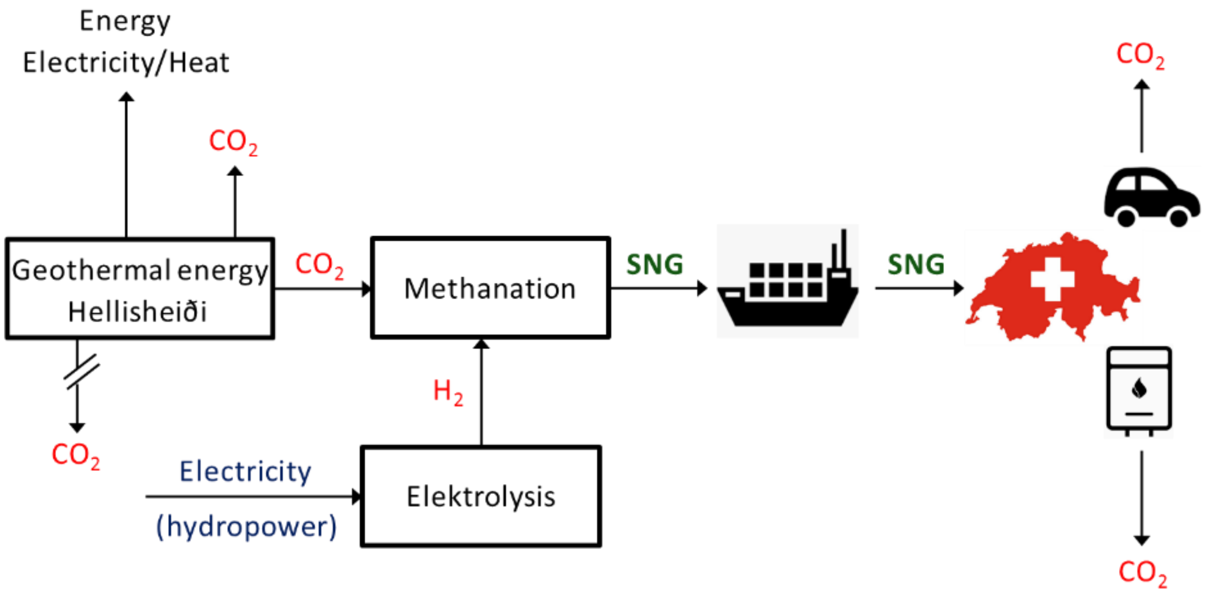

Figure 1: Schematic visualization of SNG production in Iceland and use in Switzerland.

The product system is partially hypothetical in the sense that the electrolysis and methanation facilities do not exist yet, but are planned to be built. Hellisheiði has been operating for years and some fraction of the CO_2 it would release are actually already captured and re-injected into the ground. Technology performance data of all system components represent current "state-of-the-art".

Also the logistics concerning transport of the SNG to Switzerland are investigated and different options explored by a dedicated partner. The LCA of this segment of the life cycle of SNG builds upon the analysis of this logistics partner and has been carried out closely interacting.

Alternative scenarios in terms of use of CO_2, Icelandic electricity, and associated hydrogen and SNG production and use cases have not been analyzed and are considered to be out of scope of the present study. Addressing questions of optimal use of natural resources and potentially generated low-carbon fuels would go beyond Life Cycle Assessment and require the use of a European (or even global) energy system model. Such questions are important, but not in the current focus of the contractor.

4.2. Product system and system boundary

The production of SNG with feedstock carbon dioxide from the geothermal power plant represents a case of Carbon Capture and Utilization (CCU) for fuel production. LCA of such CCU fuels is a non-trivial exercise, since it involves multi-functional processes, and CO_2 both as emission to air, and as feedstock material. Thus, the LCA is subject to methodological choices, which are partially subjective and to some extent arbitrary. Furthermore, different perspectives have to be distinguished: (1) the "system perspective", including combined energy and CO_2 production at the geothermal plant as well as the end-use of SNG; and, (2) the "individual perspective" of the SNG producer/user, which requires a product-specific environmental characterization of SNG production and use. Only recently, methodological guidelines for LCA of CCU-based products and CO_2 captured and used as feedstock have been developed on top of general LCA guidelines [1], [2]. The present LCA applies these guidelines as far as possible, but also highlights additional aspects to be considered.

The geothermal power and heat generation plant supplying CO_2 for methanation can generate multiple potentially valuable (intermediate) products: electricity, heat and CO_2 (as feedstock for methanation). In Life Cycle Assessment, different approaches can be applied for dealing with such so-called "multi-output" processes, and different perspectives from different stakeholders might require different LCA approaches. According to the relevant norm ISO 14044 [3], allocation of multi-output processes should be avoided whenever possible; by either sub-dividing the multi-output unit process (i.e. in the case of this study: geothermal energy generation and CO_2 capture and processing for utilization in SNG production) into sub-processes or expanding the product system to include the additional function related to the co-product (i.e. CO_2 from the geothermal plant, which can be used as a feedstock in SNG production).

In this study, the analysis reflects two perspectives: (1) The overall system perspective, and (2) the perspectives of SNG owner and user, who need a product specific quantification of environmental burdens. Therefore, two corresponding approaches can be distinguished and are applied in this analysis: (1) system expansion and (2) substitution (Figure 2). This is in line with the recommendations on LCA of CCU-based fuels [2] on top of ISO 14044 [3], in which the authors state that "If product-specific assessments are needed to answer the initial research question, the following hierarchy of allocation method shall be applied. First, substitution shall be applied. … Please note that results obtained via system expansion shall always be computed to assess the overall effect of introducing the CCU technology."

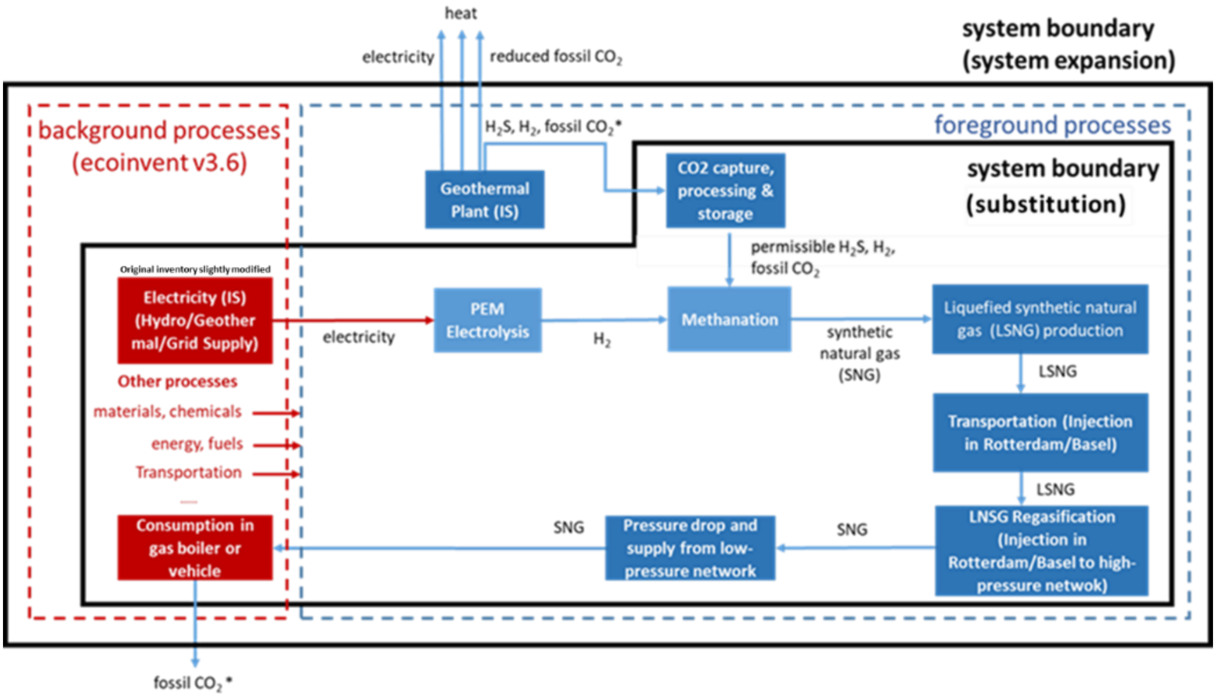

Figure 2: System boundary that are considered in this analysis, with division between foreground[3] *and background*[4] *processes; dark blue boxes indicate processes that require data collection, while light blue boxes indicate processes that will be taken from previous research* [4][5]. *LCI for unit process at Hellisheiði geothermal plant are based on* [6][7]. *Inventory data for hydropower in Iceland are mainly based on ecoinvent, but GHG emissions are modified according to* [8]. *This modified hydropower inventory is used in the electricity mix of Iceland in this analysis.*

"System expansion", as applied for the purpose of this analysis, refers to the entire SNG production and use chain: the expanded system includes the energy production at the source of CO_2, capturing and processing of CO_2, its reaction with H_2 to produce synthetic natural gas (SNG)[5], necessary transportation and processing until (and including) the end use of SNG. Useful products of the entire system are electricity (and heat) produced from the geothermal plant and heat from the combustion of SNG in a boiler, or alternatively distance travelled in case of the end use of SNG as a vehicle fuel. This system expansion avoids assigning CO_2 emissions resulting from SNG end use (i.e. combustion) to either the geothermal plant, or SNG consumer, as this CO_2 is simply part of the emissions from the overall system. A "conventional reference system", to which environmental impacts can be compared, comprises the geothermal plant without CO_2 capture for its further use and a natural gas boiler or vehicle, respectively, providing the same quantities of geothermal electricity and heat and heat from the gas boiler or distance driven with the natural gas vehicle, respectively. This overall system perspective allows for the quantification of environmental burdens and benefits of SNG production and use from a more comprehensive point of view; however, it does not provide product-specific environmental burdens for the SNG, which are required by the SNG producer.

In order to quantify these product specific environmental burdens, a second approach is applied, in line with the recommendations for quantifying carbon footprints of feedstock CO_2 [1], [2]. This "substitution" approach considers the same processes as system expansion, including SNG production, transportation, processing and end consumption, but the environmental burden at the geothermal plant is split between energy production and CO_2 supply (acknowledging the fact that with its use in methanation, CO_2 becomes a feedstock and could be considered as "product" instead of an emission (or waste)).

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[3] The foreground processes represent the processes of the system under investigation itself and are collected for the specific LCA analysis.
[4] Background processes are more generic processes used for modelling the remaining activities, and can be obtained from the LCA databases.
[5] Also referred to as "Liquefied Green Gas" or "LGG" within this project sometimes, as it needs to be liquefied to be transported oversea.

According to the terminology used in [1], [2], we apply a substitution concept, in which the geothermal plant with CO_2 capture substitutes the geothermal plant without CO_2 capture and the environmental burdens of the CO_2 feedstock are calculated as the difference between these two processes. This is equivalent to subdivision of the geothermal plant with CO_2 capture into sub-processes, quantifying the environmental burdens of feedstock CO_2 as those generated by the sub-processes required for CO_2 capture and processing at the geothermal plant and assigning the captured CO_2 with a negative emissions flow. This is also equivalent to an allocation of the CCU process (the geothermal power plant) based on physical causality, where capture and use of a unit of CO_2 results in emission reduction of the same amount of CO_2 and an increase of emissions related to the capture process [2].

From the perspective of the SNG producer/owner/user, the CO_2 captured at the geothermal plant can also be considered as "waste" (free of environmental burdens) and only burdens associated with supplying (capturing) and processing the CO_2 need to be assigned to the SNG production (and use) chain, while the burdens associated with the process of energy production at the source of CO_2 are assigned to geothermal electricity and heat. The CO_2 emitted due to SNG combustion is also assigned to the geothermal energy production in that case. This procedure can be considered as "recycling CO_2 for use in fuel production" and to be in line with the "Draft methodology for assessing greenhouse gas emission savings from renewable liquid and gaseous transport fuels of non-biological origin (RFNBOs) and recycled carbon fuels (RCFs)"[9], being developed by the European Commission, when the supply of CO_2 is categorized as "rigid", since an increase in its demand would not trigger an increase of geothermal energy production. From this perspective, SNG represents a "recycled carbon fuel".

Regardless of the approach applied, the key is the consistent and complete accounting for CO_2 emissions associated with the geothermal energy production, captured at the geothermal power plant and used as feedstock for the methanation process. This CO_2 represents a feedstock to produce SNG and will be released when the SNG is combusted as a fuel. Applying the substitution approach as detailed above results in an attribution of CO_2 emissions due to SNG combustion to the geothermal plant as CO_2 supplier violating physical reality. From a carbon emission accounting perspective, such a procedure requires a corresponding legislation, which is being developed. It must be ensured that these CO_2 emissions do not "disappear" in the accounting framework, i.e. that not both the CO_2 supplier and user claim the credit for CO_2 emission reduction.

This analysis will apply both approaches (system expansion and substitution), and compare the corresponding LCA results. A thorough methodological discussion on different approaches and appropriate selection of the approach when CO_2 feedstock is concerned can be found in [1], [2].

