ISEC 2024 – 3rd International Sustainable Energy Conference
Policies for Phase-Out Fossil Fuels and Carbon Management
https://doi.org/10.52825/isec.v1i.1055

Published: 19 Apr. 2024

REA: Resource Exergy Analysis – A Key to Climate Sustainability

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Abstract. Resource exergy analysis (REA) is a method to comprehensively assess the resource consumption of technical systems. It is based on the physical property "exergy", which goes beyond conventional energy analysis by considering energy quality. Combining exergy with a scientific definition of natural resources, REA can provide a comprehensive quantification of the resource consumption caused by any demand. REA introduces resource exergy consumption as a new key metric for the assessment of technical systems. In combination with an assessment of the direct greenhouse gas emissions, it allows quantifying climate sustainability consistently. The use of REA can be a key to climate sustainability by helping to minimize wastefulness and, consequently, indirect greenhouse gas emissions.

In this paper, a sample comparison using REA and a complementary greenhouse gas analysis is provided that illustrates why REA is a key to assessing the climate impact of technologies more comprehensively than with many alternative methods. Specifically, the following systems are compared: heat supply using an individual natural gas boiler, an individual boiler using green hydrogen from wind power and district heating generated with a large heat pump using wind power. To illustrate the differences, exergy passes are used. They are a visualization tool to make REA results more transparent.

The sample analysis illustrates how REA helps to avoid greenwashing and thus support climate sustainability by complementing direct greenhouse gas emissions analysis.

Keywords: Exergy, Resources, Energy, District Heating, Large Heat Pumps, Hydrogen, Technology Comparison, Methodology, Climate Protection, Sustainability, Renewable Energies, Wind Power

1. Introduction

The central goal of the energy transition is achieving climate neutrality as fast as possible. A realistic and target-oriented assessment of energy systems is key to achieving this objective.

With the increasing use of non-fossil sources, problems with existing evaluation systems for energy products and energy consumers become more relevant. In particular, the following are worth mentioning:

1. Non-renewable primary energy factors do not adequately consider the climate impact. For example, natural gas and hard coal are valued the same. Furthermore, they do not allow for differentiation of renewable energy supply systems.

2. Total primary energy factors are usually not suitable for assessing overall efficiency. Energy from solar thermal, waste heat, photovoltaics and natural gas are rated approximately the same.
3. Greenhouse gas emission factors cannot contribute to the effective implementation of the “efficiency-first” principle for energy systems that emit low amounts of greenhouse gases. Thus, despite much greater inefficiency, the combustion of green hydrogen in boilers would be considered almost equal to the use of green electricity in heat pumps using this indicator.
4. The indicator “share of renewable energies” is misleading in some cases. Even systems with high shares of renewable energies can contribute significantly to ecological damage, e.g. when using palm oil from former rainforest areas.

A sound solution to these problems is the combination of two, independent, reality-based indicators.

The frequently used non-renewable primary energy factors can be replaced by realistic greenhouse gas emission factors. However, these only allow an estimate of direct emissions.

The comprehensive implementation of the “efficiency first” principle is only possible through an additional assessment of the resource exergy consumption (REC). The physical quantity exergy, which considers not only energy but also energy quality, combined with suitable balance boundaries provides an optimal basis for this.

Furthermore, reduced REC helps to minimize indirect greenhouse gas emissions. This effect is caused by the demand-oriented supply usually expected from energy systems. If demand always needs to be covered, and all available low-carbon energy sources are used as intensively as possible, then any wastefulness leads to an increased use of other, usually fossil resources somewhere in the supply chain. This in turn causes indirect emissions due to resource wastefulness. [1]

2. Definition

To assess resource exergy it needs to be defined consistently. Commonly, a resource is understood to be a naturally existing stock of something that is [constantly] needed for a specific purpose, especially for human nutrition and economic production. Resource exergy is the exergy associated with this stock.

Resources can form a stock in the present form. Consequently, only energy flows are considered resource exergy flows that can be stored directly in their present form without further conversion or transmission.

Energy flows that are lost to the global technical energy system if they are not used directly, such as solar energy, kinetic energy of wind and water currents, and geothermal and waste heat, do not constitute stocks and are therefore not considered resources.

In these cases, where the primary energy cannot be stored without conversion or transmission to a technical system, the first secondary energy that can be stored directly, without conversion or transmission, is considered a resource.

This means that when generating electricity from solar radiation or the kinetic energy of wind or river water, the electricity generated is considered a resource.

In the case of solar thermal systems, the hot water produced with it at a certain temperature level is considered a resource.

