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The trade-off between exergy-output and capital costs: the example of bioenergy utilization paths

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Abstract:

Exergy analyses are able to provide insight to energy systems that may not be gained with purely energetic approaches. Due to the high variety of possible bioenergy utilization paths this question in particular is relevant for the analysis of bioenergy systems. Thus, in this paper we are investigating to which extent higher investment costs are required for achieving higher exergy outputs. We have selected bionergy chains based on two different resources (woody biomass and biogas) producing thermal energy, electricity and mechanical energy (transport). A special focus is on the transport sector where we are comparing combustion engines fuelled with liquid and gaseous biofuels on the one hand with electric cars with bio-based electricity on the other hand. The results show that there are high differences with respect to exergetic efficiencies. For some sub-sectors we can observe a very clear (almost) linear trade-off between exergetic efficiency and capital costs. According to the data we used for woody biomass it turns out that bioenergy based electric mobility is more than 3-4 times more exergy efficient than comparable 2nd generation biofuels. At the same time the electric mobility path shows lower costs, though higher investments. Moreover, conclusions are derived for a possible long-term vision for efficient bioenergy utilization.

Keywords: Exergy, Bioenergy, Biomass

1 Introduction

1.1 Motivation

One of the key characteristics of bioenergy is the multitude of technology paths. This variety results on the one hand from the numerous types of biomass resources which can be processed by different conversion technologies. On the other hand there are the different outputs of bioenergy technologies. All these energy forms on the input and on the output are characterized by different qualities, e.g. with respect to their ability to provide work. This aspect in particular is relevant for the investigation of plants with various products (polygeneration). The exergetic assessment of these products is a methodology that considers these different qualities. While the output “space heating” (i.e. Energy on a low temperature level) shows low exergy content, that of CHP (electricity + low temperature heat) is clearly higher.

Not only the exergy output, also the costs (and possible revenues) of these biomass utilization paths are quite different. For other energy systems, [1] shows that the use of high exergy sources can be substituted by a higher capital input. Now, we can ask whether this is also true with respect to the exergy output (i.e. the exergy efficiency) of a certain bioenergy technology. Thus, the question arises: How high are the additional costs for gaining a higher exergetic value from biomass resources?

1.2 Objective of this paper

The core target of this paper consists of the following two aspects:

- Analyse and compare the costs and exergetic efficiencies of selected bioenergy paths.
- Investigate the tradeoff between exergy output and (capital) costs of these selected bioenergy systems.

1.3 Approach

The approach of this paper consists out of the following steps:

- Description of bioenergy pahts. In particular, we have selected technologies out of the following categories:
    - Heating boilers
    - CHP plants
    - Liquid fuels for transport
    - Gaseous fuels for transport
    - Electric vehicles (using electricity generated from bioenergy plants) as a comparison to the combustion engine based vehicles using liquid or gaseous biogenous fuels.
- Analysis of the exergetic efficiency of these bioenergy paths
- Analysis of the generation costs of these bioenergy pahts (distinction between capital and variable costs)
- Identification of the trade off between (capital) costs and exergy output

More detailed aspects of the methodological approach are described below.

The main part of this work is related to the concept of exergy assessments. The idea behind this is to quantify the ability to work of a certain energy type. The analysis of the chemical exergy content only partly is related to this idea, because neither with best available technologies nor under perfect thermodynamic conditions it is possible to 100% make use of fuel's exergy content.

This aspect has already been discussed in the literature [1], [2]. We are following here a definition of the exergy content that considers the potential technical realization.

The work presented in this paper has been carried out in the course of the Austrian participation in IEA implementing agreement ECBCS (Energy conersvation in building and community systems), Annex 49 (Low Exergy Systems for High Performance Buildings and Communities). The objective of Annex 49 is to disseminate the exergy concept, investigate and provide low-exergy solutions and thus support the further penetration and utilization of high efficient low-exergy systems, in particular in the heating sector.