Since the mentioned legislative accounting framework for CO_2 emissions from CCU-based fuels is not yet in place and the attribution of CO_2 emissions could also be determined by an agreement between CO_2 supplier and user – especially once the transport and the residential sector will be included in the European (CO_2) Emission Trading System (ETS) – we perform a sensitivity analysis on the attribution of CO_2 emissions due to SNG combustion within the substitution approach: (a) as "base case", we attribute these CO_2 emissions entirely to the geothermal plant as CO_2 supplier, corresponding to the recommendations by [1], [2]; in addition, we (b) attribute these emissions to the SNG end-user, which corresponds to physical reality in terms of where emissions take place; and (c), we assign 50% of these CO_2 emissions to each CO_2 supplier and end-user, which reflects the maximum possible CO_2 reduction of 50% from the overall system perspective and the shared responsibility for such reduction. Corresponding LCA results are shown and discussed in section 5.1.2.

In this context and beyond the issue of CO_2 accounting, it should be noted that CO_2 capture and processing substantially reduces Sulphur emissions of the geothermal plant, since the catalyst used in thermo-chemical methanation does not even tolerate traces of Sulphur in the CO_2 supply stream. This does not concern impacts on climate change, but the overall environmental performance of SNG will benefit from this reduction, because the emission reduction will be accounted for as positive impact on the environment assigned to feedstock CO_2, hence SNG production.

4.3. Reference flows and functional unit

The functional unit of the investigated system is defined as 1 kWh of SNG supply and its use (i.e. combustion) in a small-scale gas boiler (e.g., for single family house) or a CNG vehicle. The LCA therefore represents a so-called "cradle-to-grave" analysis of SNG as CCU fuel [2]. Higher heating value (HHV) is applied in the end use in gas boiler, and lower heating value (LHV) is applied in the end use of SNG in a vehicle, due to the difference of these two applications in utilizing the heat released from water condensation (i.e. condensing gas boiler utilizes the heat from water condensation, but combustion of SNG in a vehicle does not). This corresponds to the following reference flows[6] (or, associated products), as visualized in Figure 3:

- SNG for heat production: 3.6 MJ of heat generation by gas boiler and 16.3 kWh of electricity production
- SNG as vehicle fuel: 1.3 km of distance travelled and 18.2 kWh of electricity production

These combined products (either heat and electricity, or distance travelled and electricity, respectively, depending on the SNG end use) are associated with the use and production, respectively, of 1 kWh SNG within the investigated product system. These products are considered in the system expansion approach in combination, while in the substitution approach, only 3.6 MJ of heat generation or 1.3 km of distance travelled is considered (corresponding to the service provided by SNG combustion in a boiler or vehicle), as the system boundary is limited to the power-to-gas (P2G) system, processing and transportation of SNG and its end use only, providing a product-specific environmental footprint. The key flows associated with the functional unit are illustrated in Figure 3.

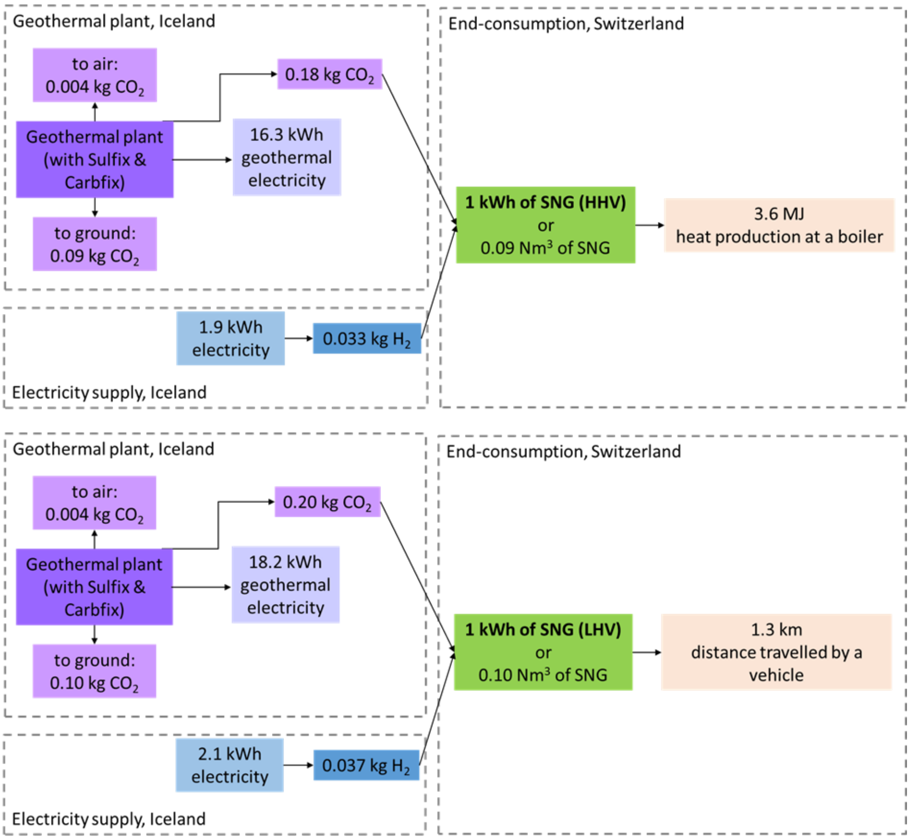

Figure 3: Key flows associated with the functional unit.

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[6] All the emissions at the geothermal plant are allocated to electricity production, as we haven't received any heat generation data from ON Power – the utility in Iceland – and it is not publicly available. But the allocation of environmental burdens between electricity and heat at the geothermal plant is not relevant for the analysis in this report (i.e. different choices of allocation won't change the results of the analysis regarding SNG production and use).

4.4. Reference system (for comparison)

The reference systems considered for comparison and quantification of potential reduction of emissions due to SNG production and use depend on the approach applied (section 4.2) and are visualized in Figure 4 with a CNG vehicle as end user. The analysis also includes petrol vehicles and in case of use of SNG for heating gas and oil boilers, both not shown here. In case of system expansion (left), the combined environmental burdens of SNG production, end-use, and geothermal energy production with reduced CO_2 emissions (due to CO_2 capture) will be compared to the reference system consisting of geothermal energy production without carbon dioxide capture (but with emissions removal process at the plant, namely Sulfix and Carbfix[7]) and conventional natural gas (or oil or petrol) supply and end use. In case of substitution (right), SNG supply and use in a vehicle (or gas boiler) will be compared to fossil natural gas (or oil/petrol) including both supply and end use. The key flows related to the functional unit of the reference systems are illustrated in Figure 5.

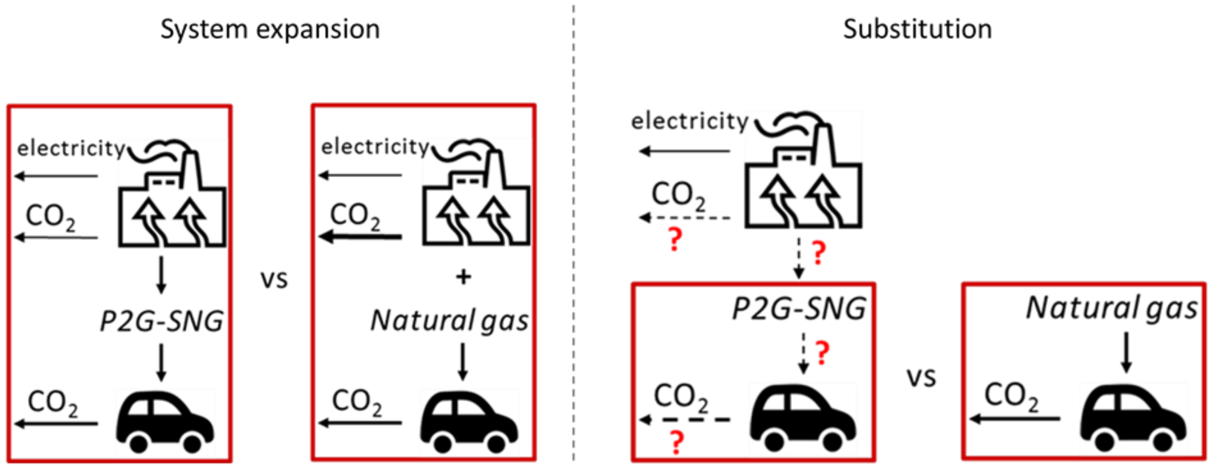

Figure 4: Boundaries of reference systems the investigated P2X system will be compared with – left: system expansion, right: substitution. The question marks represent ambiguity in attribution of CO_2 emissions of P2G product systems to either geothermal energy or SNG end-use.

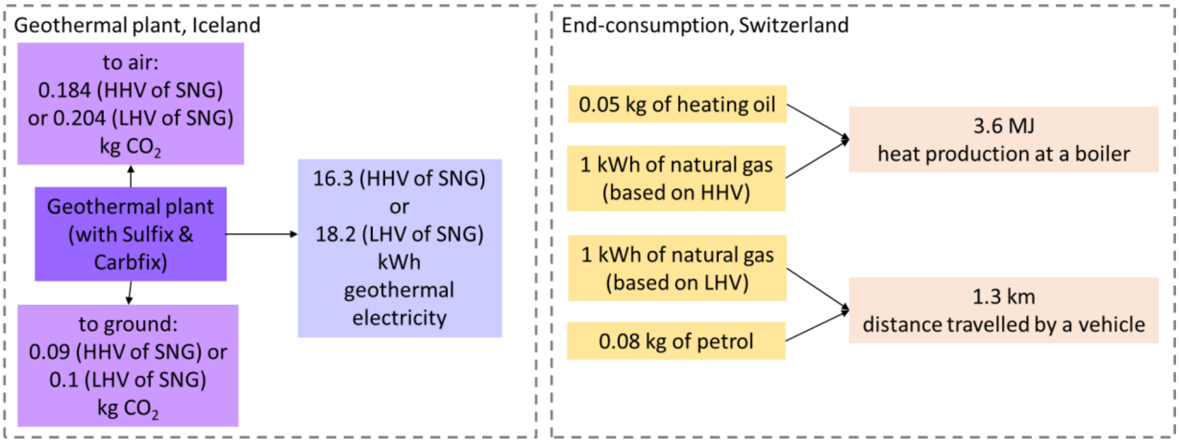

Figure 5: Key flows associated with the functional unit in reference systems.

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[7] The process of Sulfix and Carbfix are applied to capture the H_2S and CO_2 respectively, which are present as part of the non-condensable gas in the geothermal fluid for energy generation, and would have been otherwise emitted to the atmosphere. More information for these processes can be found in https://www.mannvit.com/projects/carbfix-and-sulfix-ncg-treatment-plant-for-a-geothermal-plant/.

4.5. Life cycle inventory (LCI)

Detailed LCI by process can be found in the file lci_IMPEGA.xlsm on Switchdrive: https://drive.switch.ch/index.php/s/yBavE3aFy31XLvw.

4.5.1. Electricity supply to electrolysis

The type of electricity supply for electrolysis and its GHG intensity is among the key drivers determining life-cycle GHG emissions of SNG production [10] and therefore, several options are taken into account in the present analysis. Due to economic reasons, i.e. in order to allow for competitive SNG production costs, specific electricity from hydropower plants in Iceland will be purchased for SNG production.[8] The contracts (not to be disclosed) guarantee only a small share (ca. 10%) of "firm power" (corresponding to non-interrupted supply) used for balance of plant operation of the SNG production unit. The rest of supply can be interrupted by the utility, in case of shortage of hydropower during dry periods of time, which are, however, expected to be rare. Such electricity supply is substantially cheaper than 100% firm power, which e.g. data centers in Iceland have to purchase.

Based on this information, Icelandic hydropower is used per default for electrolysis and methanation in the present LCA. This means that most of the results presented (all the results except those in Figure 9, Figure 10, and Figures S2-4 in the Appendix) represent 100% Icelandic hydropower use for SNG production. LCI data for Icelandic hydropower production is based on ecoinvent version 3.6, system model "Allocation, cut-off by classification" [11], with modifications of direct CO_2 emissions from hydropower plants in Iceland based on the National Inventory Report, Emissions of Greenhouse Gases in Iceland from 1990-2017 [8].[9] Alternative options have been raised by the SNG production operator, representing mixes of Icelandic grid mix and hydropower, and four corresponding scenarios have been formed to investigate the influence of this electricity supply mix on the life cycle GHG emissions of SNG supply, with different shares of average grid supply mix and hydropower (assumptions in Table 2, results in Figure 10, section 5.3). In addition and as a sensitivity analysis, LCA results considering 100% Icelandic average power supply are included in the Appendix in Figure S2-4.

In general, there are different approaches in LCA to account for life cycle GHG emissions and other environmental burdens of electricity with certificates, depending on the types of certificates and whether these certificates reflect the physical consumption of the renewable electricity for which certificates are purchased. The product environmental footprint guideline by the European Commission has suggested that the supplier (entities issuing renewable electricity certificates) shall guarantee that the renewable electricity supplied to the organization to produce the product is effectively the supplied energy and that it is not put into the grid to be used by other consumers (e.g., Guarantee of Origin) [12]. Other research has recommended to disregard certificates independently the traded certificates in product and service LCA as long as the LCI of national electricity mixes is based on international statistics disregarding RECS trade. If certificates are linked to the production and delivery of renewable electricity, it is recommended to include the respective share of renewables in the electricity mix [13].

Since the contracts for supply of hydropower guarantee the physical link between electricity consumption and production (i.e. it is only produced and supplied, if consumed by the SNG production facility), purchased hydropower is indeed represented by Icelandic hydropower in the analysis (with LCA as described above). However, it is not considered as "burden-free" excess electricity, since the purchase price is not zero or negative.

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[8] Information on electricity purchase and associated contracts provided by Oliver Stankiewitz, per e-mail, 22.12.2020.