The resource potentially provided by waste heat and geothermal energy is the heat after transfer to a technical system (e.g. a water circuit). Waste heat is considered in the same way as geothermal energy, with the difference that the effort required to transfer it to a technical system is usually much lower. The necessity of releasing waste heat to the surroundings of the waste heat generator allows considering it as if it is extracted from the environment, thus making it a quasi-natural energy source.

3. Application

Water in reservoirs represents an artificially generated resource, as the storage of water preserves part of its original potential energy, e.g. water in mountains. Accordingly, when considering water from reservoirs, losses in the conversion of potential energy into electricity must be properly considered for the determination of RE.

Thus, natural fuels represent the only naturally occurring resources for the energy system, as they are already stored as they are, without transfer to a technical system. This includes fossil, biogenic and nuclear fuels. [1]

One goal of REA is to help assess climate sustainability. This is achieved by calculating resource exergy consumption (REC) in parallel to the greenhouse gas emissions (GHGE) caused by a considered energy system that supplies a given demand. REC and GHGE are complementary metrics for any energy system scenario. Thus, alternative energy systems – such as existing and possible future ones – can be compared. This in turn allows the identification of the least wasteful and polluting systems, enabling decision makers to favour these systems above less sustainable ones. A detailed guide for assessing all types of energy systems [1] is available since 2023 to allow consistent quantitative comparison of all potentially viable energy systems on an individual, communal and even international scale.

4. Application Example

In the following, REA has been applied to an individual natural gas condensing boiler (Natural gas boiler), an individual hydrogen boiler using green hydrogen from wind power (Green H2 boiler) and district heating from a large heat pump using wind power (Green LHP DH). The equations used are presented in [1]. The following table lists the calculation assumptions used. The demand assumptions of 1 GWh/a total have been made for illustration purposes.

Table 1. *Calculation assumptions used for the comparison of the three presented heat supply alternatives*

	"Natural gas boiler" Individual natural gas boiler	"Green H2 boiler" Individual hydrogen boiler with green hydrogen from wind power	"Green LHP DH" District heating from a large heat pump using dedicated wind power and a river as a heat source
Space heating demand at 20 °C	800 MWh/a	800 MWh/a	800 MWh/a
Hot water heating from 10 °C to 43 °C	200 MWh/a	200 MWh/a	200 MWh/a
Final energy bought	Natural Gas	Green hydrogen from wind power	Green electricity from wind power
Specific Greenhouse gas emissions in CO2 equivalents over a 100-year period [1]	0.272 kg_{CO2e}/kWh	0.016 kg_{CO2e}/kWh	0.011 kg_{CO2e}/kWh
Specific resource exergy consumption of first directly storable energy form [1]	1.26 kWh/kWh	1.06 kWh/kWh	1.06 kWh/kWh
Efficiency of conversion from first directly storable energy form to final energy bought	100 %	70 %	100 %
Heat losses outside the supply target in percent of the heat produced	0%	0%	10 % [2]
Auxiliary power consumption for thermal network operation in percent of the heat produced	0%	0%	1.5% [3]
Ratio of higher to lower heating value of the final energy bought	0.901 [4]	0.840	1.000
Heat output of heat generator, relating to the lower heating value of the final energy bought (energy efficiency / coefficient of performance)	0.96 [5]	0.96 [5]	2.7 [6]

