Environomic optimization of SNG production from lignocellulosic biomass using Life Cycle Assessment

Leda Gerber [a]***, Martin Gassner*** [a] ***and Francois Marechal*** [a]

[a] *Industrial Energy Systems Laboratory, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland*

Abstract: This paper discusses strategies for the environomic optimization of renewable energy conversion technologies that are at the conceptual process design stage and produce multiple energy services, using Life Cycle Assessment (LCA). It is illustrated by an application to the thermo-chemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass, producing both SNG and electricity. The MJ of wood at the inlet of the process is selected as the functional unit. In a first time, the effects of process scale on environmental impacts are investigated using three different impact assessment methods. This is done by performing multi-objective optimization with the SNG production costs and the cumulated environmental impacts of each impact assessment method as the two objectives. The process size is included in the decision variables. The identified optimal size range varies depending on the impact assessment method. For all methods, the impacts increase with the process size in this optimal range. This is due to a joint effect of the biomass logistics and of the scaling of the gasifier, which leads to an increased resource consumption per unit of volume with an increasing size. In a second time, multi-objective optimization is conducted at fixed process size, using three objectives. The two first objectives are the SNG output and the electricity output, and the third one is either one of the three environmental indicators or the SNG production costs. Results show that the choice of the impact assessment method and of the hypothesis for electricity substitution have an important influence on the results, and favor either the production of SNG or of electricity. In all cases, process efficiency is one of the most important aspects for impact reduction.

Keywords: Life cycle assessment, multi-objective optimization, environomic optimization, biofuels, synthetic natural gas, optimal process scale, process design, renewable energy conversion systems

1. Introduction

Environmental impacts of emerging technologies such as the production of biofuels have become an important concern. To assess these impacts, life cycle assessment (LCA) is a widely used and well-established method, standardized in [1, 2]. Several LCAs surveys have been conducted to highlight the environmental impacts generated by the production of fuels from biomass, like the study of Zah et al [3] on the Swiss level, or the study of von-Blottnitz and Curran [4] on the international level. However, in such studies the life cycle inventory (LCI) is established using average technologies and data from different sources that are not necessarily consistent. With this conventional approach, the changes in process design, the effects of process integration and scaling, and the possible technology evolutions are not considered. Therefore, it is not possible for engineers to integrate LCA at the conceptual process design stage to target simultaneously not only the economic performance but also the environmental impacts. In a former article [5], the authors proposed a methodology to integrate the LCA in a computer aided process design platform that allows for the optimal thermo-economic design of production processes, and demonstrated its application to the design of thermochemical production of synthetic natural gas (SNG) from lignocellulosic biomass, using the model described in Gassner and Marechal [6]. The authors did however not present the application in an optimization framework.

Several authors have conducted studies on the environomic optimization for the identification of optimal process design for energy conversion systems, which refers to the simultaneous optimization of economic, thermodynamic and environmental aspects. Von Spakovsky and Frangopoulos [7] introduced the concept of environomic for energy systems by taking into account not only the total costs as performance indicators, but also the exergy and

Corresponding author: Leda Gerber, Email: leda.gerber@epfl.ch

some environmental aspects, such as direct emissions and resource consumption. Later, Li et al included also environmental criteria in the multi-objective optimization (MOO) framework of district heating systems [8] and of combined cycle power plants including CO2 separation options [9]. Lazzaretto and Toffolo [10] also conducted work on the thermo-environomic optimization and published the results of a MOO considering the three aspects of economy, exergy and environment, calculating the corresponding Pareto surface for a cogeneration plant. However, all of the above studies do not consider the use of LCA, and focus only on the emissions or the resource consumption to represent the indicator of environmental impacts. Regarding the integration of LCA in the optimization procedure, Bernier et al [11] use process integration techniques and thermo-economic analysis in combination with LCA for the design of natural gas combined cycle power plants including CO2 separation options, and perform an environomic optimization. They yet focus only on global warming potential, which is relevant in the case of fossil energy systems, but may not be the case for renewable energy systems.

In the present paper, we propose a strategy for the environomic optimization using LCA applied to the conceptual process design of renewable energy conversion systems producing multiple energy services and integrating the biomass supply chain aspects. It is illustrated by an application to the thermochemical production of SNG from lignocellulosic biomass. The important aspects specific to the application of LCA to process design by multi-objective optimization are as well highlighted.