[9] Basically, the direct GHG emissions of reservoir hydropower plants in Iceland as represented by ecoinvent based on a global model are considered to be too high and not appropriately reflecting the climatic conditions in Iceland. More details can be found in sheet "electricity supply in Iceland" in detailed LCI by process; the influence of these modifications on results can be found in section 5.3.

Table 2: Scenarios for electricity supplies to electrolysis.[10]

Scenarios	Grid supply (MWh/year)	% of grid supply in total supply	Hydropower supply (MWh/year)	% of hydropower supply in total supply	Equivalent full-load operation hours (hrs/year)
Scenario A	40650	25%	120250	75%	6436
Scenario B	42525	24%	132275	76%	6992
Scenario C	40650	29%	99950	71%	5624
Scenario D	43463	23%	143363	77%	7473

4.5.2. Polymer electrolyte membrane electrolysis (PEM) electrolysis

Table 3: Key data and assumptions for electrolysis

Parameter	Amount	Unit	Data Source
Hydrogen production	3302 (36’729’770)	ton/year (Nm^3/year)	[14]
Electricity consumption in electrolysis stacks	180	GWh/year	[14]
Water consumption in electrolysis	36500	ton/year	[14]
Modular PEM stack size	1	MW	Power input to PEM electrolyzer that scaling of stack is based on
System electricity consumption of PEM electrolyzer	5.2	kWh/Nm^3	Corresponding to the unit energy consumption per Nm^3 of hydrogen generation; calculated based on data given in “200221_Schema & technische Daten PtG-Anlage_Gorre.pdf”
Balance of Plant (BOP)	0.26	kWh/Nm^3	BOP unit energy consumption per Nm^3 of hydrogen generation, in kWh/Nm^3, non-liner for different sizes
Stack	4.9	kWh/Nm^3	Stack unit energy consumption per Nm^3 of hydrogen generation, in kWh/Nm^3, constant for all sizes
Lifetime	22	years	14 to 30 years of system lifetime in 2015, given 8400 hours of operation per year, according to “Development of Water Electrolysis in the European Union, 2014”[11]
Annual operation hours	7614	hrs/year	Equivalent full-capacity operation hours; Personal communication, Jachin Gorre, 30.04.2020
Stack lifetime	67000	hours	in hours; range of stack lifetime is assumed based on: 30,000 - 90,000 hours in 2015 according to “Development of Water Electrolysis in the European Union, 2014”
Fraction of active area in stack	0.8		Fraction expressed in decimal number; unitless; average data from expert judgement
Operational power density	3.75	W/cm^2	Wattage on unit area of stack; in W/cm^2; average data from expert judgement
Unit_Hydrogen_Tank_Weight	47	ton/tank	email communication with Jachin Gorre, 28.04.2020; each can store up to 295 kg hydrogen.
HydrogenStorageTank_Lifetime	20	years	email communication with Jachin Gorre, 28.04.2020
Number_of_Hydrogen_Tank	5	tanks	

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[10] Scenarios of electricity supplies are based on email communication with Christopher Stahel on May 14th 2020.

[11] Page 72, available at http://www.fch.europa.eu/sites/default/files/study%20electrolyser_0-Logos_0_0.pdf

4.5.3. Methanation

Table 4: Key data and assumptions for methanation.

Parameter	Amount	Unit	Data Source
Hydrogen consumption per Nm^3 of SNG production	4	Nm^3	[4]
Carbon dioxide required per Nm^3 of SNG production	1.96	kilogram	[4]
BOP electricity consumption for Power-to-Gas plant	20	GWh/year	[14]
BOP electricity consumption for Power-to-Gas (except electrolyzer BOP) plant	10.53	GWh/year	calculated based on [14]
SNG production	6612	ton/year	[14]
Electricity consumption for P2G plant BOP (except electrolyzer BOP) per kg of SNG production	1.59	kWh/kg	calculated based on [14]
Catalyst consumption	20	kg	For a system producing 1 Nm^3 SNG per hour, based on information from HSR; linearly scaled up
(Electricity consumption in catalyst production)	693	kWh/kg	Electricity consumption in the production of Ni/Al$_2$O$_3$-based catalysts [15] (only considered in the discussion of the results (see footnote 22) and not in the results figures, because the data source is erroneous, intransparent and thus considered to be unreliable)
Lifetime of catalyst	5	years	own assumption
Lifetime of methanation reactor	20	years	self assumption
P2G operation hours per year	7614	hours/a	personal communication with Jachin Gorre, 30.04.2020
Product SNG composition, Methane	99.4%		assumption based on LBG composition shared by Elimar Frank, 20.05.2020
Product SNG composition, Hydrogen	0.3%		
Product SNG composition, Carbon Dioxide	0.3%		

4.5.4. Liquefied synthetic natural gas production, transportation, regasification

Production of liquefied SNG from its gaseous form is based on the ecoinvent dataset “natural gas production, liquefied” for the Middle East (RME) region. But consumption of natural gas in the original dataset was replaced with the electricity supplied by hydropower from Iceland to match the project-specific condition. The amount of electricity consumption is assumed to be 1.66 kWh/kg of SNG.[12]

For SNG transportation, seven cases with two types of SNG containers are considered. The detailed assumptions are summarized in Table 5 and Table 6 below.

Table 5: Key assumptions for SNG transportation containers.

Parameter	22.8-ton container	16-ton container	Unit
1 kg LNG	0.0137		MWh
Capacity of container, in kg	22'800	16'000	kg
Capacity container, in GWh	0.308	0.219	GWh
Minimum LNG content in container	300	300	kg
Real Capacity Container	22'500	15'700	kg
Weight of container	13'000	11'000	kg
Energy content of LNG per ton of (LNG and container)	0.0086	0.0081	GWh/ton of (LNG + container)
Energy content of LNG per ton of (LNG and container)	30'997	29'227	MJ/ton of (LNG + container)

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[12] Based on personal information provided by Elimar Frank (project meeting on Nov 7, 2020)

Table 6: Assumed distances for the 7 cases of transportation pathways.

injection point	**Basel**	**Basel**	**Basel**	**Rotterdam**	**Bern**	**Bern**	**Basel**	**Bern**
container size (ton)	**22.8**	**22.8**	**16**	**22.8**	**16**	**16**	**16**	**16**
Route	**Case 1.0**	**Case 2.0**	**Case 2.1**	**Case 3.0**	**Case 4.0**	**Case 5.0**	**Case 6.0**	**Case 7.0**
Hellisheidi <->Harbor, Reykjavik, by truck (km)	34	34	34	34	34	34	34	34
Harbor, Reykjavik<->Harbor, Rotterdam, by sea ship (km)	2271	2271	2271	2271	2271	2271	2271	2271
Rotterdam Harbor<->Basel Train Station, by train (km)	533				533			
Rotterdam Harbor<->Basel Harbor, by river barge (km)		552	552			552		
Basel Train Station/Harbor<->Basel Schweizerhalle Muttenz (injection point), by truck (km)	8	8	8					
Rotterdam Harbor<->Rotterdam injection point, by truck (km)				5				
Basel Train Station/Harbor<->Bern Forsthaus-Areal, by truck (km)					96	100		
Rotterdam Harbor<->Basel Schweizerhalle Muttenz (injection point), by truck (km)							765	
Rotterdam Harbor<->Bern Forsthaus-Areal, by truck (km)								847

Regasification of SNG to its gaseous form is based on the ecoinvent dataset “evaporation of natural gas” for the European (RER) region with the following adjustments: 1) deleted the inventory flows for transportation as project-specific transportation is incorporated; 2) updated the electricity supply location depending on injection points in the Netherlands or Switzerland 3) unit conversion of reference product from cubic meter (treated the unit of original flow in ecoinvent as normal cubic meter, gaseous form) to kilogram.

4.5.5. End use of SNG in gas boiler

After the SNG is re-gasified, it is injected into the high-pressure natural gas network, and subsequently low-pressure network before it is combusted in end-use. The LCI for this process is taken from the existing ecoinvent dataset “market for natural gas, low pressure, CH”. The LCI for the end use of SNG in the gas boiler is adapted from the ecoinvent dataset "heat production, natural gas, at boiler condensing modulating <100kW" for the region “CH”: conventional supply of natural gas is replaced by the SNG supply from the low-pressure natural gas network. Each MJ of heat production requires 0.025 Nm^3 of synthetic natural gas. The CO_2 emissions in the original ecoinvent dataset are adjusted by reducing 10% of the emissions, in order to balance with the CO_2 feedstock in methanation during the production of SNG. In this study, the SNG is assumed to consist of 99.4% methane, 0.3% CO_2 and 0.3% of hydrogen[13], while conventional natural gas often has tracing amount of heavier organic

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[13] It is known that the percentage of methane from methanation is only about 90%, so gas upgrade is needed in P2G system. It usually involves a membrane which will separate CO_2 from methane, and the separated CO_2 will be fed back to the methanation reactor to be

compounds (C2-C6)[14]. The reduction of CO_2 emissions of the original unit process ensures a correct CO_2 balance.

4.5.6. Reference systems

Reference systems include the end use of conventional natural gas, or oil in boilers, or alternatively, the end use of conventional natural gas or petrol in a medium-size combustion engine vehicle, as well as electricity production at the geothermal plant without CO_2 capture for methanation (Figure 4).

The LCI for the end use of natural gas and oil in boilers, as well as the end use of conventional natural gas and petrol in a medium-size combustion engine vehicle are from the ecoinvent database (activity "heat production, natural gas, at boiler condensing modulating <100kW" and activity “heat production, oil, at boiler 10kW condensing, non-modulating” for the region “CH”, “transport, passenger car, medium size, natural gas, EURO 5” and “transport, passenger car, medium size, petrol, EURO 5” for the region “RER”).

The LCI for electricity production at the geothermal plant are compiled based on [6][7]. Note that in order to reduce the H_2S (due to higher regulation requirement) and CO_2 emissions at the geothermal plant, there are emission removal facilities (i.e. namely Sulfix and Carbfix) at the plant. These emission removal processes were not considered in Karlsdóttir et al. 2015 [6], but in Karlsdóttir et al. 2020 [7]. The effect of these emission removal processes were considered (i.e. by reducing direct emissions at the plant), while the contribution of life cycle environmental impacts caused by the construction of emission removal infrastructure is considered to be negligible[15]. As a result, 34% of CO_2 and 68% of H_2S emission reduction by these processes are considered based on monitored direct emissions at the plant from 2015 to 2019 [16], while the construction of facilities and material consumption during emission removal are not considered in this study.

4.5.7. Data quality

Data quality of the overall LCA model is considered to be high; however, the data quality of the assumptions applied for facilities and material consumption for SNG production (e.g., processes for CO_2 processing in order to qualify as the CO_2 source for thermo-chemical methanation, upgrade of methane content in the synthetic product gas, influence of partial loading and dynamic operation of PEM electrolyzer on its lifetime and energy consumption, etc.) can be improved. Since the process LCI for the geothermal plant is mainly based on data from [6][7] in Iceland, while the assumptions related to CO_2 capture and processing is provided by the Swiss project partners, the consistency of data between these two processes is ensured by crosscheck of key assumptions (e.g., CO_2 available after existing emission removals at the plant, CO_2 available for utilization, remaining CO_2 emitted to the atmosphere, etc.) with both the Swiss project partners and geothermal plant operator from ON power in Iceland, which is crucial for LCA results.

4.6. Life cycle impact assessment, database, analytical tool

Impacts on climate change in terms of life cycle GHG emissions per functional unit are quantified according to IPCC (2013) with a time horizon of 100 years [17]. Ecoinvent v3.6, system model “allocation, cut-off by classification” is used as background database [11]. A python-based open source LCA analytical tool Brightway2 is used for the analysis in this study [18]. In addition to impacts on climate change and upon request of the contractor, the method of ecological scarcity [19], supposed to represent aggregated, “total” impacts on the environment, has been applied. Results and their

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further used as a feedstock to produce synthetic methane. This upgrade is not included in the analysis, but given the insignificant contribution from this process given the previous study [5], this exclusion won’t change the conclusion of this analysis.

[14] Eigenschaften des in der Schweiz verteilten Erdgas: https://gazenergie.ch/fileadmin/user_upload/e-paper/SVGW/G10001_Erdgas_Eigenschaften_2019_d.pdf, accessed May 2, 2020.

[15] Personal communication with Karlsdóttir, May 11th, 2020.

discussion are provided in the appendix.[16] However, and despite of the fact that the Swiss administration requires a quantification of LCA results according to the ecological scarcity method, it must be noted that for a product system as the one analyzed within the present study with the majority of processes (and thus, associated environmental burdens) located beyond the Swiss borders, the meaningfulness of LCA results applying a Swiss-specific method reflecting environmental policy and concerns in Switzerland is limited. Main concerns in this context are discussed together with the results in the Appendix.

