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Research Article

Ecological Impact of Renewable Resource-Based Energy Technologies

Karl-Heinz Kettl, Nora Niemetz, Nora Sandor, Michael Eder, and Michael Narodoslawsky

Institute for Process and Particle Engineering, Graz University of Technology, Inffeldgasse 21a, 8010 Graz, Austria
Address correspondence to Karl-Heinz Kettl, kettl@tugraz.at

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Abstract Renewable resource-based energy technologies are currently gaining a strong interest, particularly in the light of global climate change and volatile energy markets. A major argument for their use is their ecological advantage. The paper will compare the ecological impact of various biofuel technologies, technologies providing electricity and heat on the base of different resources, both biogenic and direct as well as indirect solar energy. Sustainable Process Index (SPI) is used to compare on the same level with an consistent methodology, a comprehensive and sensitive ecological measure addressing resource provision as well as emissions and global warming with a consistent methodology. The paper will analyze different aspects of the ecological impacts of energy technologies and biofuels. On the base of this analysis, conclusions will be drawn regarding the most important factors influencing the ecological performance as well as unresolved questions for a solid evaluation for these technologies.

Keywords sustainable process index; ecological footprint; energy technologies; biofuels

1 Introduction

The quest for an energy provision that will mitigate human-caused climate change and the necessity to brace for the decline in the availability of fossil energy resources like crude oil and natural gas (Schindler and Zittel [17]; International Energy Agency (IEA) [6]) have increased interest in alternative energy technologies considerably since the turn of the century. There is a general consensus that energy technologies on the base of renewable sources such as solar radiation, wind power and biomass will not only achieve a sea change in terms of global warming but also will be inherently friendly to the environment too. Recent studies (Heedegard et al. [4]) however challenge these assumptions at cost for biofuels and call for a more careful analysis of ecological impact of energy technologies over the whole life cycle.

There is a methodological challenge in comparing different energy technologies that is caused by the fact that they are based on widely different sources and techniques to exploit these sources. Conventional energy technologies are mostly based on fossil resources like coal, crude oil and natural gas. These technologies usually exhibit their largest pressure on the environment during operation by emitting CO_2 into the atmosphere and thus changing the global carbon flow systems with grave consequences for the global climate.

Technologies based on biofuels and biomass in general exert quite different pressures on the environment. For these technologies the pressures caused by agriculture as well as transport become important, as do pressures caused by pollutants like NO_x produced during burning biogenic energy carriers. Especially fossil fuel which is commonly used in mechanized agriculture is a very important factor for the ecological footprint for biofuels. Another main factor on the emission side of agricultural crop production is the production of N_2O from the usage of mineral fertilizers (Kendall and Chang [8]). CO_2 emissions during operation however have almost no importance for those technologies as biogenic resources per se do not change global carbon flows. In general, a detailed view on the substrates, co-products and transport emissions during the life cycle is necessary.

Finally, there is a group of energy technologies that do not cause appreciable environmental pressure during operation such as wind power, solar heat and photovoltaic and to a lesser extent hydro power. For these technologies, the main environmental pressure is linked to the construction and installation of the equipment like PV panels, wind turbines and solar collectors. The task of comparing these different energy technologies in terms of their environmental pressures requires a tool that must take into account different qualities of environmental impacts yet still leads to a meaningful evaluation of the overall environmental performance of the technique.

There are several methodologies available for evaluating environmental impacts like MIPS (material input per service unit, (Schmidt-Bleek and Bierter [18])), CML-Method (Centrum voor Milieukunde Leiden, (Heijungs et al. [5])), CED (cumulative energy demand, (Ökoinstitut e.V. [13])), Energy footprint (Stöglehner [19]) and even more as Fijal [2] and Finnveden and Moberg [3] are describing in their work. For a complete environmental impact assessment, an analysis tool is needed which can evaluate material flows, energy flows and emissions. This calls for a measure that is highly aggregated (to allow comparison) but evaluates different impacts in a transparent scientifically based way. The sustainable process index (SPI) (Narodoslawsky and Kroteschek [9]) is such a measure which follows the rules of the ISO 14040 norm. The SPI has already proved its usefulness in a number of studies involving renewable resource-based technologies (Narodoslawsky et al. [11]; Narodoslawsky and Niederl [12]; Niederl and Narodoslawsky [10]) and is freely available on the internet (Sandholzer et al. [16]) via the website http://spionexcel.tugraz.at.