2. Methodology

The thermo-economic design approach described in [12] is repeated in figure 1. It is based on a computational platform which creates interfaces between different models required for the energy system design. In a first step, the energy flow model based on given operating conditions is calculated to obtain the mass and energy flows in the process, as well as the corresponding thermodynamic states. These results are used to generate the energy integration model, which optimizes the heat recovery and the combined heat and power production in the system by minimizing the total exergy depletion or the operating cost under the heat cascade constraints. The results of the energy-flow and the energy integration models are used to size the equipments, estimate the cost and evaluate the performance of the process configuration, including the environmental impacts calculated by life cycle impact assessment (LCIA). The performance indicators are then further used in a MOO framework, in which an evolutionary genetic algorithm is used.

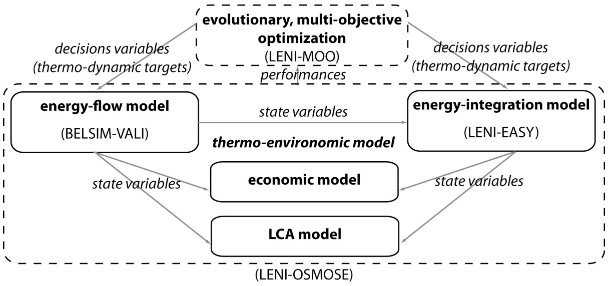

Figure 1: Overall computation sequence including the LCA model

2.1. LCA model

The methodology used to develop the LCA model, based on the ISO-norms [1], and to link the LCI flows with process design and scale is described in [5], and the same application example of the SNG production process from [6] is taken here as an illustrative example.

2.1.1. Goal and scope definition

The goal and scope of the study, and therefore the functional unit (FU) and system boundaries are first defined [1]. From the LCA perspective, the goal and scope of the study can be defined as the identification of the process configurations for SNG production that minimize the environmental impacts generated by the conversion of lignocellulosic biomass into useful energy services. Unlike for the example case presented in [5], which uses the MJ of produced SNG as FU, the MJ of input wood is chosen here. Indeed, the process can, under certain conditions, simultaneously produce both SNG and electricity as energy services, and the present study becomes therefore a resource allocation problem. Moreover, this choice of FU allows to fix as constant the impacts per MJin due to wood production at forest, on which the design of the process has no influence. The impacts per MJin due to wood supply chain from the forest to the plant and back, wood conversion to SNG, and the beneficial impacts due to the substitution of the produced energy services will remain variable.

2.1.2. Life Cycle Inventory

The second step is the establishment of the LCI and its linking with the flows of the thermo-economic model. The LCI database ecoinvent [13] is used to find equivalences for each process flow and equipment. The LCI of the process was established in [5] and is illustrated in Figure 2. Same systems boundaries and LCA model are kept in the present study. To account for the benefit of the produced energy services in the optimization procedure, the electricity produced by the process is assumed to substitute the Swiss mix including the imports, and the SNG is assumed to substitute the extraction and transport of fossil natural gas, as well as to avoid fossil CO_2 emissions from fossil natural gas combustion.

2.1.3. Life Cycle Impact Assessment

The third step is the choice of the impact assessment methods used in the LCIA phase, which are used as indicators for the environmental performance of the system configuration. The general equation to aggregate the emissions and extractions of the LCI in more general indicators by the mean of an impact assessment method is described by Equation 1.

$$\begin{bmatrix} F_{1,1} & \dots & F_{1,n} \\ \dots & \dots & \dots \\ F_{m,1} & \dots & F_{m,n} \end{bmatrix} * \begin{bmatrix} E_1 \\ \dots \\ E_n \end{bmatrix} = \begin{bmatrix} I_1 \\ \dots \\ I_m \end{bmatrix} \qquad (1)$$

where, $F_{i,j}$ is the weighting factor to convert the LCI emission i into the impact category j, E_i is the emission or extraction i calculated at the LCI, and I_j is the impact category j of the impact assessment method. Since the weightings vary among the different impact assessment methods, it is necessary here to use more than one of them. Three different impact assessment methods are chosen: Ecoscarcity06 [14], Ecoindicator99-(h,a) [15], and the Global Warming Potential at 100 years (GWP,100a) of the Intergovernmental Panel on Climate Change [16]. The first one is based on the scientifically supported goals of the Swiss environmental policy, the second one uses a damage oriented-approach, and the third one specifically targets the global warming issue using a problem-oriented approach. The different endpoint impact categories of these three methods are summarized in Table 1.