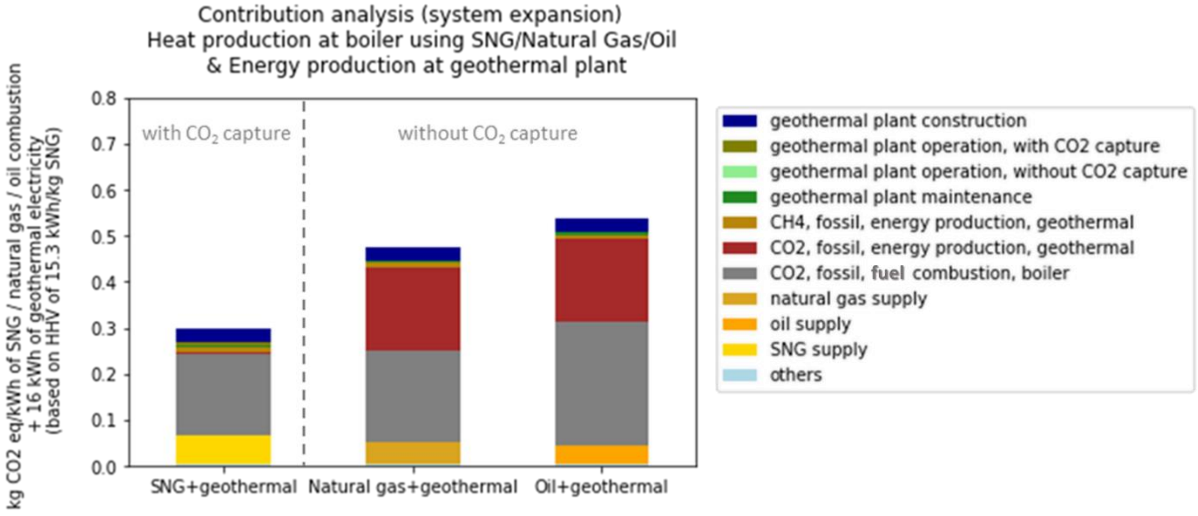
Further LCIA midpoint indicators have not been calculated, since such results are not requested by the contractor. A more comprehensive analysis could address potentially relevant midpoint indicators in addition, such as acidification potential, resource consumption, and land use.

5. Results and Discussion

5.1. Contribution analysis – impacts on climate change

5.1.1. System expansion

For end use of SNG in a vehicle, the emission reduction of the expanded system achieved is 0.17 kg (27%) and 0.24 kg (34%) of CO_2 equivalents in comparison with the systems with natural gas and petrol supply, respectively, per functional unit. If the contributions from car manufacturing, maintenance and road are excluded from the expanded system (representing SNG production, supply, and use only), the emission reduction achieved would be 0.17 kg (33%) and 0.24 kg (41%) of CO_2 equivalents in comparison with the systems with natural gas and petrol supply, respectively.



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[16] This Life Cycle Impact Assessment method is currently being updated. The new version is supposed to be available early 2021. With the update, GHG emissions will be of higher importance compared to other environmental impacts as a result of the current Swiss climate policy aiming at "net-zero" emissions by 2050.

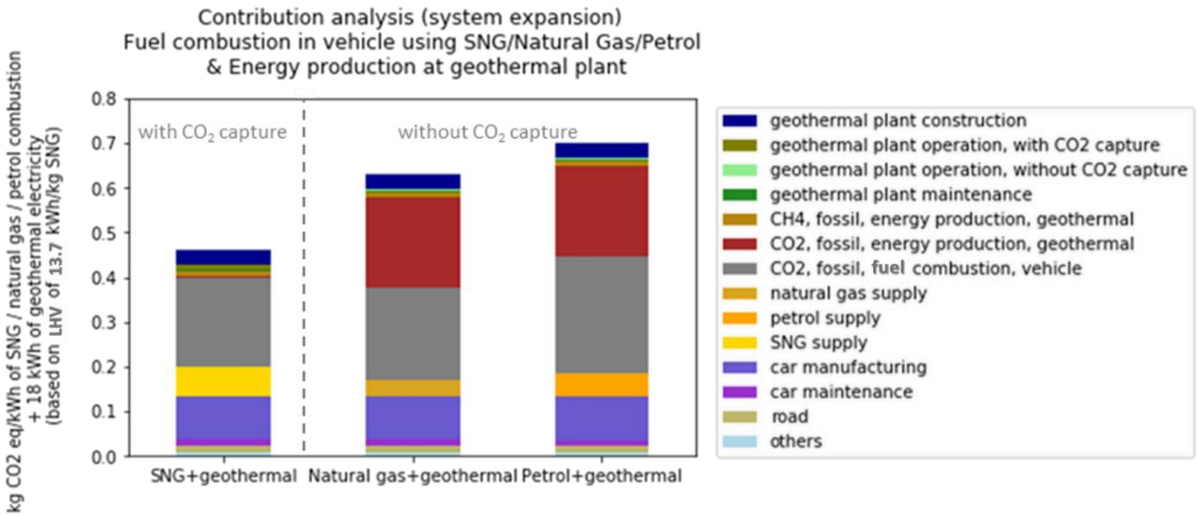

Figure 6 shows the life-cycle GHG emission results when the system expansion approach is applied, in which both electricity production at the geothermal power plant and the production, transportation and end use of SNG are considered. The CO_2 emissions due to SNG combustion after the end uses are indicated as "CO_2, fossil, SNG combustion, boiler" and "CO_2, fossil, SNG combustion, vehicle" in the legend.[17] This represents the origin of emissions, taking place at the end user.

When CO_2 is utilized in producing SNG, there is only a negligible amount of CO_2 emissions at the geothermal plant as CO_2 is either captured, and reinjected back to the ground, or captured and utilized in subsequent SNG production. In comparison with the expanded reference system, in which CO_2 is not utilized at the geothermal plant[18], and conventional natural gas or heating oil are consumed at the boiler, the systems with CO_2 utilization and SNG consumption at the boiler (natural gas or oil) exhibit emission reductions of 0.18 kg (37%) and 0.24 kg (44%) of CO_2 equivalents, respectively, per functional unit. For end use of SNG in a vehicle, the emission reduction of the expanded system achieved is 0.17 kg (27%) and 0.24 kg (34%) of CO_2 equivalents in comparison with the systems with natural gas and petrol supply, respectively, per functional unit. If the contributions from car manufacturing, maintenance and road are excluded from the expanded system[19] (representing SNG production, supply, and use only), the emission reduction achieved would be 0.17 kg (33%) and 0.24 kg (41%) of CO_2 equivalents in comparison with the systems with natural gas and petrol supply, respectively.

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[17] The terms "fossil" and "geogenic" are equivalent in the context of CO_2 emissions originating from CO_2 supply from geothermal energy.

[18] 66% of it is emitted to the atmosphere and 34% of it is captured by the existing Carbfix facilities at the geothermal power plant and reinject to the ground.

[19] The relevant legal regulation might require to exclude these contributions.

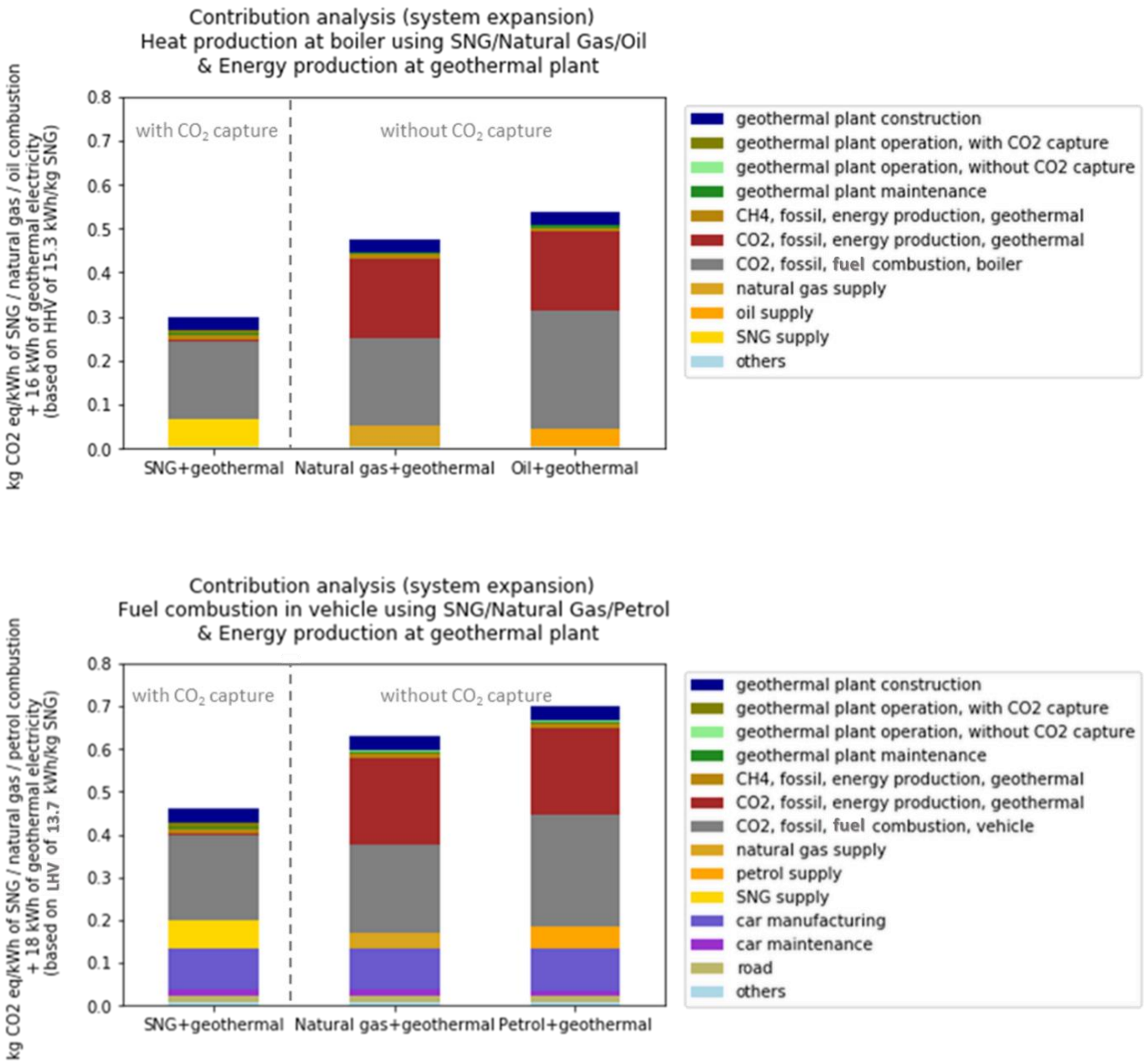

Figure 6: Contribution analysis of expanded system; top: life cycle GHG emissions per kWh of SNG combustion in a boiler (corresponding to 3.6 MJ of heat production) and 16 kWh of electricity production at the geothermal plant with CO_2 utilization vs. 3.6 MJ of heat production in a boiler with natural gas or heating oil, and 16 kWh of electricity production at the geothermal plant without CO_2 utilization; bottom: life cycle GHG emissions per kWh of SNG combustion in a CNG vehicle (corresponding to 1.3 km of distance travelled) and 18 kWh of electricity production at the geothermal plant with CO_2 utilization vs. 1.3 km of distance travelled by a CNG vehicle with conventional natural gas supply in Switzerland, or by a vehicle powered by petrol, and 18 kWh of electricity production at the geothermal plant without CO_2 utilization. In the systems with SNG as fuel for end use, SNG transportation case 1.0 is applied, and 100% hydropower in Iceland is used in PEM electrolysis to produce hydrogen.

5.1.2. Substitution

When substitution is applied, the system boundary is limited to the SNG production, processing and its end use. The CO_2 used as feedstock in methanation is considered as input with specific environmental burdens, which are quantified using the recommended substitution concept as detailed in [1] as default option (case (a) in all associated figures). This allows for the quantification of product-specific environmental burdens of SNG production and use.

However, whether a legally binding accounting scheme or rules for CO_2 emissions from CCU-based fuels such as SNG – to be implemented by EU or Swiss regulatory bodies – will be in line with the recommended LCA approach, is not yet clear (see sections 4.2 and 4.3 for methodological considerations). Therefore, different options for assigning CO_2 emissions to SNG end user and CO_2 supplier, respectively, are applied to explore the impact of the chosen option. In the left figure of

Figure 7(a), corresponding to the recommended default LCA approach, the emission of CO_2 is entirely assigned to the geothermal power plant, resulting in zero emissions from SNG combustion in terms of accounting (in fact, the SNG supply is associated with negative CO_2 emissions from CO_2 capture, which are compensated for by the CO_2 due to SNG combustion). The GHG emissions associated with production and supply of SNG however make the overall emission reduction less substantial: about 0.19 kg of CO_2 equivalents (74%) in comparison with conventional natural gas used in a boiler, and 0.25 kg of CO_2 equivalents (79%) in comparison with oil used in a boiler. This is the highest emission reduction for SNG users that can be achieved among the three different options for accounting of CO_2 emissions shown in Figure 7. The emission reduction for the other two options (i.e. 100% of CO_2 emissions are assigned to SNG producer/consumer (b), and CO_2 emissions are equally shared between geothermal power plant and SNG producer/consumer (c)) are significantly lower. When SNG is used as a vehicle fuel, similar results can be observed and they are shown by the right panels in Figure 7. For case (a), the GHG emission reduction of SNG vehicles compared to natural gas and petrol vehicles amounts to 47% and 55%, respectively (71% and 77% without accounting for vehicle and road infrastructure).