2 Methodology

Several aspects are crucial for determining exergetic efficiencies of (bio-) energy systems. The following sub-sections are dealing with those that are most relevant for our paper: (1) how to determine the exergy content of different energy forms, (2) how we are defining and calculating the tradeoff between capital costs and exergy efficiency and (3) how we defined the system boundaries of this analysis.

2.1 Determining the exergy content of energy forms

$$Ex = 1 - \frac{T_0}{T_1}$$

Table 1. Exergy content of energy forms relevant for this paper

Unit	ambient temperature °C	(usable, possible) temperature °C	exergy content %
Electricity			100%
mechanical energy (engine)			100%
space heat	0	20	7%
process heat	0	300	52%
Woody biomass	0	800	75%
FT-Diesel	0	1500	85%
Maize silage / Manure mix	0	800	75%
biogas crude	0	800	75%
biogas fed into gas grid	0	1800	87%

2.2 Calculating the trade off between capital costs and exergy efficiency

The economic and exergetic results are calculated based on the following formulars:

$$C_{tot} = \frac{IC \cdot \alpha}{T_{FL}} + \frac{O\,\&\,M}{T_{FL}} + \frac{p_{fuel}}{\eta_{el}} - \frac{p_{heat}}{\eta_{th}}$$

C_{tot} Total energy generation costs (€/MWh main output)

IC Investment costs (€/kW main ouput)

α annuity factor

T_{FL} Full load hours (h/yr)

O&M Operation and maintenance costs (€/kW main output/yr)

p_{fuel} Energy price (€/MWh)

p_{heat} Heat price (only for CHP) (€/MWh)

η_{el} electric efficiency

η_{th} thermal efficiency

$$\varepsilon = \frac{EX_{out}}{EX_{in}}$$

ε Exergy efficiency

EX_{out} Exergy content output

EX_{in} Exergy content input

The exergy content of energy input and output is calculated as a weighted average of exergy contents of the single energy streams:

$$EX_{out} = \sum_i ex_i \cdot \beta_i$$

$$EX_{in} = \sum_j ex_j \cdot \gamma_j$$

2.3 System boundaries

An important aspect is the choice of system boundaries. We have made the following assumptions:

- For thermal output the system boundary on the input part is the biomass resource and on the output part the provided space heating temperature level.
- For CHP the system boundary on the input part is the biomass resource and on the output part the produced electricity and the provided space heating temperature level.
- For mobility applications the system boundary on the input part is the biomass resource and on the output part the produced mechanical energy on the drive (and the thermal energy from the CHP plants for providing space heating).
- In this paper, we are assuming for all considered bioenergy chains a homogenous biomass resource. In particular for biogas generation (using e.g. biowaste or manure) this assumptions is not valid. This should be discussed in further investigations.
- We are not considering the non-energetic use of biomass. A possible interpretation of this assumptions is that in the considered utilization paths only such biomass resources are used for energetic purposes that are either on the end of a cascadic utilization path or which are not in competition to non-energetic purposes.

Extending these system boundaries will be subject to further analysis in future research work.

3 Bioenergy chains: exergetic efficiency and costs

3.1 Selected bioenergy systems

We selected the following bioenergy chains:

- Woody biomass
  - Large scale wood chips heating plant (not including costs for heat distribution in the district heating grid) producing thermal energy for space heating.
  - Large scale wood chips CHP with steam turbine (not including costs for heat distribution in the district heating grid) producing electricity and thermal energy for space heating.
  - Large scale wood chips fluidized bed gasification with IGCC (not including costs for heat distribution in the district heating grid) producing electricity and thermal energy for space heating
  - Large scale wood chips fluidized bed gasification with gas turbine (not including costs for heat distribution in the district heating grid) producing electricity and thermal energy for space heating