The SPI is a member of the ecological footprint family and measures the area that is necessary to embed a human activity sustainably into the ecosphere, taking resource provision, energy use, waste and emissions into account. By referring the environmental pressures incurred by manufacturing and construction of equipment to the economic life time of the installation, the environmental impact of infrastructure can also be considered.

2 Differing environmental pressures for different technologies

Energy provision technologies offer an opportunity to investigate the environmental profiles of technologies based on widely different resources and technological structures. There are many ways to provide heat, electricity and fuel but there is a product that is very comparable, namely the energy output in MJ. Evaluating the impact of different technologies with the SPI is therefore not only interesting from the point of view which is that technology providing the needed energy while causing the lowest impact on nature, but also interesting from the point of view of what particular impact a certain technology causes as this may be the starting point for optimization as well as supporting strategic planning against the background of changing structures in the resource base of society in the 21st century. The following figures show that “renewable resource-based energy technologies” represent a very diverse range of technologies with large differences in both their overall pressure as well as the distribution of this pressure into different impact categories. For better overview, the information rendered by the SPIonExcel program has been condensed in seven categories: the use of fossil-carbon, non-renewable and renewable resources (whereas the amount of fossil-carbon represents the impact on global carbon cycle), area utilization and emissions to air, soil and water. Despite of these 7 categories, only 3 of them (fossil-carbon resource, emissions to air and to water) are considered in this report (e.g. Figures 2 and 5) because the rest are in that case negligible. All comparative values of footprints refer to the impact incurred by providing 1 MJ of the energy form in question at the point of distribution.

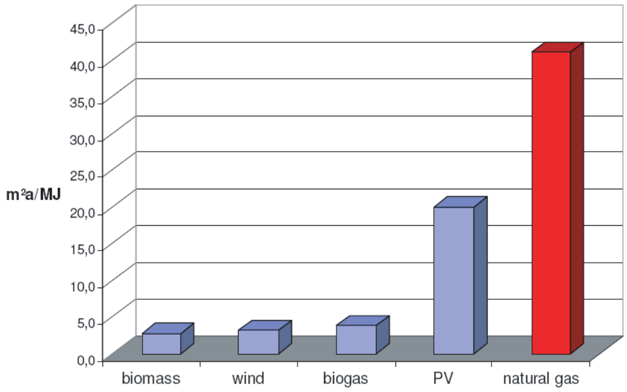

Figure 1: Comparison of ecological footprints for different electricity provision technologies.

2.1 Electricity provision technologies

Figure 1 shows the comparison between five different technologies to supply electricity. The unit m^2a/MJ from Figures 1 to 5 means footprint area per year of production and produced MJ.

Part of the diagram is a wind turbine based on data from a Vestas 3 MW turbine (Vestas Corporation [20]), a monocristalline photovoltaic panel based on data from ecoInvent (Jungbluth and Tuchschmid [7]), a biogas unit (producing heat and power through a micro gas turbine, based on a mix of grass-, corn- and clover silage), a biomass ORC (organic rankine cycle) unit powered by wood chips (Bauer [1]) and a high performance natural gas combined heat and power system (with a 90% overall efficiency and a 45% electricity efficiency with respect to the gas input).

It goes without saying that the value for the biogas unit can only be seen as one value within a range of ecological footprints for this technology as the impact on the environment is critically dependent on the raw material, fossil fuel usage for machinery and application of mineral fertilizers. The calculation for the biogas unit assumes that biogas manure is used as a biological fertilizer on the fields to substitute mineral fertilizers. Footprints may become considerably higher (by a factor of three at least) if biogas production is based on conventionally produced crops.