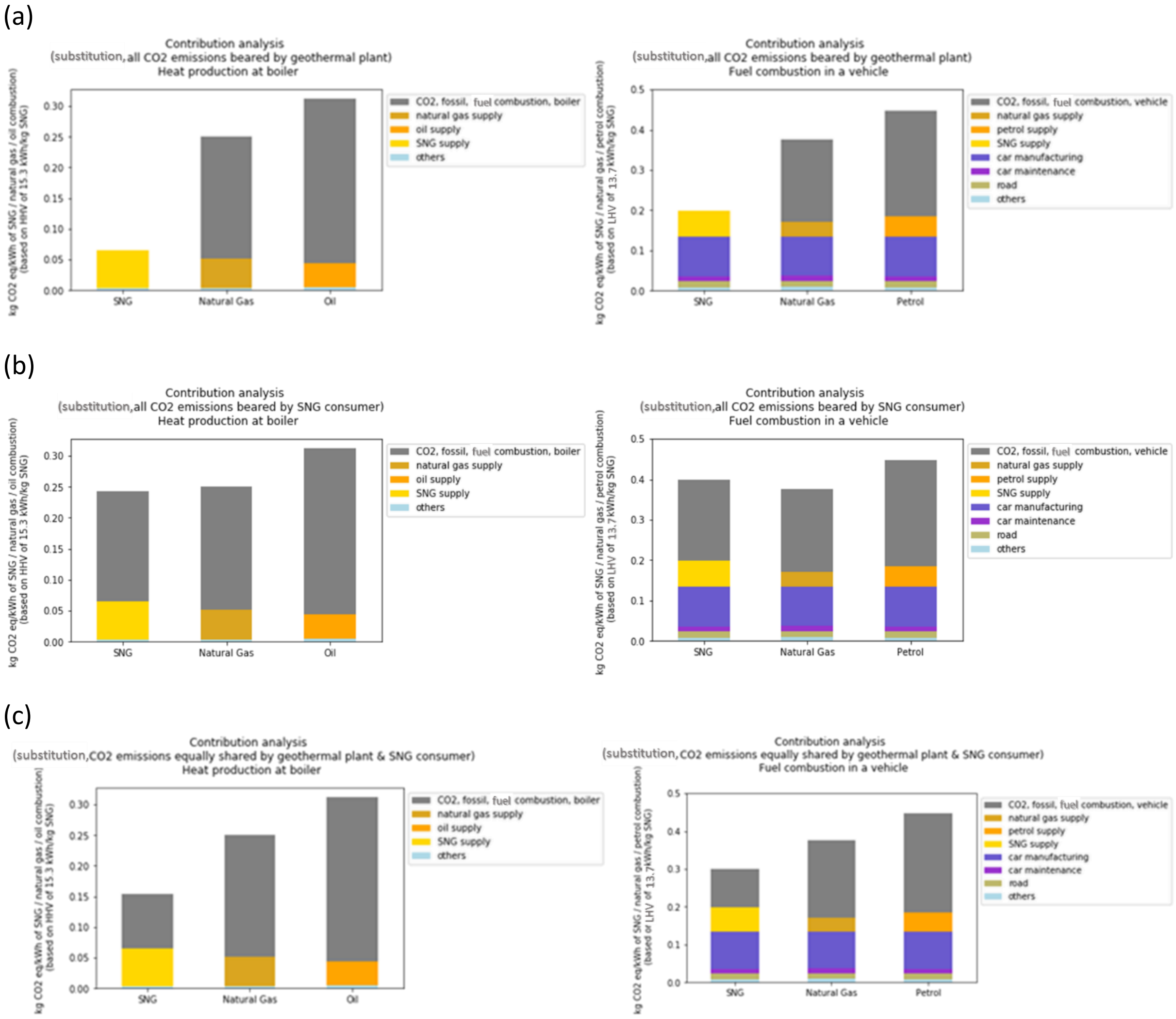

Figure 7: Contribution analysis of GHG emissions per functional unit (substitution): (a) emissions of CO_2 after the end-consumption of SNG are assigned to electricity production at the geothermal plant, despite the physical emissions of CO_2 after the combustion of produced SNG in Switzerland; (b) emissions of CO_2 after the end-consumption of SNG are assigned to the SNG consumer as physical emitter; (c) emissions of CO_2 after the end-consumption of SNG are equally shared between geothermal plant (50%) and SNG end-consumer (50%); 100% Icelandic hydropower for electrolysis is applied in all three options.

The absolute life cycle GHG emissions reductions comparing the system with SNG and with conventional natural gas or oil are the same as shown in the system expansion approach; the only difference is, all the emissions reductions as a result of CO_2 capture and utilization are assigned to the system of SNG production, transportation, processing and end-consumption, when CO_2 emissions are entirely attributed to the geothermal power plant (CO_2 supplier).

Assigning zero, 50%, or 100% of the CO_2 emissions to the SNG end-user might seem arbitrary. However, there are certain lines of argumentation behind these fractions.

Zero, i.e. complete assignment of CO_2 emissions to the geothermal power plant as CO_2 supplier, corresponds to the argument that these emissions would have happened anyway, independently of the capture and use as SNG feedstock – therefore, the SNG user would not be responsible for these emissions. As long as the availability of CO_2 from point sources such as geothermal power plants is way beyond the demand for CO_2 for e.g. synthetic fuel production, this argument can be considered as legitimate, as also discussed in [1]. In other words, as long as CO_2 emissions from point sources exceed demand for feedstock CO_2 by far, an increase in CO_2 demand would not increase CO_2 production of these point sources and they can be considered as "rigid", and their CO_2 emissions as "happening anyway".

Assigning 100% of CO_2 emissions to the SNG end-user corresponds to the physical reality of elementary flows: emissions take place due to SNG combustion and the emissions of the CO_2 point source (CO_2 supplier) are actually reduced by the amount of CO_2 captured and supplied as feedstock. Therefore, from the perspective of the CO_2 supplier, there might be a very limited willingness to be attributed with these CO_2 emissions, especially if CO_2 emission allowances have to be purchased (e.g., as part of the EU ETS), or if CO_2 emitters (producers) aim for CO_2 reduction as strategic goal triggered by climate policy. However, CCU-based SNG production is unlikely to take place, if SNG as fuel cannot be credited with reduced CO_2 emissions.

Finally, assigning 50% of the overall reduction of CO_2 emissions to both CO_2 supplier and SNG end-user would be in line with the maximum overall reduction of CO_2 emissions achievable with CCU-based synthetic fuels substituting fossil fuels, which is 50%.[20] Such a procedure might be considered as "fair benefit/burden sharing", as soon as the transport and/or the residential sector would be included in the European Emissions Trading System (ETS).

5.2. Contribution analysis of SNG production

The contributions to overall life cycle GHG emissions for SNG production and supply by process in the production and supply chain up to the end-user are shown in Figure 8, while their absolute GHG emissions, main assumptions and references used are listed in Table 7. The life-cycle GHG emission of SNG supply before its end use/combustion is about 62 g CO_2-eq per kWh SNG (based on HHV, equivalent to 0.09 Nm^3 of SNG, which is sufficient for 3.6 MJ of heat production by a gas boiler). Out of this, 18 g of CO_2-eq (29%) are contributed by hydrogen production via electrolysis, in which electricity supply from the Icelandic hydropower is a major contributor (14 g of CO_2-eq per 1 kWh SNG production). The second largest contributor to GHG emissions is CO_2 processing and supply from geothermal power plant, which is about 13 g of CO_2-eq (20%), mainly contributed by the processing facilities. The contributions from chemical consumptions (e.g., activated carbon, etc.) to process the CO_2 supply is insignificant. Although the consideration of facilities and material consumption required

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[20] Using CO_2 from a fossil/geogenic point source for production of CCU-based fuels shifts the CO_2 emissions from the point source from this point source to the CCU-fuel combustion. If the CCU-fuel replaces conventional fossil fuel, the emissions due to combustion of this fossil fuel are avoided – the amounts of CO_2 emissions at the point source captured and released due to fuel combustion must be identical. Therefore, compared to a system of CO_2 point source and fossil fuel without CCU in place, the system with CCU in place can reduce overall CO_2 emissions by 50% at best, if 100% of CO_2 at the point source are captured and used for CCU-fuel production [22]. In practice and from an LCA perspective, reductions will always be less due to indirect emissions from energy and material supply chains in the CCU system.

for the CO_2 processing can be further refined, it is not expected to increase this contribution significantly. Contribution of transportation (Case 1.0 in Figure 8 is considered for illustration purpose) of SNG from Iceland to Switzerland is in general less significant, contributing about 11%. Remaining contributions are those from the methanation process (8%), which is dominated by the electricity consumption, gas regasification from its liquid form (11%), gas injection and transport (6%), gas from gaseous to liquid (5%) and others miscellaneous emissions (13%, such as infrastructure in other processing steps, etc.).

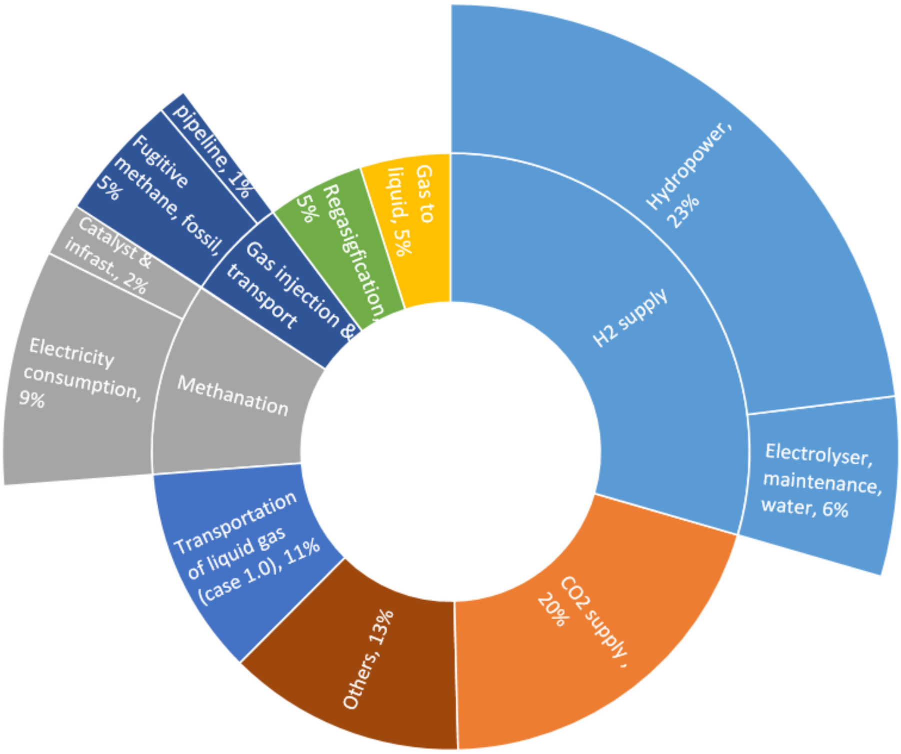

Figure 8: Contribution analysis of life cycle GHG emissions of SNG production and supply (transport case 1.0, see below; 100% Icelandic hydropower for electrolysis); "Others" include other processing facilities throughout the production and supply chain (e.g., condensation unit after methanation, etc.).

Table 7: Absolute life cycle GHG emissions per kWh SNG, as shown in Figure 8, corresponding key assumptions and references by process.

Processes	**Life cycle GHG emissions** (g of CO_2-eq/kWh SNG, based on HHV)	**Key assumptions and reference**	**Key references**
H_2 supply	18	System electricity consumption of PEM electrolyzer: 5.2 kWh/Nm3 of SNG (more details in Table 8)	Zhang et al. 2017 [4]
		Life cycle GHG emissions of Icelandic hydropower supply: 8 g CO_2 eq/kWh, which is estimated based on the Icelandic hydropower production dataset in ecoinvent, with updates of direct CO_2 emissions from hydropower plants in Iceland	ecoinvent v3.6, allocation cut-off system model [11] National inventory report, Iceland, 2019 [8]
Gas injection & transportation to low-pressure network	4	Mainly adapted from ecoinvent dataset "market for natural gas, low pressure, CH" with updated gas supply of SNG (section 4.5.5) and reduced fugitive methane emissions according to the feedback of project partner[21]	ecoinvent v3.6, allocation cut-off system model [11]
CO_2 supply	12	Required chemicals, facilities per kg of CO_2 supply: - MEA: 4.8E-5 kg - Activate carbon: 1.2E-3 kg - 4.4E-10 unit of chemical factory, organics as in ecoinvent - storage unit not considered	Zhang et al. 2020 [5] ecoinvent v3.6, allocation cut-off system model [11]
Transportation of liquid gas (case 1.0)	7	Project-specific assumptions (section 4.5.4)	-
Gas regasification from liquid	3	Adapted from ecoinvent activity "evaporation of natural gas, RER" by: 1) deleting transportation as project-specific transportation is included; 2) updating the electricity supply location depending on injection point	ecoinvent v3.6, allocation cut-off system model [11]
Methanation	6[22]	2.7 kg of CO_2 and 0.5 kg of H_2 is required to produce 1 kg of SNG	Zhang et al. 2017 [4]
Gas from gaseous to liquid	3	Mainly adapted from ecoinvent dataset "natural gas production, liquefied, RME"	ecoinvent v3.6, allocation cut-off system model [11]
		Updated electricity supply to be Icelandic hydropower, with a consumption of 1.66 kWh/kg of SNG for liquefaction of gas.	Project partner information
Others	6	-	-

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[21] Personal communication by Bettina Bordenet, Dec 7, 2020.