  - Using electricity from each of the mentioned CHP plants in electric vehicles, producing thermal energy (from the CHP) for space heating and mechanical energy on the drive chain of an electric car.
  - Second generation FT Diesel based on wood chips producing mechanical energy on the drive chain of a conventional combustion engine car.
  - Second generation ligno-cellulose ethanol based on wood chips producing mechanical energy on the drive chain of a conventional combustion engine car.
- Biogas
  - Biogas (based on maize/manure mix) CHP with local gas engine producing thermal energy for space heating and electricity
  - Biogas (based on maize/manure mix) electricity generation with local gas engine producing electricity without making use of heat output
  - Cleaning and upgrading of biogas (based on maize/manure mix) and feed-in into the natural gas grid. Using biogas in decentral small scale gas heating boilers producing thermal energy for space heating.
  - Cleaning and upgrading of biogas (based on maize/manure mix) and feed-in into the natural gas grid. Using biogas in small scale decentral gas engines producing thermal energy for space heating and electricity.
  - Cleaning and upgrading of biogas (based on maize/manure mix) and feed-in into the natural gas grid. Using biogas in large scale gas turbines producing electricity and thermal energy for space heating and electricity.
  - Cleaning and upgrading of biogas (based on maize/manure mix) and feed-in into the natural gas grid. Using biogas in large scale IGCC producing electricity and thermal energy for space heating and electricity.
  - Cleaning and upgrading of biogas (based on maize/manure mix) and feed-in into the natural gas grid. Using biogas in combustion engine cars producing mechanical energy on the drive chain.
  - Using electricity from each of the mentioned biogas CHP plants in electric vehicles, producing thermal energy (from the CHP) for space heating and mechanical energy on the drive chain of an electric car.

The following tables show the main technology data (efficiency, cost data) for woody biomass, biogas and vehicles.

Table 2. Main technology data woody biomass

	Woody biomass			
	Thermal	CHP		
	heating plant	steam turbine	SNG, IGCC	SNG, gas turbine
full load hours (h/yr)	5000	7000	7500	7500
eta 1	75%	28%	41%	29%
eta 2	0%	52%	22%	34%
eta 3	0%	0%	0%	0%
eta total	75%	80%	62%	62%
investment costs (€/kW)	420	2000	2778	2228
O&M costs (€/kW/a)	13	27	153	253
Fuel price (€/MWh)	24	24	24	24

(*) depending on bioenergy generation costs + distribution costs (electricity, biogas or liquid fuels)

Table 3. Main technology data biogas

	Biogas						
	Biogas feed-in	Thermal	CHP				
	fermentation, cleaning, up-grading	decentral heating boilers	local CHP	local ele (w/o heat utilization)	(decentral) gas engines	(central) gas turbine	(central) IGCC
full load hours (h/yr)	7500	1500	3500	4500	2000	7000	7000
eta 1	64%	90%	29%	30%	30%	36%	54%
eta 2	0%	0%	29%	0%	57%	42%	27%
eta 3	0%	0%	0%	0%	0%	0%	0%
eta total	64%	90%	58%	30%	87%	78%	81%
investment costs (€/kW)	1350	250	2500	2500	1400	700	1700
O&M costs (€/kW/a)	73	58	150	150	42	180	80
Fuel price (€/MWh)	18	(*)	18	18	(*)	(*)	(*)

(*) depending on bioenergy generation costs + distribution costs (electricity, biogas or liquid fuels)

Table 4. Main technology data electric vs. conventional vehicles

	Mobility	
	electric vehicle (additional costs only)	conventional vehicle
full load hours (h/yr)	250	250
eta 1	75%	20%
eta 2	0%	0%
eta 3	0%	0%
eta total	75%	20%
investment costs (€/kW)	235	0
O&M costs (€/kW/a)	0	0
Fuel price (€/MWh)	(*)	(*)

(*) depending on bioenergy generation costs + distribution costs (electricity, biogas or liquid fuels)

3.2 Exergetic comparison

Making use of the approach for exergy efficiency calclulation described above results in values for the exergy efficiency which are shown in the next two figures.