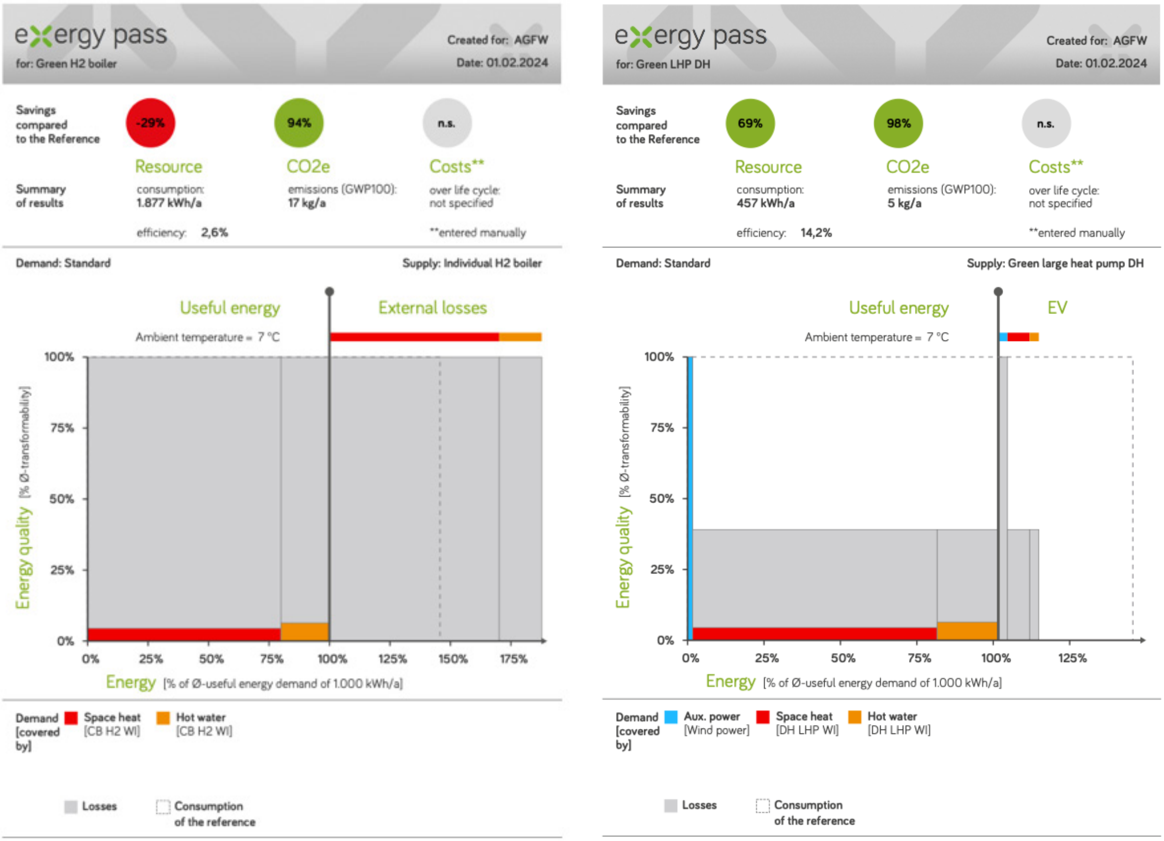

Figure 1. *Exergy passes for a hydrogen boiler with green hydrogen from electricity from wind power (left) and heat supply from district heating using a large heat pump driven by electricity from wind power*

Exergy passes have been introduced as “ExergyFingerprints” in [7] and developed to their current form in [8].

The exergy passes presented in Figure 1 visualize how different heat supply options with similar greenhouse gas emission (CO2e) savings can be in terms of resource exergy consumption. The size of the total area in the middle in relation to the area within the dotted line shows how many resources are consumed to cover the demand displayed in red, orange and blue.

The area on the left side is differently shaped and much larger than the one on the right side. Just by looking at the two areas, it becomes obvious that there is a stark difference between the two shown scenarios.

A summary of the quantitative results of REA of the three scenarios considered is shown in Figure 2.