[22] This could increase to 20 g of CO_2-eq/kWh SNG (or 23% increase in comparison with the current life cycle GHG emissions of SNG production of 62 g CO_2-eq/kWh) if the electricity consumption in catalyst production, as reported by Agarski et al. 2017 [15]) were considered (~700 kWh/kg for Ni/Al_2O_3 catalyst). However, since this is the only data source on electricity consumption in catalyst production in literature, and the quality of the study is questionable (potential misuse of the datasets from incorrect system model of the background data base or versions was observed, and the figure on electricity consumption cannot be reproduced using original literature), it is per default not included in this study. This is however subject to future improvement once more data is available.

5.3. Electricity supply to electrolysis

Although 100% Icelandic hydropower is used in this analysis as default option, depending on the detailed contract of power purchase, the electricity supply to PEM electrolysis to produce hydrogen could actually be partially supplied from medium-voltage Icelandic grid power supply, which consists of 76% hydropower and 24% of geothermal power. Since the greenhouse gas emission accounting approach applied to this power supply depends on whether the purchased power has "added" renewable electricity to the power system[23], it is important to understand the difference of these different potential power supplies, and their influence on the life cycle GHG emissions of SNG production. Thus, the life cycle GHG emissions for these power supplies are shown in Figure 9, in which grid power supply has 0.019 kg CO_2-eq/kWh, while the updated hydropower supply (with CO_2 emissions from fuel combustion and land use change in the reservoir according to [20]) has 0.008 kg CO_2-eq/kWh[24] and geothermal power supply has 0.023 kg CO_2-eq/kWh. Note that Icelandic grid supply takes into account the GHG emissions associated with the transmission and distribution of electricity as well as the grid infrastructure, thus it is not only the weighted sum of life cycle GHG emissions from hydropower and geothermal power directly.

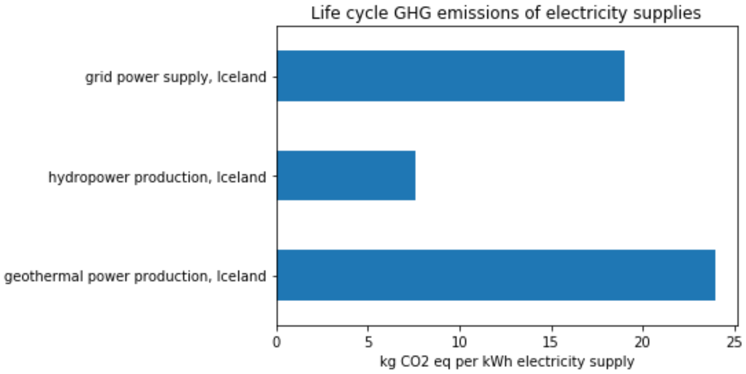

Figure 9: Life cycle GHG emissions of potential electricity supplies for electrolysis in Iceland. The result for geothermal power production is produced using a dataset from ecoinvent v3.6, allocation, cut-off model, while the result for hydropower production is generated by updating the corresponding ecoinvent dataset with data from the National GHG inventory report from Iceland. The result for grid power supply from Iceland takes into account the updated hydropower datasets for Iceland in the gird supply mix and includes GHG emissions from electricity transmission and distribution as well as grid infrastructure.

Depending on which type of electricity will be purchased for how many units of electricity consumed in the electrolyzer, the life cycle GHG emissions associated the SNG supply can vary. The type of electricity certificates to be purchased for this SNG production project allows for claiming the credits of consuming renewable electricity, since the generation of hydropower to be consumed depends on its consumption; in other words, the amount of hydropower guaranteed by the purchase contract and consumed by the electrolyser is only produced, if supplied to and consumed by the electrolyzer. The resulting variation of life-cycle GHG emissions is shown in Figure 10. Two approaches in terms of how electricity with hydropower certificates can be treated in LCA are investigated: 1) the purchased hydropower is surplus electricity[25] and thus has zero-emissions; 2) the purchased hydropower will have reduced life cycle GHG emissions due to increased utilization of existing power plant infrastructure (currently assumed as 25% increase of utilization). The results show that, depending on

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[23] «Vorschlag der PtX Allianz zur Ausgestaltung und Gewichtung der Kriterien für den Strombezug von Elektrolyseuren zur Produktion erneuerbarer Kraftstoffe nach Art. 27 der Erneuerbare-Energien-Richtlinie (RED II)»: https://www.ptx-allianz.de/vorschlag-der-ptx-allianz-zur-ausgestaltung-und-gewichtung-der-kriterien-fuer-den-strombezug-von-elektrolyseuren-zur-produktion-erneuerbarer-kraftstoffe-nach-art-27-der-erneuerbare-energien-richtlini/

[24] The original life cycle GHG emissions for Icelandic hydropower supply according to ecoinvent v3.6 (system model "allocation, cut-off by classification") are 0.051 kg $CO_{2\text{-eq}}$/kWh. The result from the updated dataset is much lower, which is a result of the corrected direct CO_2 emissions from the non-alpine reservoir and other assumptions that more precisely reflect the situation in Iceland.

[25] Since Iceland is not connected to the European electricity grid, the electricity market is relatively small and hydropower plant operators could generate more electricity than they currently do in the existing power plants without modifying their facilities. Such production could be considered as "surplus hydropower".

the approach, the life cycle GHG emissions of electricity supply will range from 4 to 10 g CO_2-eq/kWh, which is about 50% to 77% decrease of emissions in comparison with the current Icelandic grid supply (19 g CO_2-eq/kWh), but very similar to average Icelandic hydropower (8 g CO_2-eq/kWh), which is applied in the analysis per default. Due to these minor differences of scenarios A-D compared to the average hydropower in Iceland, the effect of these scenarios A-D on the overall impacts on climate change from SNG supply and use is minor and is not further analyzed in calculating overall LCA results. However, for comparison and as a "worst case option" in terms of GHG emissions, overall LCA results are also quantified using the Icelandic grid mix for electrolysis.

The option of considering the purchased hydropower as "excess electricity" with zero environmental burdens is also dismissed, since such excess electricity is usually associated with zero or even negative electricity prices, which is not the case in the present analysis.

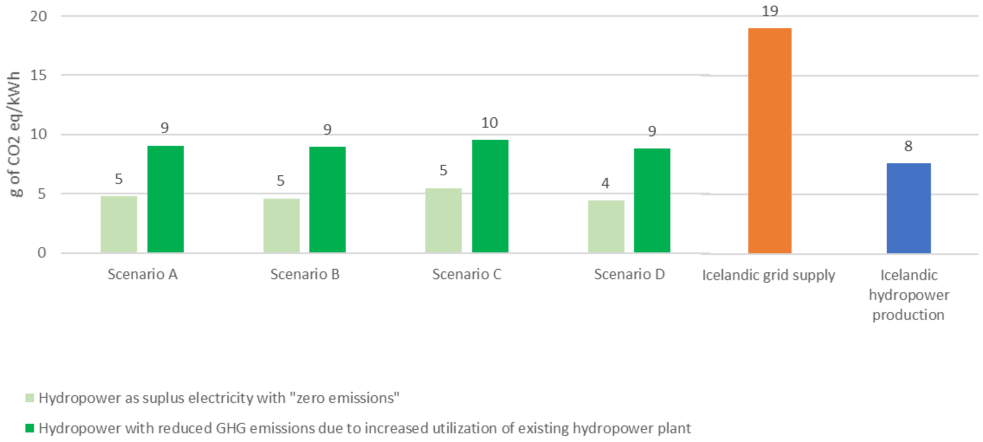

Figure 10: Life cycle GHG emissions of electricity supplies for electrolysis considering different scenarios (as shown in Table 2). 100% Icelandic hydropower is applied in Figure 6, Figure 7 and Figure 8, while results considering 100% Icelandic grid supply are included in the Appendix Figure S2-4 for comparison.

5.4. Transportation of SNG

Different cases of SNG transportation pathways (Table 6) are investigated. As shown in Figure 11, case 3.0 shows the lowest life cycle GHG emissions (4 g CO_2-eq/kWh of SNG transportation), while case 7.0 has the highest life cycle GHG emissions (15 g CO_2-eq/kWh of SNG transportation). But in general, the contribution from transportation to the overall life cycle GHG emissions of SNG supply (7 g CO_2-eq/kWh of SNG supply in case 1.0, as shown in Figure 8), remains low, and the associated potential variations should not be considered as determining factor choosing a certain transport pathway.

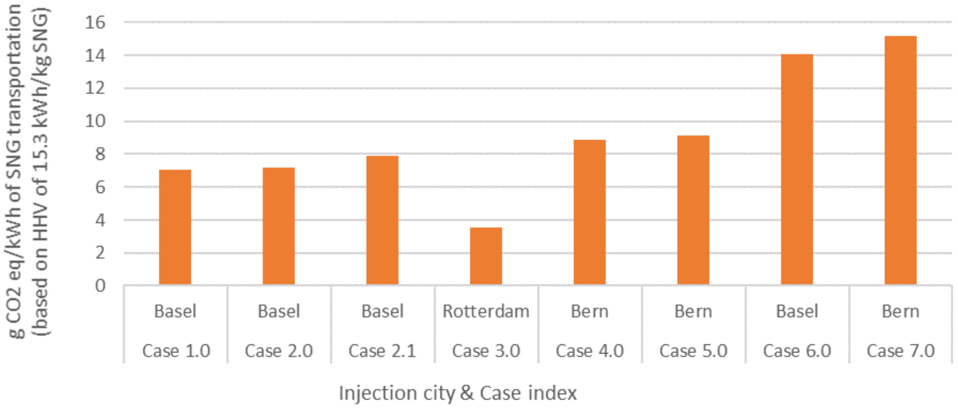

Figure 11: Life cycle GHG emissions per kWh of SNG transportation, in g CO_2-eq/kWh of SNG (based on HHV) transportation from Iceland to Switzerland.

6. Conclusions

This analysis has quantified life-cycle GHG emissions (and “ecological scarcity scores”, supposed to represent overall environmental impacts) of synthetic natural gas (SNG) production in Iceland using local hydropower for electrolysis and CO_2 captured at the geothermal power plant Hellisheiði, and its subsequent transport and use in Switzerland – either as heating, or vehicle fuel. Different alternatives for electricity supply for the electrolyzer and transport of SNG to Switzerland have been taken into account.

SNG production with CO_2 captured at the geothermal power station and its use as fuel represents a case of “Carbon Capture and Utilization” (CCU). There are different approaches for dealing with CCU-based fuels in LCA and they can be decisive regarding LCA results. The present analysis shows indeed, that the approach for how to deal with the multi-functionality of the geothermal power plant (generating electricity, heat, and CO_2 used as feedstock for methanation) represents a decisive factor regarding impacts on climate change of SNG production and use. Both system expansion and substitution have been applied in this analysis. System expansion represents the overall system perspective including both geothermal electricity production and SNG use for heating or mobility; substitution allows for the quantification of product-specific environmental burdens of SNG and represents the individual perspectives of the operators and producers of the geothermal plant and SNG, respectively.

Attributing the CO_2, which is emitted by the SNG user, to either geothermal energy or SNG combustion can be avoided by a system expansion approach, which quantifies combined environmental impacts of geothermal energy generation, and SNG production and use. From this perspective, using SNG in boilers and passenger vehicles instead of natural gas can reduce overall system life-cycle GHG emissions by 37% and 27%, respectively. This overall system perspective might, however, not be applicable or useful from the point of view of regulating authorities, SNG producers, and geothermal facility operators. From these individual perspectives, attributing CO_2 emissions to specific processes is likely to be required, and for this purpose, the substitution approach is applied (as recommended by relevant guidelines). If CO_2 emissions of SNG boilers and vehicles are entirely assigned to the geothermal energy plant, SNG can achieve life-cycle GHG emission reductions in comparison to natural gas of more than 70% and almost 50% when used as heating and passenger vehicle fuel, respectively.

The LCA confirms the importance of low-carbon electricity for electrolysis to allow for a substantial reduction of life-cycle GHG emissions by substituting natural gas with SNG. However, basically all available options in Iceland exhibit low GHG emissions and therefore, differences between potential options are minor in terms of impacts on climate change. Transport of SNG from Iceland to Switzerland in general is of minor relevance in terms of contributions to life-cycle GHG emissions.

Applying the method of ecological scarcity to the SNG production, supply and use chain results in negative scores, i.e. a positive impact on the environment. This is a result of exhaust gas cleaning at the geothermal plant required when CO_2 is captured and supplied as feedstock for methanation. Methanation does not tolerate Sulphur and the gas cleaning reduces H_2S emissions to such an extent that this positive impact on the environment is higher than all the burdens along the SNG production, supply, and use. However, this result must be interpreted carefully, since the ecological scarcity method is Swiss-specific – quantifying environmental burdens and benefits in Iceland according to environmental issues and policy goals in Switzerland hardly represents the situation in Iceland appropriately, especially when it comes to acidification (to which H_2S emissions contribute), which is largely due to agriculture in Switzerland.

Main uncertainties in the current LCA are related to the fact that it often has to rely on more or less generic literature data for process performance, since the SNG production and transport chain is not yet in place. However, it is not expected that process performance in reality will substantially differ from currently used figures and therefore, LCA results (regarding life-cycle GHG emissions) can be regarded as reliable. Uncertainties in the regulatory context are by far more decisive when it comes to practical implementation of the evaluated SNG production and use chain.