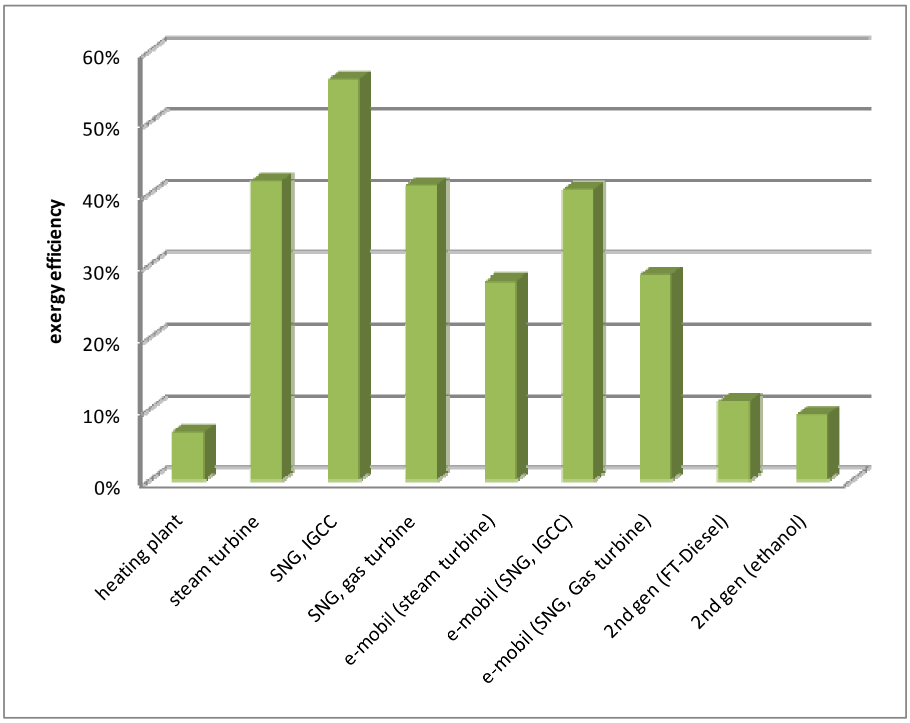

Figure 1. Exergy efficiency of selected woody biomass chains

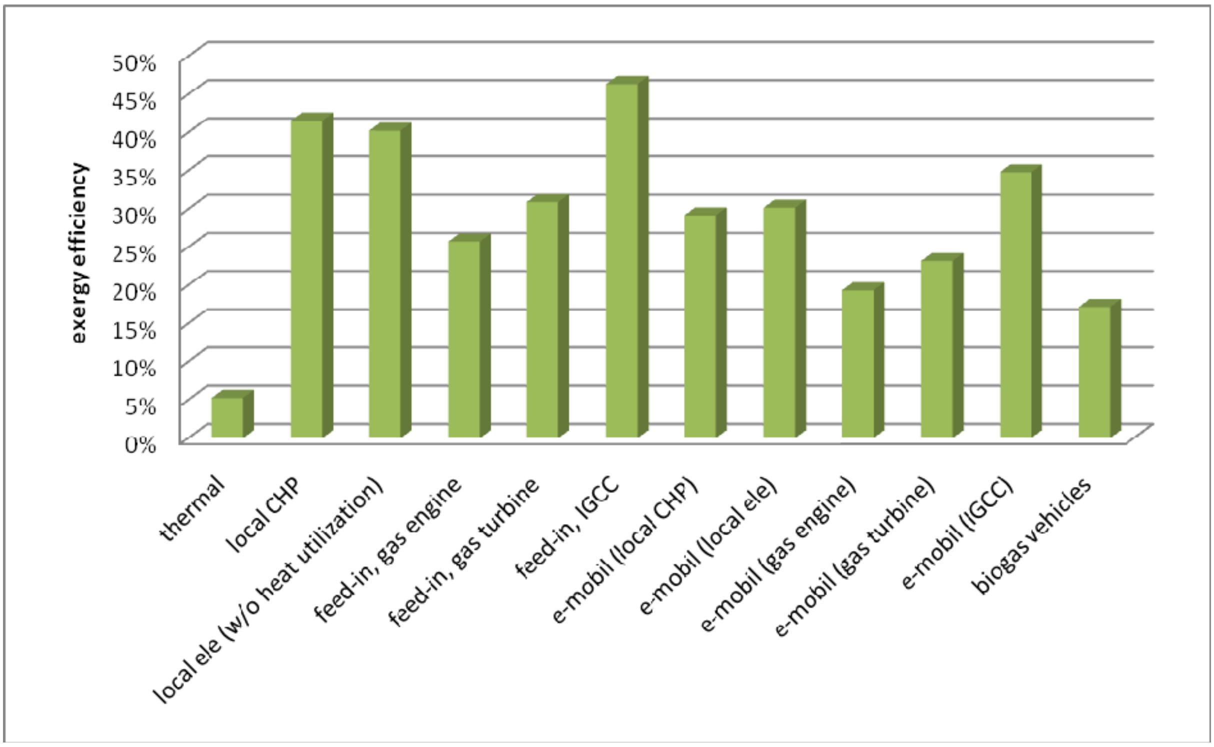

Figure 2. Exergy efficiency of selected biogas chains

Of course, due to the low temperature level of space heating applications, these systems show very low exergetic efficiencies (about 5%). Depending on the electric efficiencies and pre-treatment of resources (e.g. losses of exergy during biogas up-grading and cleaning) the exergetic efficiency is clearly higher for CHP. Due to the low efficiency of combustion engines, the exergetic efficiency of these bioenergy chains is in the range of 10%-15%. The related biobased e-mobility chains show exergy efficiencies up to 35%-40%.

3.3 Economic comparison

The following figures show a comparison of energy generation costs for the selected bioenergy technology chains. As described above, we are calculating energy generation costs for the following energy forms: thermal, electric and mechanical energy. Due to this approach the low efficiency of combustion engines in conventional vehicles, combined with relatively high biofuel production costs leads to very high energy generation costs. For electric vehicles, capital costs are the dominant component. Thus, the results are sensitive to full load hours, interest rate and depreciation time.

The bars for variable costs include O&M costs as well as fuel costs minus heat revenues in case of CHP. This explains the very low values for the "steam turbine" case where thermal efficiencies are relatively high compared to total costs.