3. Process optimization

Multi-objective optimization is performed to calculate the trade-offs between the environmental performance indicators and the thermo-economic performance indicators of the system, such as the SNG production costs and the energy efficiency, and to identify the optimal process configurations.

Table 1: Impact assessment methods used

Method	Impact category	Units
Ecoscarcity06	Air emissions	pts
	Surface water emissions	pts
	Groundwater emissions	pts
	Top soil emissions	pts
	Energy resources	pts
	Natural resources	pts
	Deposited waste	pts
Ecoindicator99-(h,a)	Human health	pts
	Ecosystem quality	pts
	Resources	pts
IPCC	Global warming pot., 100a	$kgCO_2$-eq

Although the chosen impact assessment methods allow for a detailed analysis of the different impact categories in the case of Ecoscarcity06 and Ecoindicator99-(h,a), it seems more appropriate to use a single synthetic indicator for each impact assessment method representing the overall environmental performance. Indeed, although the use of an evolutionary algorithm allows easily for multi-objective optimization and thus for the use of several environmental indicators at the same time, this makes the results interpretation difficult, especially when the goal is to calculate the trade-offs between environmental objectives and other objectives (economic). The maximal number of objectives is then preferably limited to three, in which at least one is economic, and the single score is therefore chosen as the representative optimization objective with respect to environmental performance. It is calculated by the weighted sum of the normalized impact categories:

$$I_{tot} = \sum_{i=1}^{m} I_i * w_i \qquad (2)$$

where w_i is a factor used for the normalization and weighting of the different impact categories.

3.1. Optimal process scale

3.1.1. Optimization strategy

Considering the biomass supply chain, the optimal process scale can be calculated, considering economic and environmental objectives. Indeed, while

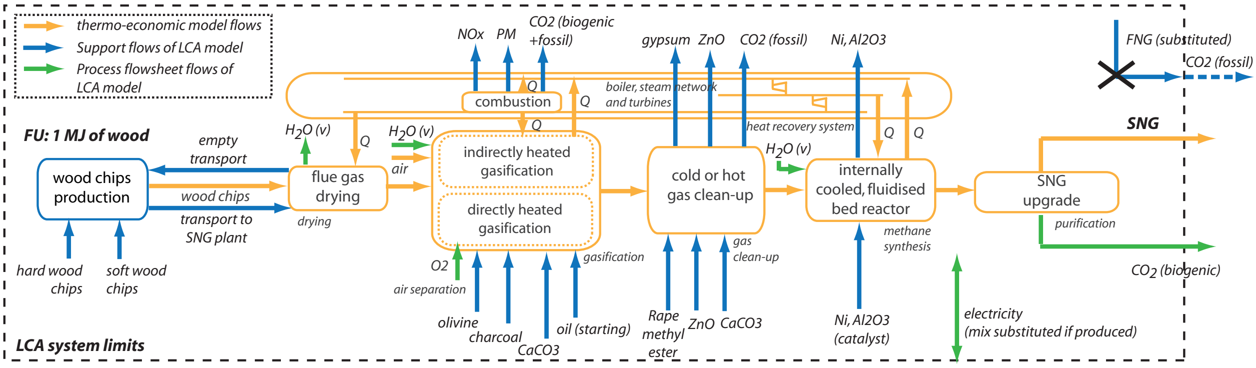

Figure 2: Flows of environmental concern included in the LCI

the impacts due to the biomass logistics should increase with process scale because of increased transportation distance, the impacts due to the process equipment and to the increase in process efficiency should be decreasing with process scale. Therefore, there should be an optimal trade-off with respect to process scale. This is calculated by simultaneously minimizing the single score of a selected impact assessment method, and by minimizing the SNG production costs per MWh.

The chosen technology for this scenario is the indirect gasification at atmospheric pressure using steam drying and membranes for CO_2 removal. This scenario is chosen over the more evolved technologies described in [17], since it uses larger process equipment and more resources during gasification than the other scenarios. The optimization is more likely to identify if the variations in process design allow for a significant impact reduction due to these contributions. For the optimization, the same decision variables and ranges are used than in [17]. The process size is given as an additional decision variable of the optimization problem, and is expressed as the thermal capacity in terms of biomass input, in the range of 5 to 50 MW_{th}. Three optimizations are performed, one for each impact assessment method.