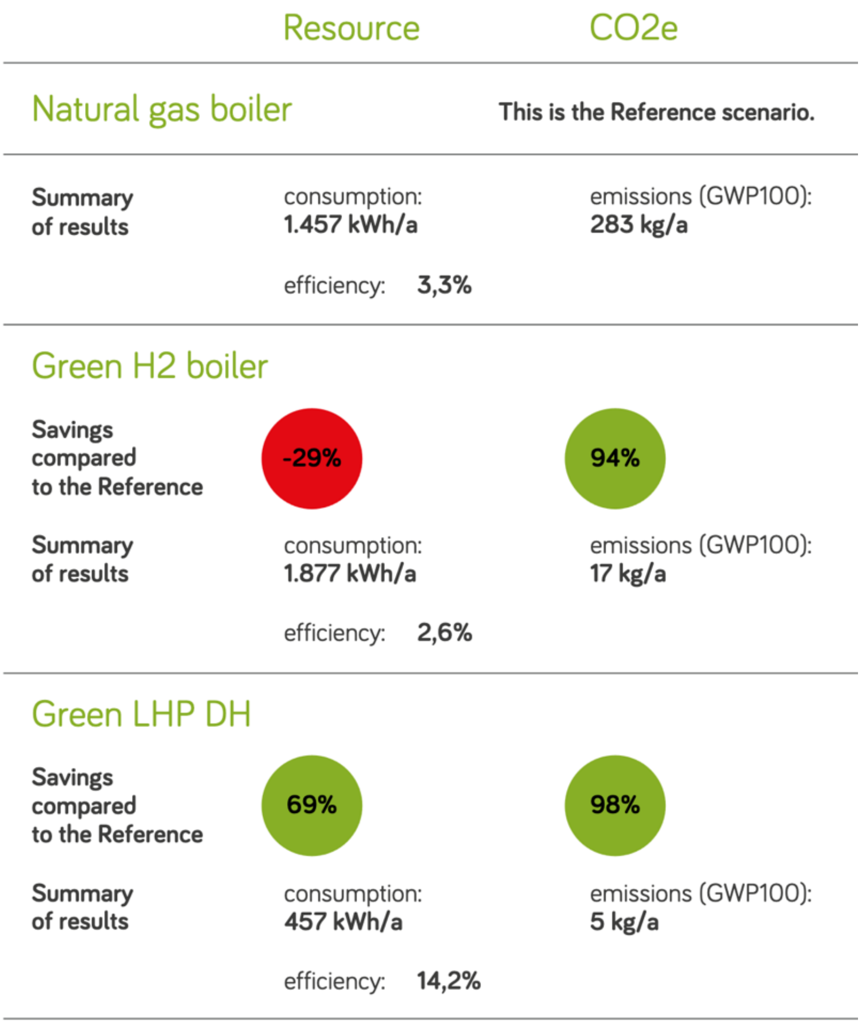

Figure 2. *Results of the sample comparison*

The analysis results presented in Figure 2 show that the “Green H2 boiler” and “Green LHP DH” generate similar savings in terms of greenhouse gas emissions vs the reference scenario “Natural gas boiler”. At the same time, they cause significantly different resource exergy consumption (abbreviated as resource consumption).

The “Green H2 boiler” causes more than four times more resource exergy consumption than the heat supply with the “Green LHP DH”. It also causes 29 % more resource exergy consumption than the “Natural gas boiler”.

The impact on climate sustainability becomes apparent if considering that global energy supply follows global energy demand. As a simplification, it can be assumed that low-carbon energy such as wind power is deployed and used as much as the current political situation allows. This means any quantity of wind power produced is used in the global energy system. Either directly as electricity or in storable forms such as green hydrogen from wind power.

Since the “Green H2 boiler” uses more than four times the resources of the “Green LHP DH”, it “wastes” more than three units of wind power per unit of heat demand covered at the considered site. Consequently, more than three units of resource exergy need to be added to the global energy system to compensate that loss to keep covering global demand. As all low-carbon sources are assumed to be used to the maximum extent, the added units of resource exergy are very likely of high-carbon origin. Their use in turn will generate indirect emissions that could have been avoided if using “Green LHP DH” instead of “Green H2 boilers”.

In theory, it could be possible to quantify the indirect emissions caused by wastefulness. However, an accurate assessment would require immense and comprehensive amounts of real-time data, which is currently not available. Quantifying resource exergy consumption, however, is much easier and can help to minimize indirect emissions.

This example illustrates that resource exergy consumption offers an option for a key ecological decision criterion, particularly for energy systems with low greenhouse gas emissions.

5. Conclusion

It has already been shown that primary energy factors are not suitable for a sensible comparison of low-carbon technologies [9]. The sample analysis in this article demonstrates the effectiveness of REA in enabling climate sustainability when looking at heating systems using low-carbon energy sources.

It is key to remember that effective climate protection is the main goal of the energy transition. Therefore, all aspects impacting this target must be considered appropriately.

The provided example demonstrates, it is not enough just to reduce direct greenhouse gas emissions. Avoidable indirect greenhouse gas emissions must also be reduced. These arise when an energy system consumes more resources than necessary.

Therefore, in addition to minimizing direct greenhouse gas emissions, comprehensive and effective climate protection requires reducing resource exergy consumption and the associated indirect greenhouse gas emissions.

Resource exergy analysis (REA) provides a key to help minimize those indirect greenhouse gas emissions effectively and reach climate sustainability as fast as possible.

Author contributions

The author contributed to this work in all roles according to the CreDIT guidelines here.

Data availability statement

The data used in the presented sample has been referenced in Table 1. The equations used to generate the results in Figure 2 are presented in [1].

Competing interests

The author declares that he has no competing interests."

Funding

This research has been conducted as part of the real-lab research project: "Reallabor der Energiewende – Großwärmepumpen in Fernwärmenetzen" (FKZ 003EWR008A). It has been partially funded by the German Federal Ministry of Economic Affairs and Climate Action and the European Union. Another part of the research funding has been provided by AGFW | The Energy Efficiency Association for Heating, Cooling and CHP.

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