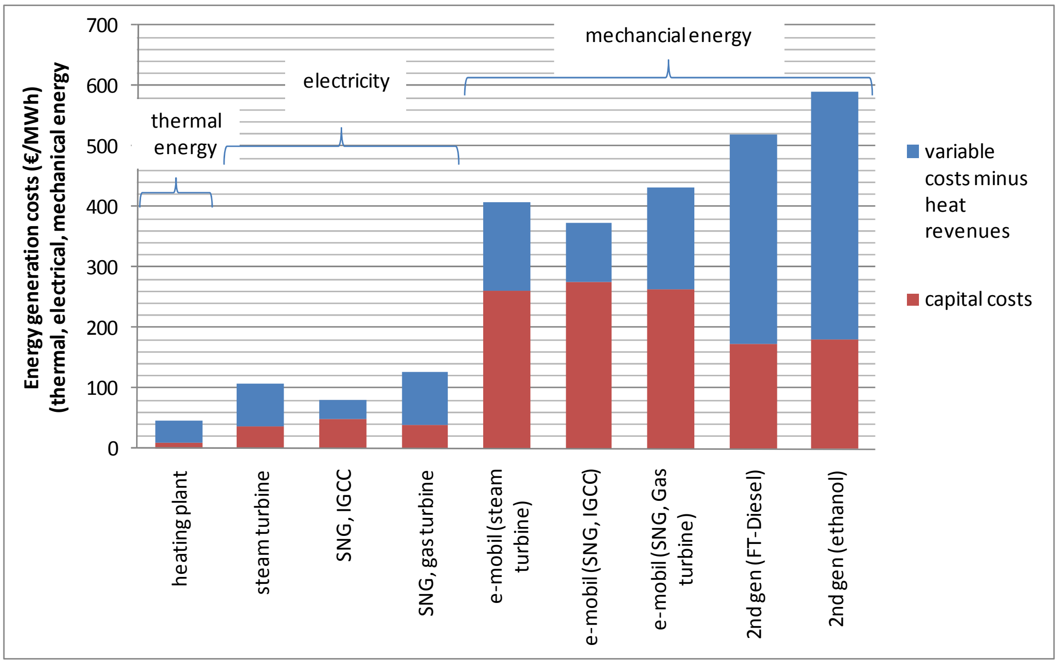

Figure 3. Comparison of different energy generation costs (thermal, electrical and mechanical energy), woody biomass

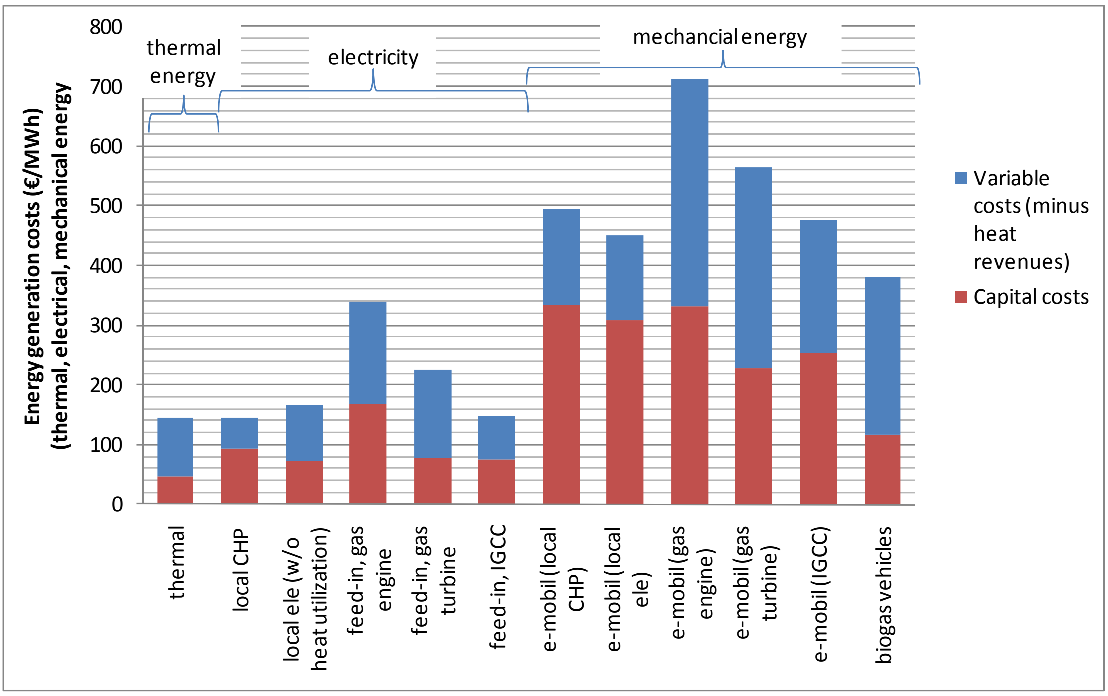

Figure 4. Comparison of different energy generation costs (thermal, electrical and mechanical energy), biogas

Several conclusions may be drawn from this comparison:

- Of course all mobility applications show clearly higher costs than CHP or pure heating plants (on the one hand due to high capital costs and on the other hand due to low efficiency).
- However, if we are comparing just the mobility systems, we can learn that the 2nd generation liquid biofuels are more expensive than the related bio-based e-mobility systems. Of course this conclusion is sensitive to the related technology data. Assuming a relatively cheap polygeneration plant which can make use of by-products (heat, electricity) this could lead to lower costs, too. This in particular holds for SNG based on woody biomass in the transport sector which we did not include in our analysis.
- The same result does not hold for the biogas related systems: Vehicles driven with biogas are cheaper than the related biogas based e-mobility systems. Again, this result is highly sensitive to some input parameters, in particular to the capital costs of electric vehicles which could come done essentially assuming higher full load hours (e.g. by car sharing systems).
- Feed-in of biogas leads to relatively high costs for the case of heating appliances and those CHP plants with relatively low electric efficiencies. For mobility applications, this might be an economically reasonable path compared to other biobased mobility applications.

3.4 The trade-off between exergy efficiency and (capital) costs

The following figures are combining the exergy efficiency and the capital costs of the investigated systems. If we are separating the areas (1) thermal plants and CHP and (2) mobility (because the latter shows clearly additional costs for different reasons) we can observe that there is a clear tradeoff between exergy output (efficiency) and capital costs (for the selected woody biomass chains this is an almost linear relation, for the selected biogas chains the situation is not that clear). This shows that there are clearly higher investments necessary in order to make use of the full exergetic potential of biomass resources.

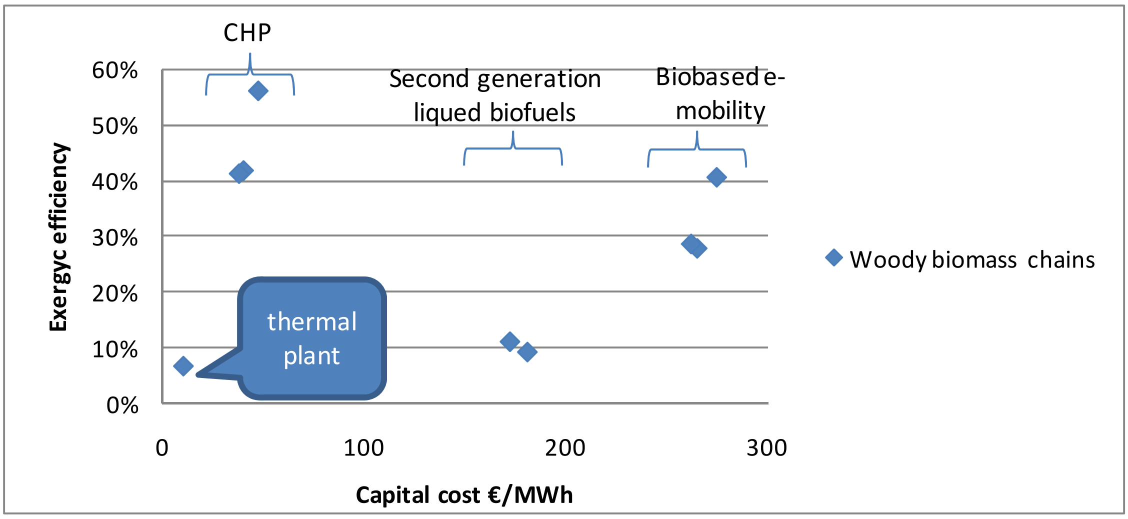

Figure 5. Exergy efficiency and capital costs (woody biomass)