3.1.2. Results

The results obtained by the successive use of the three impact assessment methods show that there is a trade-off between SNG production costs and environmental impacts. This is shown in Figure 3 for the method of Ecoscarcity06, and in Figure 4 for the method of Ecoindicator99-(h,a). Results obtained with the GWP,100a are not displayed here, but show a similar trend to the results obtained with

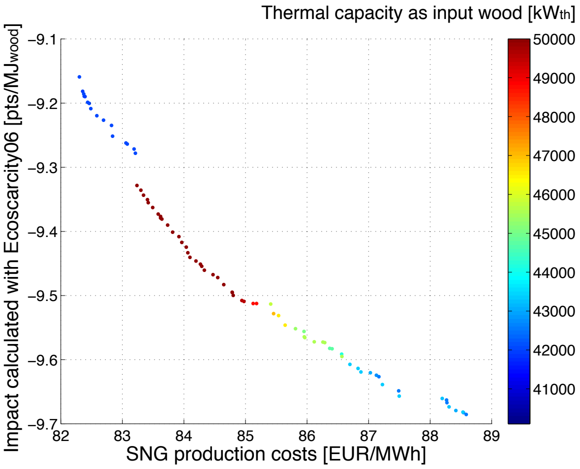

Figure 3: Pareto curve for Ecoscarcity06 and SNG production costs with varying process size

Ecoindicator99-(h,a). However, the range of process sizes concerned by this trade-off varies among both impact assessment methods. While in the case of Ecoindicator99-(h,a), the whole range of process sizes is represented in the optimal process configurations, in the case of Ecoscarcity06, the range of selected sizes considers rather large scales, and goes from 42 to 50 MW_{th}. In both cases, a larger process size within the optimal range tends to lead to higher environmental impacts and lower SNG production costs.

The different results produced by the impact assessment methods are explained by the different weightings attributed in the impact assessment methods, which give more importance to one energy service produced or another. By its high weight attributed to nuclear electricity, the solutions proposed by the Ecoscarcity06 objective favor the production of electricity substituting the Swiss mix. As the co-produced electricity is sold for the market price, this reduces the SNG production costs. Ecoindicator99-

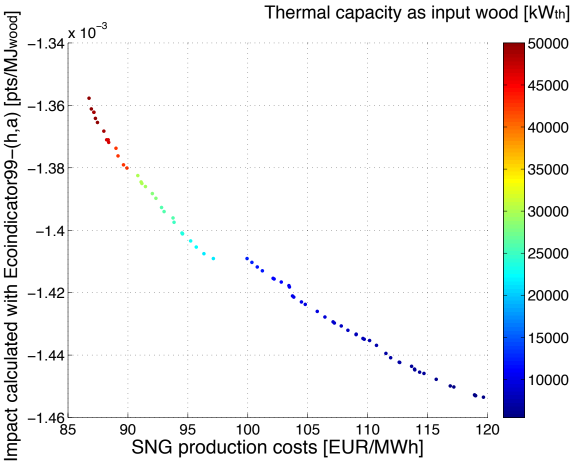

Figure 4: Pareto curve for Ecoindicator99-(h,a) and SNG production costs with varying process size

(h,a) and the GWP,100a give on the contrary a higher weighting to the fossil energy resources emitting high amounts of CO_2. The solutions obtained with this indicator therefore favor the substitution of fossil natural gas with lower level of electricity production.

Small process sizes have the effect to penalize the cogeneration of electricity, which decreases the avoided impacts from electricity substitution and increase the investment costs that are accounted in the SNG production costs. This has the effect that small-scale processes are not considered as optimal. For Ecoindicator99-(h,a) and the GWP,100a , the SNG production is favored over the production of electricity. However, specific SNG production varies to a less extent with process scale, unlike the cogeneration of electricity. This is shown in Table 2 that compares the specific electricity and SNG production per unit of wood for two extreme points of the Pareto curve shown in Figure 4. However, the impacts from wood transport and from specific resource consumption by the gasification are increasing with process scale. For the biomass logistics, this is due to the increase of the average distance from forest to SNG plant. For resource consumption by gasification, it is an effect of the gasifier sizing which affects the consumption of olivine, charcoal, starting oil, solid waste generated and transport of these different materials. The increase of the cumulated impacts of these different processes with process scale is stronger than the benefit from the increased electricity production for Ecoindicator99-(h,a) and GWP,100a, and explains why these impact assessment methods rather favor small-scale processes.