7. Appendix

7.1. Ecological scarcity – «Methode der ökologischen Knappheit» (Umweltbelastungspunkte)

Eco-points (Umweltbelastungspunkte "UBP") according to the Life Cycle Impact Assessment (LCIA) method Ecological Scarcity or "Methode der Ökologischen Knappheit" [19] have been quantified, supposed to represent to "overall" environmental impact of SNG production and use. These results are only included in the Appendix, because of two factors limiting the informative value of these results:

1) The method is currently being updated, mainly because the current version does no longer reflect climate policy in Switzerland[26] – according to the new version, GHG emissions will become more important compared to other impacts.
2) The method is supposed to represent Swiss policy goals, regulations, and concerns regarding environmental aspects, while a large part of the impacts of the SNG chain happens elsewhere.

Since UBP scores are a mandatory element for a request for tax exemption for "renewable-based fuels" in Switzerland, and such a request requires product-specific LCA results, only the substitution approach (see section 4.2 for a discussion of system boundaries and accounting approaches) is applied, and the same three options for assigning CO_2 emissions to CO_2 supplier and SNG user are applied as in Figure 7.

Figure S1 shows a contribution analysis for overall UBP scores per functional unit for the substitution approach. Negative scores for SNG supply are due to H_2S removal as an effect of CO_2 capture representing a positive impact on the environment, as discussed above. The same three options for attribution of CO_2 emissions as in Figure 7 are distinguished, namely (a) assigning CO_2 emissions due to SNG combustion entirely the CO_2 supplier (geothermal plant), (b) entirely to the SNG end-user, and (c) 50% to CO_2 supplier and 50% to SNG end-user. However, the effect of this differentiation on overall results is, compared to impacts on climate change, minor, since negative scores due to H_2S removal dominate the results.

shows overall eco-points according to the ecological scarcity method (substitution approach). The UBP results – supposed to represent the "overall environmental impact" – show one major difference in comparison with the life-cycle GHG emissions shown in Figure 7: due to catalyst's intolerance of sulfur content in the methanation process, the H_2S emissions after Sulfix at the geothermal power plant have to be further reduced until the Sulphur concentration reaches a level of less than 1 ppm, which is very close to zero [21]. Therefore, it is assumed that the H_2S emissions are entirely removed and reduced to zero before CO_2 is fed into methanation. Thus, capturing and supplying CO_2 for the production of SNG results in H_2S emission reduction, which is considered as a positive impact to the environment (associated with negative UBP scores). Since with the substitution approach the environmental impacts of SNG production are calculated as the difference between geothermal power generation with and without CO_2 capture and reduced H_2S emissions are an effect of CO_2 capture, SNG is assigned with the associated environmental benefit (negative UBP score).

Different from CO_2 emissions, the reduction of H_2S emission due to CO_2 capture is always entirely attributed to SNG production – justified by the fact that CO_2 is used as feedstock shifting emissions from the geothermal plant to the SNG end-user with a maximum reduction of overall emissions of 50%, while the reduction of H_2S emissions is simply due to CO_2 utilization and emissions are not shifted. In other words, both provider and consumer of the CO_2 are needed to reduce the overall system GHG

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[26] Other than climate change related aspects will be updated as well, but these are not expected to have substantial effects on LCA results as opposed to the climate change related update.

emissions (as shown in the results of system expansion as in Figure 6), thus it is arguable to which entity the CO_2 emissions should be attributed. For the H_2S emission, the further emission reduction is clearly as a result of CO_2 utilization by the SNG production, thus the “credits” for H_2S emission removal are fully assigned to the SNG producer/consumer.

The characterization factor[27] (CF) for H_2S emission in the Ecological Scarcity method is high, as a result of its relatively high acidification potential and the fact that acidification represents a major environmental concern in Switzerland. This CF amounts to 39 UBP per g of H_2S emission (in comparison for instance with the CF for CO_2, which is 0.46 UBP per g of CO_2). To produce 1 kWh of SNG, 0.178 kg of CO_2 with low sulfur content is required, which results in 0.02848 kg of H_2S emission removal (i.e. minus 0.029 kg of H_2S emission). Converting these negative emissions to UBP, minus 1110 UBP/kWh SNG as a result of this emission removal are obtained. In comparison with other contributions to the overall UBP score in SNG production and processing, this negative contribution as a result of H_2S emission removal dominates, mainly driven by the high value of characterization factor of H_2S emission, and results in overall negative UBP scores (corresponding to a positive impact on the environment) for SNG production, supply and end-use. The main positive contribution to UBP scores (i.e. negative impact on the environment) is due to use of hydropower as a potentially limited natural resource.

However, this result should be interpreted with considerable caution, due to the general limitations of the ecological scarcity method mentioned above[28], as well as the fact that acidification impact can be highly regional: actual acidification impacts depend on the fate or pathway of the emitted substances from the point of emission to the biosphere, and the background concentration in air, soil and water. However, the Ecological Scarcity method contains only Swiss-specific acidification characterization factors, to be applied globally-equal (i.e. equal acidification impact per kg of H_2S emissions regardless of the location of emissions).

Table S 1: Eco-points for 1 kWh of SNG production (100% Icelandic hydropower applied in electrolysis) and end use with substitution approach and applying the ecological scarcity impact assessment method [19]. Negative scores indicate a positive overall effect on the environment.

Approach	**Substitution**					
SNG end use	**Boiler** (per kWh SNG combustion or 3.6 MJ of heat supply)			**Vehicle** (per kWh SNG combustion or 1.3 km of distance driven)		
Attribution of CO_2 emissions from SNG end-use	100% geothermal plant	50% geothermal plant; 50%SNG consumer	100% SNG consumer	100% geothermal plant	50% geothermal plant; 50%SNG consumer	100% SNG consumer
SNG	-951	-911	-870	-771	-725	-679
Conventional alternatives						
Natural gas (boiler / vehicle)	154			439		
Oil (boiler)	225			-		
Petrol (vehicle)	-			523		

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[27] Characterization factor is a conversion factor in Life Cycle Impact Assessment that converts emissions to soil, water and air, resource extractions, and land use transformations into different environmental impacts.

[28] The main limitation in the context of the present analysis is the following: The characterization factor for H_2S emissions in Iceland is very likely to deviate considerably from the one in Switzerland, since both the current and critical flows of H_2S will substantially differ. In Switzerland, acidification is an environmental issue mainly related to agriculture and the application of manure. Current emissions of substances contributing to acidification are high and therefore, such emissions get a high weight in the ecological scarcity method. The present UBP scores are therefore unlikely to represent “true” environmental impacts in Iceland, where acidification due to agriculture cannot be expected to represent a major environmental issue, in an appropriate way.

Figure S1 shows a contribution analysis for overall UBP scores per functional unit for the substitution approach. Negative scores for SNG supply are due to H_2S removal as an effect of CO_2 capture representing a positive impact on the environment, as discussed above. The same three options for attribution of CO_2 emissions as in Figure 7 are distinguished, namely (a) assigning CO_2 emissions due to SNG combustion entirely the CO_2 supplier (geothermal plant), (b) entirely to the SNG end-user, and (c) 50% to CO_2 supplier and 50% to SNG end-user. However, the effect of this differentiation on overall results is, compared to impacts on climate change, minor, since negative scores due to H_2S removal dominate the results.

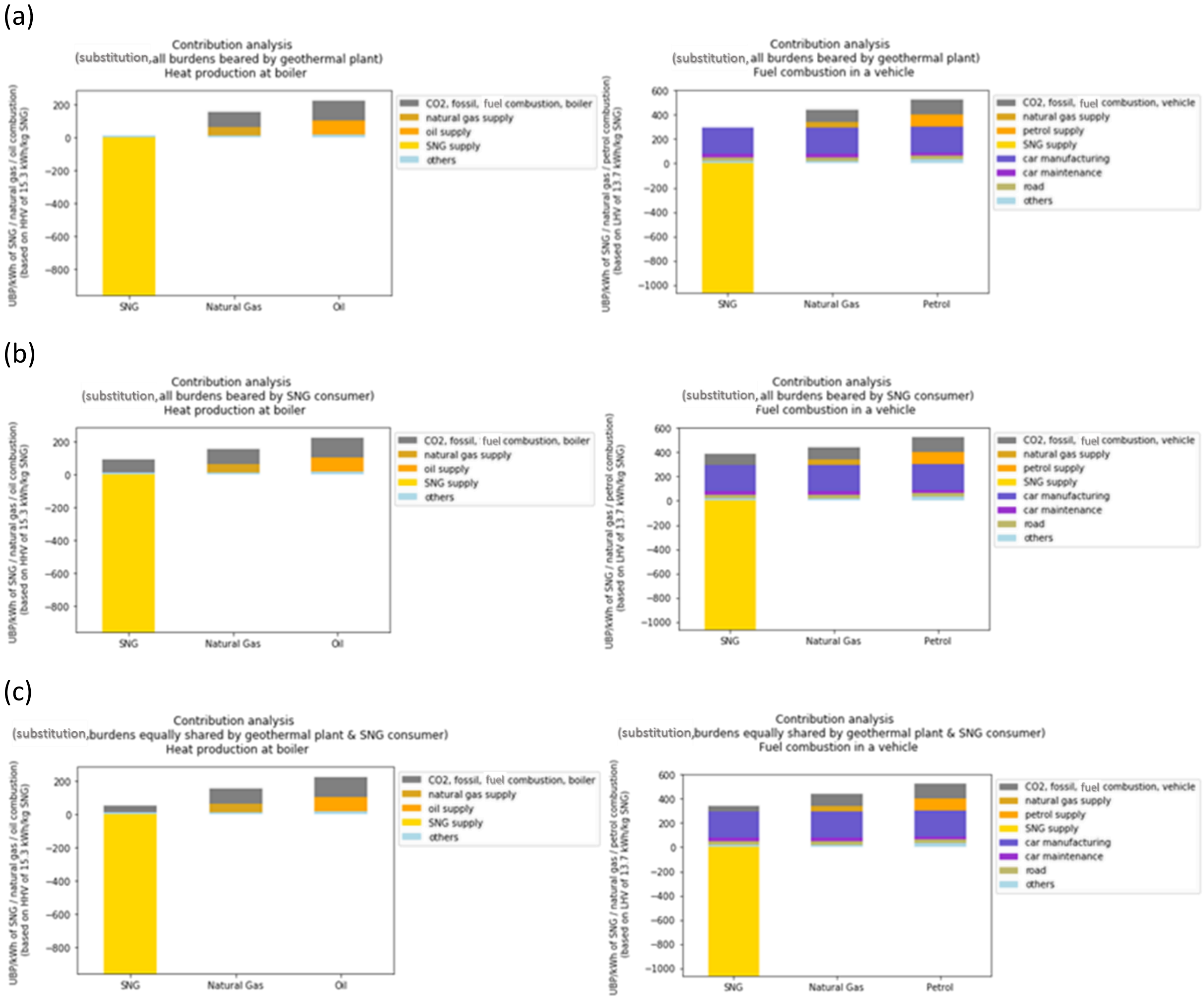


Figure S 1: Contribution analysis of UBP scores per functional unit (substitution; 100% Icelandic hydropower applied in electrolysis): (a) burdens of CO_2 emissions due to SNG combustion are assigned to electricity production at the geothermal plant, despite the physical emissions at the combustion of produced SNG in Switzerland; (b) burdens of CO_2 emissions due to SNG combustion are assigned to the SNG consumer, where CO_2 is physically emitted; (c) burdens of CO_2 emissions due to SNG combustion are equally shared between geothermal plant (50%) and SNG end-consumer (50%).

7.2. Sensitivity analysis – use of Icelandic electricity grid mix instead of hydropower for SNG production

As explained in section 5.3, sensitivity analysis on the type of electricity supply for SNG production is carried out. Results for impacts on climate change using the average electricity grid mix in Iceland for electrolysis are shown in the following two figures: applying system expansion approach in Figure S2, and substitution approach in Figure S3. Since the GHG intensity of the grid mix is slightly higher than the one of hydropower (Figure 9) (but still very low compared to other countries[29]), the GHG emissions associated with SNG production (light orange contribution in the figures) are a bit higher than with hydropower, and the reduction of GHG emissions of SNG boilers and vehicles, compared to their natural gas (and oil/petrol) alternatives, is slightly smaller than when using Icelandic hydropower.