From this figure it becomes clear that even a “clean” fossil-based technology as natural gas turbines exert a higher pressure than all renewable resource-based alternatives. The difference here is not just percent points but factors, with natural gas derived electricity (with 41.0 m^2a/MJ) exerting 10.8 times the impact of the biogas technology (with 3.8 m^2a/MJ) and still two times the impact of the

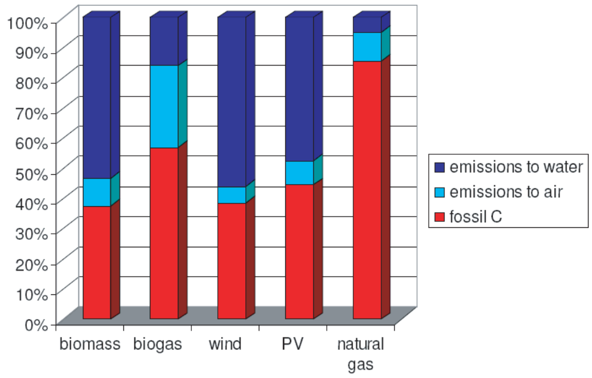

Figure 2: Environmental pressure distribution for electricity generating technologies.

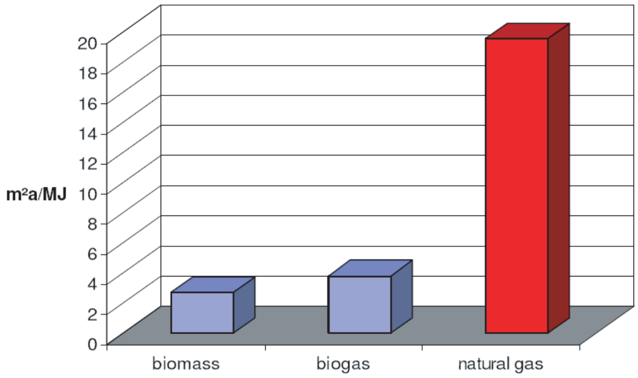

Figure 3: Comparison of ecological footprints for different heat provision technologies.

"worst" renewable based technology photovoltaics (PV with 19.9 m^2a/MJ).

It is however interesting to look at the different impact profiles of the technologies. Figure 2 shows a comparison of these pressures for biomass, biogas, wind turbine, PV and natural gas. Analyzing these, it is obvious that the pressure on climate (represented by the fossil C contributes representing CO_2-emissions) is strong in all technologies. It is clear that this pressure category dominates the natural gas technology; however it is interesting that it is also a strong influence in renewable resource-based technologies. The reason is that our current energy system is still mostly fossil based and any energy input to production and manufacturing of equipment is also causing pressures in this category.

Another interesting result is the difference in the profile between photovoltaic panels and wind turbines. A comparison reveals that the fossil carbon pressure dominates the wind turbine, reflecting the fossil contribution to steel processing. This cannot be reduced unless fossil coal is replaced by a renewable based alternative (like charcoal) in iron smelting, a change that has a low probability of realization in this century.

In photovoltaic panel production, the emissions (especially to water) are prominent, as a result of the complex chemical process employed to produce the semiconductor wafers. This points to the necessity to have a sharp eye on the emissions from this process. Moreover, it is interesting that the carbon emission pressure predominantly comes from the frames of the panels (which are made from metals), caused by the energy intensive production processes of these materials. By and large, the contribution from the raw material itself as well as the direct area use is negligible.

2.2 Heat generation processes

Figure 3 presents the comparison between three different heat providing processes. Combined heat and power technologies from Section 2.1 (biogas unit, biomass ORC unit and natural gas turbine) are sharing the ecological footprint with the electricity production part rated to their amount of output in MJ. The comparison shows a similar picture than in electricity generation, with renewable based technologies coming out on top with regard to environmental pressures.

Difference between the worst (natural gas turbine which has 19.6 m^2a/MJ) and the best technology (biomass ORC unit with 2.7 m^2a/MJ) results in a 7.3 times higher footprint for the natural gas turbine. Which is not such a big difference as in Figure 2 but again the fossil carbon technology is much worse compared to renewable based technologies.

2.3 Biofuel systems

A particularly interesting picture arises with fuels. Figure 4 compares different biofuel systems based on renewable as well as fossil resources.