Table 2: Detailed energy service production for two points of the Pareto curve calculated with Ecoindicator99-(h,a)

	Point 1	Point 2
Thermal capacity [MW_{th}]	5	50
SNG [MW/MW_{wood}]	0.704	0.701
Electricity [kW/MW_{wood}]	0.9946	5.606

In the case of Ecoscarcity06, the joint effect of the biomass logistics and of the specific resource consumption by gasification is only visible after the specific electricity production does not increase significantly with size anymore, in the upper range of the potential process sizes.

It should be noted that the impact contribution of the process equipment is decreasing with process scale. However, unlike for the SNG production costs which are affected in an important way by the investment, it does not affect the optimal process configurations with respect to the impact, since this effect is not significant compared to the effect of electricity cogeneration, biomass logistics and specific resource consumption by gasification.

3.2. Environomic design

3.2.1. Optimization strategy

Fixed-scale process environomic optimizations are conducted, with respect to three objectives: the SNG output, the electricity output, and either the SNG production costs or one of the environmental indicators. Using both the SNG output and the electricity output as optimization objectives instead of the single objective of energy efficiency allows one to clearly identify the trade-offs between the environmental impacts and the production of one of these services. A process size of 20 MW_{th} of input wood thermal capacity has been assumed, and the technological scenario considered is the same than for the varying size optimization.

3.2.2. Results

The results for the optimization of SNG production costs, SNG output and electricity output are shown in Figure 5.

A trade-off between the minimization of SNG production costs and electricity and SNG maximization is observed. As it can be seen, minimization of the costs prefers slightly the SNG over the electricity

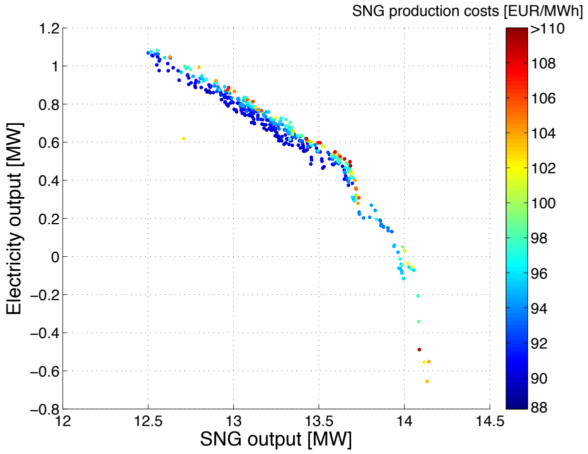

Figure 5: Pareto curve for SNG output, electricity output, and specific SNG production costs

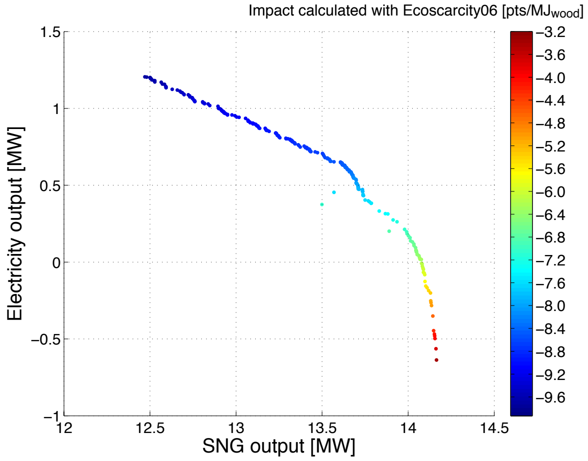

Figure 6: Pareto curve for SNG output, electricity output, and single score of Ecoscarcity06

output, but it could however be shown that there exist solutions with similar SNG production costs for both trends. This indicates also that the selection will be based on other criteria or could be adapted to account for the market prices of energy. Furthermore, the most efficient solutions are not necessarily the most economic ones since the investment cost becomes dominant.

The results for the optimization of environmental impacts, SNG output and electricity output are shown in Figure 6 and 7. Results for the optimization of the GWP,100a are not displayed here, since they show the same trend than the results obtained with Ecoindicator99-(h,a).