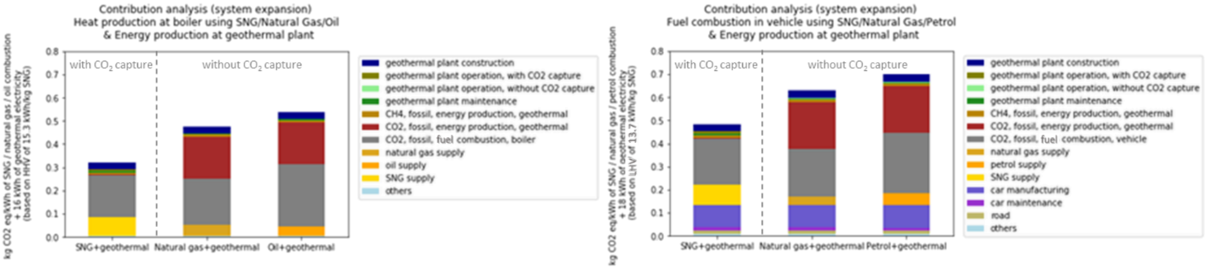
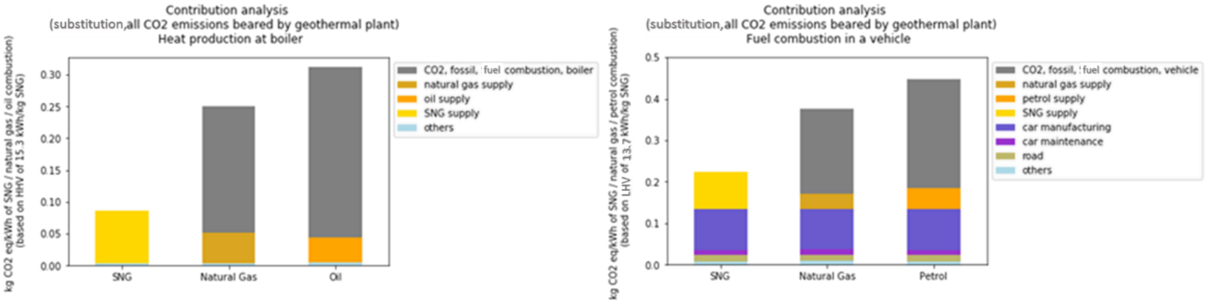
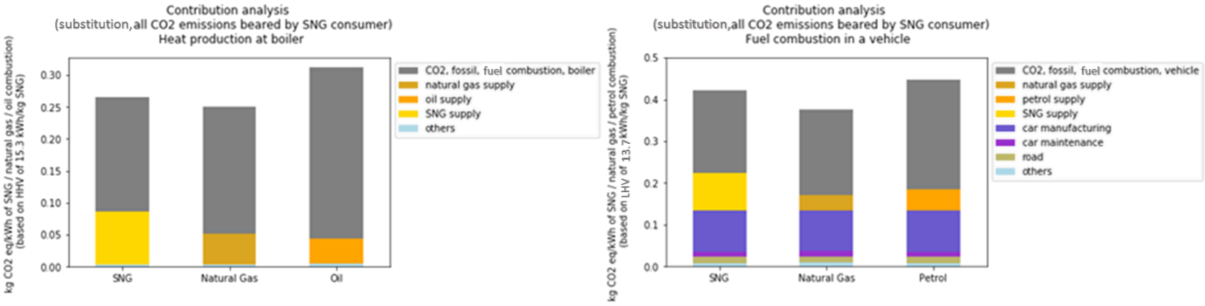


Figure S 2: Contribution analysis for GHG emissions, system expansion approach; left: life cycle GHG emissions per kWh of SNG combustion in a boiler (corresponding to 3.6 MJ of heat production) and 16 kWh of electricity production at the geothermal plant with CO_2 utilization vs. 3.6 MJ of heat production in a boiler with natural gas or heating oil, and 16 kWh of electricity production at the geothermal plant without CO_2 utilization; right: life cycle GHG emissions per kWh of SNG combustion in a CNG vehicle (corresponding to 1.3 km of distance travelled) and 18 kWh of electricity production at the geothermal plant with CO_2 utilization vs. 1.3 km of distance travelled by a CNG vehicle with conventional natural gas supply in Switzerland, or by a vehicle powered by petrol, and 18 kWh of electricity production at the geothermal plant without CO_2 utilization. In the systems with SNG as fuel, SNG transportation case 1.0 is applied, and 100% Icelandic grid electricity supply is used in PEM electrolysis to produce hydrogen.

(a)



(b)



(c)

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[29] For comparison – GHG intensity grid mix Iceland, as used in this analysis: 19 g CO_{2eq}/kWh (similar to wind power); Switzerland: 100-150 g CO_{2eq}/kWh (depending on the annual imports); EU: ca. 400 g CO_{2eq}/kWh.

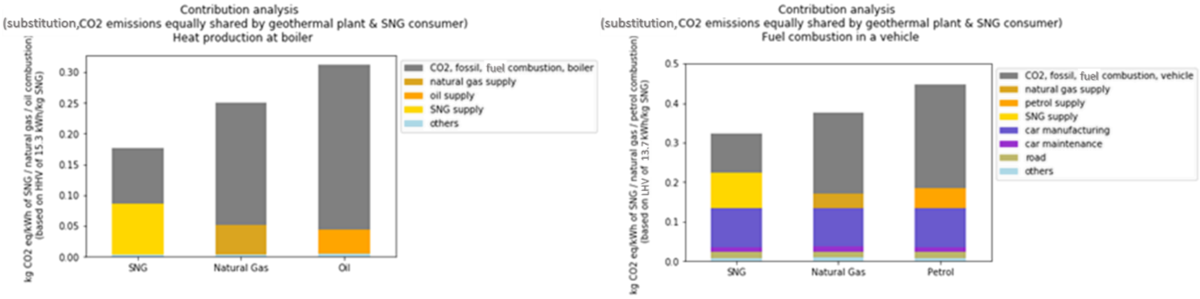

Figure S 3: Contribution analysis of GHG emissions, substitution approach: (a) emissions of CO_2 due to SNG combustion are assigned to electricity production at the geothermal plant, despite the physical emissions of CO_2 due to combustion of SNG in Switzerland; (b) emissions of CO_2 due to SNG combustion are assigned to the SNG consumer as the physically emitter; (c) emissions of CO_2 due to SNG combustion are equally shared between the geothermal plant (50%) and SNG end-consumer (50%); 100% Icelandic grid electricity supply for electrolysis is applied.

Applying the system expansion approach (Figure S2), the SNG boiler reduces system GHG emissions by about 33% compared to the natural gas boiler and about 41% compared to the oil boiler (as opposed to 37% and 44%, respectively, with Icelandic hydropower). Applying the substitution approach for the quantification of product-specific life-cycle GHG emissions for SNG production and use, and attributing CO_2 emissions due to SNG combustion entirely to the geothermal plant (CO_2 supplier), results in a reduction of life-cycle GHG emissions of SNG as heating fuel by 65% and 72%, compared to a natural gas and oil boiler, respectively (Figure S3(a), left panel). Applying the same approach for SNG as vehicle (Figure S3(a), right panel) fuel results in reductions of life-cycle GHG emissions of SNG by 41% and 50%, respectively, compared to a natural gas and a petrol vehicle.

Figure S4 shows the contribution analysis for life-cycle GHG emissions of SNG production and supply to the end-user in Switzerland, using Iceland's electricity grid mix for SNG production. Compared to using hydropower, emissions per unit of SNG slightly increase from 62 g CO_2-eq per kWh SNG (based on HHV) to 84 g CO_2-eq per kWh SNG. The emissions associated with grid mix electricity supply for electrolysis increase to almost half of the total emissions per unit of SNG production and supply, which shows that low GHG emissions of SNG production crucially depend on low-carbon electricity.

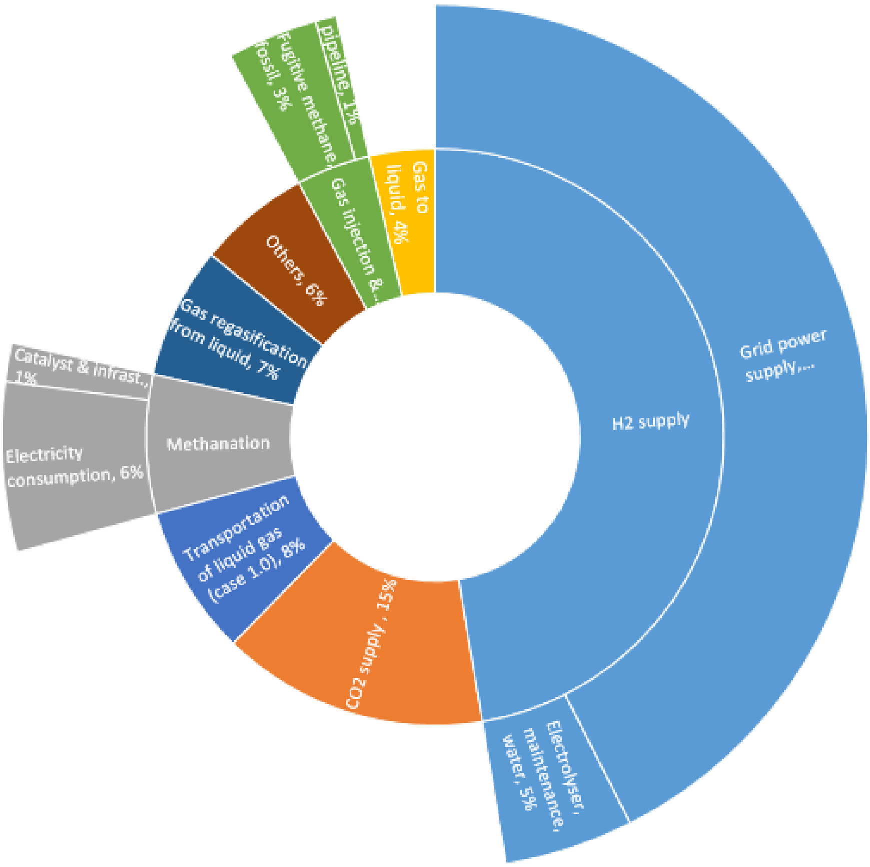

Figure S 4 Contribution analysis of life cycle GHG emissions of SNG production and supply (transport case 1.0); 100% Icelandic grid supply for electrolysis; "Others" include other processing facilities throughout the production and supply chain (e.g., condensation unit after methanation, etc.).

References

[1] L. J. Müller *et al.*, “The carbon footprint of the carbon feedstock CO2,” *Energy Environ. Sci.*, vol. 13, no. 9, pp. 2979–2992, 2020.

[2] L. J. Müller, A. Kätelhön, M. Bachmann, A. Zimmermann, A. Sternberg, and A. Bardow, “A Guideline for Life Cycle Assessment of Carbon Capture and Utilization,” *Front. Energy Res.*, vol. 8, no. February, pp. 1–20, 2020.

[3] ISO, “ISO 14044: Life cycle assessment — Requirements and guidelines,” *International Organization for Standardization*, vol. 14044. p. 46, 2006.

[4] X. Zhang, C. Bauer, C. L. Mutel, and K. Volkart, “Life Cycle Assessment of Power-to-Gas: Approaches, system variations and their environmental implications,” *Appl. Energy*, vol. 190, pp. 326–338, Mar. 2017.

[5] X. Zhang, J. Witte, T. Schildhauer, and C. Bauer, “Life cycle assessment of power-to-gas with biogas as the carbon source,” *Sustain. Energy Fuels*, 2020.

[6] M. R. Karlsdóttir, Ó. P. Pálsson, H. Pálsson, and L. Maya-Drysdale, “Life cycle inventory of a flash geothermal combined heat and power plant located in Iceland,” *Int. J. Life Cycle Assess.*, vol. 20, no. 4, pp. 503–519, Apr. 2015.

[7] M. R. Karlsdottir, J. Heinonen, H. Palsson, and O. P. Palsson, “Life cycle assessment of a geothermal combined heat and power plant based on high temperature utilization,” *Geothermics*, vol. 84, p. 101727, Mar. 2020.

[8] The Environment Agency of Iceland, “National Inventory Report, Emissions of Greenhouse Gases in Iceland from 1990-2017,” p. 421, 2019.

[9] R. Edwards, J. Rejtharova, M. Padella, J. Wachsmuth, and S. Lehmann, “Draft Methodology for Calculation of GHG emission avoidance First Call for proposals under the Innovation Fund - Discussion Paper in support of Technical Workshop 5 February 2020,” 2020.

[10] X. Zhang, C. Bauer, C. Mutel, and K. Volkart, “Life Cycle Assessment of Power-to-Gas: Approaches, system variations and their environmental implications,” *Appl. Energy*, vol. 190, pp. 326–338, 2017.

[11] B. P. Weidema *et al.*, “Data quality guideline for the ecoinvent database version 3,” 2013.

[12] JRC EC, “Product Environmental Footprint Category Rules Guidance,” 2018.

[13] R. Frischknecht and R. Itten, “Book , trade and claim systems in LCA : how to model certificates delinked from physical flows,” *SETAC 6th World Congr. Eur. 22nd Annu. Meet.*, no. May 2012, pp. 4–6, 2012.

[14] G. Jachin, “System design for IMPEGA, from Hochschule für Technik Rapperswil, on Apr 30,” 2020.

[15] B. Agarski, V. Nikolić, Ž. Kamberović, Z. Anđić, B. Kosec, and I. Budak, “Comparative life cycle assessment of Ni-based catalyst synthesis processes,” *J. Clean. Prod.*, vol. 162, pp. 7–15, Sep. 2017.

[16] Orkustofnun Data Repository, “Gas Emissions of Geothermal Power Plants and Utilities 1969-2019, Iceland,” 2020.

[17] IPCC, *Climate Change 2013*, vol. 5. 2014.

[18] C. Mutel, “Brightway: An open source framework for Life Cycle Assessment,” *J. Open Source Softw.*, vol. 2, no. 12, p. 236, 2017.

[19] R. Frischknecht and S. Büsser Knöpfel, “Swiss Eco-Factors 2013 according to the Ecological Scarcity Method,” 2013.

[20] L. Scherer and S. Pfister, “Hydropower’s biogenic carbon footprint,” *PLoS One*, vol. 11, no. 9, Sep. 2016.

[21] M. Götz *et al.*, “Renewable Power-to-Gas: A technological and economic review,” *Renewable Energy*, vol. 85. Elsevier Ltd, pp. 1371–1390, Jan-2016.

[22] J. C. Abanades, E. S. Rubin, M. Mazzotti, and H. J. Herzog, “On the climate change mitigation potential of CO2 conversion to fuels,” *Energy Environ. Sci.*, vol. 10, no. 12, pp. 2491–2499, 2017.