The two left-hand columns in this figure represent the ecological pressure of bioethanol, with the first column on the left side showing the value for a production of ethanol from corn, using biomass for the provision of electricity and heat for the process. The column to the right shows the pressure exerted by ethanol from a process that uses natural gas as a source of process energy and again corn as substrate. The comparison shows that the energy source for the process decides about the impact of two otherwise similar ways to produce fuel.

Ethanol from corn is according to this calculation environmentally advantageous compared to fossil gasoline. As Reijnders and Huijbregts [15] show, this effect can be even increased if sugar cane is used as a resource.

The comparison of the impact profiles is shown in Figure 5 for the two bioethanol alternatives, gasoline and diesel. The main pressure for bioethanol from corn using natural gas as process energy source is clearly dominated by the fossil carbon impact. Even in the case of the bioethanol production using biomass as process energy source fossil carbon is an important environmental factor. The absolute

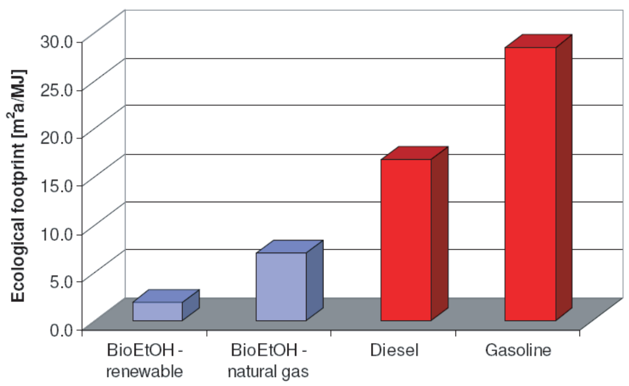

Figure 4: Comparison of ecological footprints for different fuel systems.

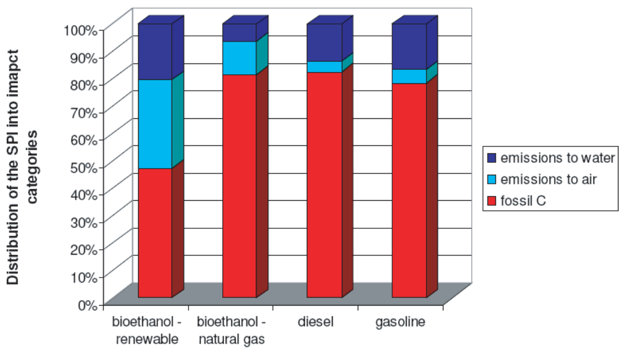

Figure 5: Environmental pressure distribution for biofuel systems.

size of the impact however is much lower and the origin is different. Whereas in the former case fossil carbon (and thus carbon dioxide emissions) is linked to the energy provision of the process, in the latter case the impact results from agriculture, especially the fossil energy to generate fertilizer and the fuel for machines. The large fraction of fossil carbon impact for diesel and gasoline is however not surprising. The fossil carbon part in biofuels can be decreased by using biofuels for agriculture machinery and transport systems by Ometto and Roma [14].

3 Conclusion

Comparing different energy technologies with the SPI reveals some interesting insights as follows.

The environmental pressure of fossil-based technologies and fuels are indeed much larger than that of comparable technologies and products on the base of renewable resources. The impact of fossil technologies is by factors larger than that of renewable resource-based technologies.

Fossil carbon plays a major role in the pressure even of renewable resource-based technologies. This is linked to the fossil orientation of our current resource system as coal, fossil oil and gas dominate the energy provision of industry as well as transport and energy provision for society.

Using fossil energy in processes based on renewable resources inevitably raises the ecological impact considerably as is evidenced by the bioethanol case.

There are large differences in between different technologies/products based on renewable resources regarding their environmental pressure. Just using a renewable source does not qualify a technology or product to become overall sustainable.

Technologies which exhibit high pressures stemming from energy provision (like photovoltaic panels) will become more attractive the more the overall energy system becomes more sustainable.

In general, the evaluation confirms that a switch towards renewable resource-based technology systems is indeed capable of reducing human pressure on the environment dramatically. This is mainly true because these technologies shift the environmental pressure away from fossil carbon impacts that currently dominate environmental considerations.

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