The optimization shows different trends in the impact assessment when one use one or the other environmental indicator, Ecoscarcity06 favoring electricity cogeneration while Ecoindicator99-(h,a) favors SNG production. It is shown that increased substitution of a single service is more important than the potential impact reduction of any other contribution. It means that in the case of a similar renewable energy conversion system producing only one single energy service, it might be possible to assimilate the environmental impact reduction to the maximization of the process efficiency. However, the results show clearly that this can not be assumed here, in the case the process produces multiple energy services. Indeed, the optimizer may environmentally favor one or the other energy service which leads to the higher avoided impacts. Here, the results differ completely depending on the used impact assessment method, and this demonstrates the necessity to use different impact assessment methods giving different weightings to the produced energy services, which may lead otherwise to mistaken conclusions and affect the decision making. This further demonstrates the importance of the hypothesis made regarding the electricity mix substitution, which may thus be questioned, since it greatly influences the configurations that will be evaluated. This is an issue that has to be studied in detail in further work.

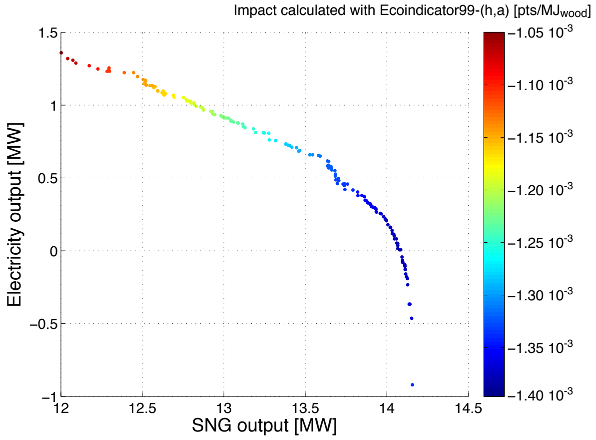

Figure 7: Pareto curve for SNG output, electricity output, and single score of Ecoindicator99-(h,a)

In the case where a trade-off is observed between an economic objective and an environmental objective, like it is the case here for the Ecoscarcity06 and the SNG production costs that do not favor the same energy service, it is possible to conduct further optimizations to calculate the optimal configurations. This is done by a 3-objective optimization with the SNG production costs, the environmental impacts, and the energy efficiency of the process expressed as SNG equivalent, which replaces the two objec-

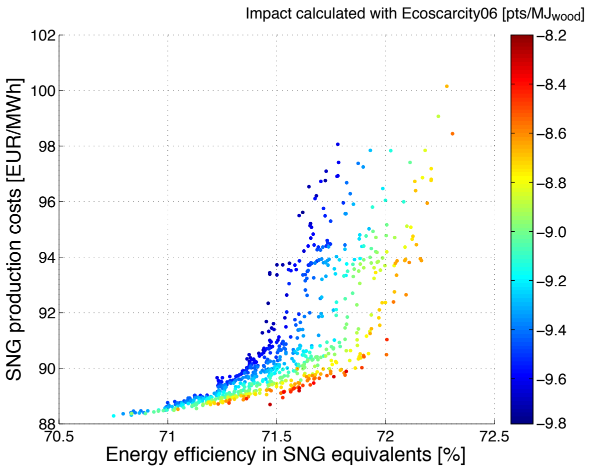

Figure 8: Pareto curve for chemical energy efficiency, specific SNG production costs and single score of Ecoscarcity06

tives of SNG output and electricity output. The results of this optimization are shown in Figure 8. The trade-off between energy efficiency, environmental impact and SNG production costs, are explained by the higher avoided impacts by the electricity production, but which leads to a lower SNG production and overall efficiency.

4. Conclusions

A strategy for the multi-objective environomic optimization of energy conversion systems that produce multiple energy services using LCA has been proposed. It was illustrated by an application to the thermochemical production of SNG from lignocellulosic biomass with power cogeneration.