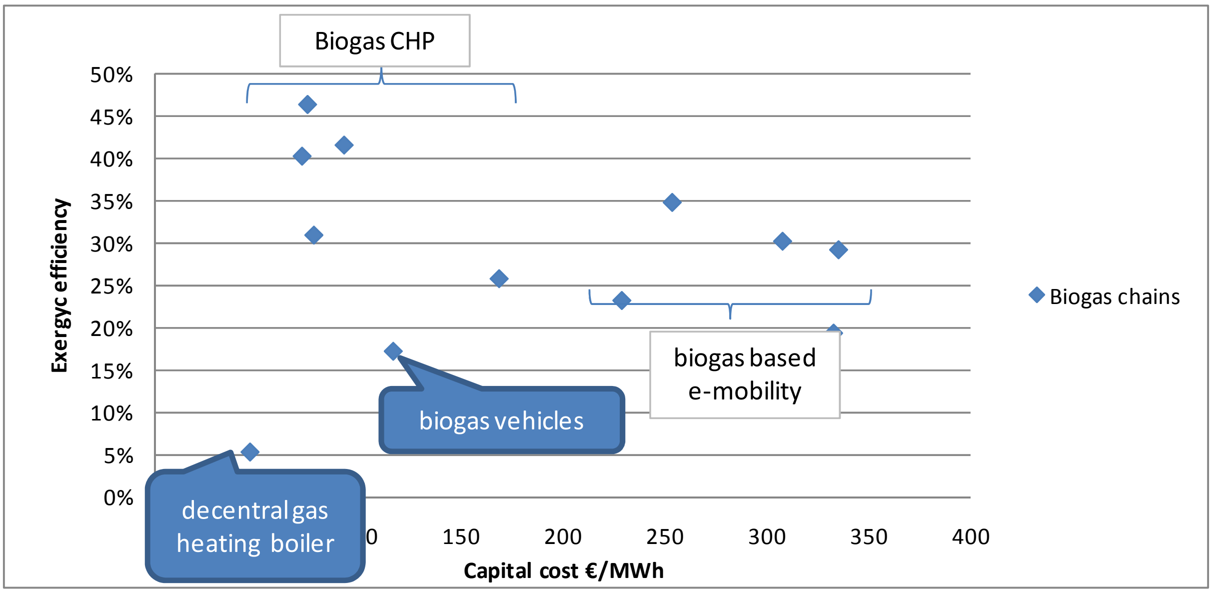

Figure 5. Exergy efficiency and capital costs (biogas)

If we would follow the objective to gain a highest possible exergetic use of biomass resources with a minimum of capital cost, we would have to draw an envelope line in these figures connecting those points situated on the left hand and top side of each graph. This would lead to the conclusion, that biomass for transport purposes in any case is not efficient, both from an exergetic and from a investment costs point of view. Moreover, for biogas plants feeding biogas into the gas grid and generation electricity and heat in large scale IGCC plants (top point in figure 5) could be an efficient option (not taking into account grid constraints!).

However, if we are considering that currently there is a high demand for individual transport systems, the least exergy losses would be achieved with biobased e-mobility schemes compared to combustion engines. This would require clearly higher investment costs (which are partly offset, at least for the case of 2nd generation liquid biofuels by lower running costs).

4 Conclusions

The exergy losses in the (bio-) energy system are very high. There is the potential to reduce these exergy losses substantially by making use of more exergy efficient bioenergy paths. These paths are on the one hand CHP plants with high electric efficiencies and on the other hand bio-based e-mobility. However, the analysis shows that there are higher capital costs required for making use of this high exergy potential of biomass. This has to be considered as a major barrier.

On the other hand, if we are considering that currently not only biomass is wasted from an exergetic point of view for producing space heating, but also (and in fact first of all) fossil energy, the replacement of these fossil energy by biomass is a cheap and effective way of reducing CO_2-emissions.

Thus, the concept of exergetic analysis (and combining it with economic analysis) can give us a hint of how an “optimum” long-term future of biomass utilization could look like: Since space heating will be supplied by a large share of highly efficient technologies (low and passive houses) and solar thermal energy, it will be possible to allocate biomass to higher exergetic purposes: Producing electricity (of course besides non-energetic purposes like construction material etc) in large scale CHP plants, using the waste heat for industrial processes and using electricity partly in electric vehicles could be such a vision.

Many aspects and questions remained open in this paper. This includes the question of system boundaries, bioenergy chains to select (e.g. SNG in the transport sector), assessment of different biomass resources (in particular cascadic use of biomass). We are leaving this to future research work.

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