The optimal process scale has been first investigated with respect to SNG production costs and environmental impacts. In any case, minimization of SNG production costs favors large processes. For the minimization of the environmental impacts, however, the optimal process scale varies depending on the impact assessment method that is used. The impact contributions that increase with process scale are the biomass logistics and the specific resource consumption from gasification. The impact contributions that decrease with process scale are the electricity substitution and the process equipment, though this last one has generally a minor effect. Therefore, if electricity substitution is weighted more strongly, the impact assessment method will favor large processes, since at small scale, electricity cogeneration decreases while SNG production remains constant. If this is not the case, the joint effect of the biomass logistics and of the specific resource consumption from gasification become more important, and small scale processes are favored to minimize the environmental impacts.

For a fixed scale process, the environomic optimization demonstrated that the impact reduction potential lies primarily in the increase in process efficiency. This leads to a higher avoided impact from substitution, before any other design consideration which is likely to reduce the consumption of resources or the size of the equipment. However, in the case of a conversion process producing multiple energy services, it is not possible to replace the objective of impact reduction by the objective of energy efficiency, since environmentally more favorable energy service may depend on the weightings considered in the impact assessment methods. In case where the assumption on the substitution of one or more of the energy services is questionable, like it is the case for the electricity mix, this may influence the process configurations in the final solution.

Nomenclature

FU	Functional Unit
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MOO	Multi-Objective Optimization
SNG	Synthetic Natural Gas

References

[1] ISO. Environmental management - Life Cycle Assessment - Principles and framework. International Standard, ISO 14'040., 2006.

[2] ISO. Environmental management - Life Cycle Assessment - Requirements and guidelines. International Standard, ISO 14'044., 2006.

[3] R. Zah et al. Oekobilanz von Energieprodukten: okologisches Bewertung von Biotreibstoffen. Technical report, Swiss Federal Laboratories for Materials Testing and Research (Empa), St. Gallen, Switzerland, 2007.

[4] H. von Blottnitz and M.A. Curran. A review of assessments conducted on bio-ethanol as a

transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner Production*, 15: 607–619, 2007.

[5] L. Gerber et al. Integration of LCA in a thermo-economic model for multi-objective process optimization of SNG production from woody biomass. In J. Jezowski and J. Thullie, editors, *Proc. 19th European symposium on CAPE*, volume 1, pages 1405–1410, Amsterdam, 2009. Elsevier.

[6] M. Gassner and F. Marechal. Thermo-economic process model for thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass. *Biomass and Bioenergy*, 33:1587–1604, 2009.

[7] M.R. Von Spakovsky and C.A. Frangopoulos. A global environomic approach for energy systems analysis and optimization (Part II). In *Proc. Energy Systems and Ecology 93*, pages 133–144, 1993.

[8] H. Li et al. Green heating system: characteristics and illustration with multi-criteria optimization of an integrated energy system. *Energy*, 29:225–244, 2004.

[9] H. Li et al. Multi-objective optimization of an advanced combined cycle power plant including CO2 separation systems. *Energy*, 31: 3117–3134, 2006.

[10] A. Lazzaretto and A. Toffolo. Energy, economy and environment as objectives in multi-criterion optimization of thermal systems design. *Energy*, 29:1139–1157, 2004.

[11] E. Bernier et al. Multi-objective design optimization of a natural gas-combined cycle with carbon dioxide capture in a life cycle perspective. *Energy*, 35:1121–1128, 2009.

[12] M. Gassner and F. Marechal. Methodology for the optimal thermo-economic, multi-objective design of thermochemical fuel production from biomass. *Computers & Chemical Engineering*, 33:769–781, 2009.

[13] R. Frischknecht et al. The ecoinvent database: Overview and methodological framework. *International Journal of Life Cycle Assessment*, 10:3–9, 2005.

[14] G. Brand et al. Bewertung in Oekobilanzen mit der Methode des oekologischen Knappheit Oekofaktoren 1997. Technical report, Swiss Federal Office of Environment, Bern, Switzerland, 1998.

[15] M. Goedkoop and R. Spriensma. The Eco-Indicator 99: A damage oriented method for life cycle impact assessment. Technical report, PRe Consultants, Amersfoort, The Netherlands, 2000.

[16] Intergovernmental Panel on Climate Change. IPCC(2001) Climate Change 2001: The Scientific Basis. In: Third Assessment Report of the Intergovernmental Panel on Climate Change (2001). Technical report, IPCC, 2001.

[17] M. Gassner. *Process design methodology for thermochemical production of fuels from biomass. Application to the production of Synthetic Natural Gas from lignocellulosic resources.* Ph.D. Thesis, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, 2010.