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Sustainability Index to Assess the Environmental Impact of Heat Supply Systems

A sustainable heat supply is studied by defining indicators to evaluate local heat supply systems based on renewable energies compared to fossil energy reference scenarios. Besides the energy production, the evaluation considers the heat distribution network and long-term storage. The indicators include ecological, economic, and social aspects.

Keywords: Biomass, Heat generation, Heat supply system, Renewable energy, Sustainability index

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1 Introduction

The debate about energy transition, the exit from nuclear and fossil fuel energy to renewable energy, still focuses on the generation of electricity. However, just about 15 % of the total energy consumption of a typical domestic customer (Germany) is used for electrical appliances (~14 %) and electric lighting (~1.5 %). About 85 % are employed for heating (~71 %) and domestic hot water (~14 %). [1] Under this aspect, a successful transition of the heat supply based on fossil fuel to renewable energy becomes even more important to reduce the greenhouse gas emissions and limit global warming to the recommended 1.5 °C goal [2].

Nevertheless, to ensure a holistic sustainable assessment, there are three dimensions to consider: the environmental aspect, the profitability, and the social compatibility. This article gives an outlook for a sustainable index assessment based on an approved approach for local heat supply systems. The method focuses on environmental aspects supplemented by economic and social items.

In general, a sustainable local heat supply is based on three columns: renewable energy, efficiency in technology, and a careful use of resources under consideration of planetary boundaries. Efficiency is one of the major contributors to reduce the overall power consumption by lessening of the total loss of power and the selection of fuel with an appropriate heating value. Furthermore, the local use of renewable energy resources helps to reduce greenhouse gas emissions and strengthen the regional rural structure.

As of today, most of the local heat supply systems based on renewable energy installed in Germany are mainly based on biogas or biomass and fossil fuel energy for covering peak loads. According to the renewable energy sources act (EEG 2017 § 1), the objective is the generation of electricity and power input to network supply. Thus, the transition of the heat supply got out of focus. The energy efficiency also considering heat, potential environmental impact by taking and using of resources, as well as material inputs and outputs for manufacturing and production until end of life is not considered. Therefore, solar and geothermal supported local heat supply systems with reduced consumption of primary energy are still at the level of exception.

The aim of this study is to compare alternative technologies for heat generation and distribution to the existing technologies under consideration of ecological, economic, and social aspects by implementation of an appropriate sustainability index.

2 Methodology

Different scenarios of heat production from biomass, biogas, solar and geothermal energy, and fossil resources are compared using sustainability indicators. These indicators build an assessment matrix that can be used as a planning instrument for the implementation of sustainable and energy-efficient local heat supply systems. While the main focus is on ecology, economic and social aspects are considered as well. This method uses indicators for input, output, efficiency, and balance (Tab. 1). To realize improvements in comparison to the status quo, an environmental quality target to reduce the environmental impact by minimum 75 % is set [3].

In the context of the study two heating projects in the districts Speichersdorf and Mitterteich are compared. For the project Speichersdorf different coverage areas and heat consumption structures are considered. The lengths of the grids in

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Table 1. Indicators with environmental quality objective [3].

Indicator group	Indicator	Core statement
Input indicator	Cumulative renewable energy demand (CED renewable) [kWh kWh^{-1}]	Resource consumption per kWh of useful heat by using renewable resources and renewable energies – reversible
	CED nonrenewable [kWh kWh^{-1}]	Resource consumption per kWh of useful heat by use of fossil energy sources such as oil, natural gas – not reversible
	Area [m^{2}kWh^{-1}]	Space for the production of plants and primary energy sources in m^2 per kWh of useful heat
Output indicator	Specific heat price [€ kWh^{-1}]	Costs of 1 kWh useful heat according to the current energy prices including debt service operation, maintenance, and repair
	CO_2 equivalent [kg CO_2kWh^{-1}]	Climate change – relative global warming potential in kg CO_2 per kWh useful heat
	SO2 equivalent [kg SO_2kWh^{-1}]	Acidification – relative potential for soil acidification in kg SO_2 per kWh useful heat
	TOPP equivalent [kg NMVOC kWh^{-1}]	Ozone formation – relative tropospheric ozone precursor potential in kg NMVOC per kWh useful heat
	Wastewater [kg kWh^{-1}]	Wastewater per kWh of useful heat
	Waste [kg kWh^{-1}]	Waste per kWh of useful heat
	Regional added value [€ kWh^{-1}]	Capital that remains in the region and contributes to prosperity
Efficiency indicator	Overall efficiency including power loss [%]	Energy efficiency/productivity of the technology used
Balance indicator	Avoided environmental impacts	Dimensionless summary of results – reducing the environmental impact compared to the initial/actual situation
Environmental quality objective	Reducing the environmental impact by at least 75 % compared to the initial situation	

the two areas in Speichersdorf are 10 828 m and 6027 m. Those are opposed to the project Mitterteich with a grid length of 360 m and a higher heat consumption. For these three coverage areas various scenarios are calculated and evaluated [3].

The calculation of the various processes and scenarios is performed with the program GEMIS 4.8 [4] based on the total heat generated (final energy) by the respective supply type. The study examines the main system components like boilers, solar heat collectors, geothermal energy storages, geothermal heat system, and distribution network. Based on a life cycle assessment using the indicators (see Tab. 1), the energy and resource input and the emissions of each variant are calculated. In order to distinguish which part of energy consumption and emissions are caused of the district heating network itself, the variants are calculated with and without distribution network and geothermal storage.

The results of the individual indicators are summarized under the collective term “environmental impacts”. A rating system is applied to weight each indicator individually and scale them to the unit of 1 kWh. Hence, the balance indicator “avoided environmental impacts” demonstrates the overall results and compares them to the environmental quality objective. This results in the dimensionless scaling between –1 and 1. Therefore, the rating is inverse to the algebraic sign. For example, the indicator CO_2 equivalent, which is considered harmful for the environment, has a positive value and the indicator regional added value, which adds prosperity to the region, has a negative value. All the indicators with their signs and their weighting coefficients are summed up in order to evaluate the different scenarios.

3 Reference Scenario and Heat Supply Variants

The scenario V1ÖlGas serves as a reference scenario of decentralized natural gas- or mineral oil-operated heating plants. The reference is compared to the following scenarios [3]:

- V2: biomass and fuel oil to cover peak load
- V2a: biomass, biogas, and fuel oil to cover peak load
- V3Solark40: biomass, 40 % solar cover ratio, fuel oil to cover peak load
- V4Solar20: biomass, 20 % solar cover ratio and fuel oil to cover peak load
- V4aBGSolar20: biomass, biogas, 20 % solar cover ratio and fuel oil to cover peak load
- V6 Geoth: geothermal plant with fuel oil to cover peak load
- Mitterteich: biomass, natural gas to cover peak load

Each of these scenarios is analyzed with and without consideration of the heat network, in order to demonstrate the effect of the grid. The term mNetz in Fig. 1 illustrates the result of each heat supply variant including the heat distribution network. Additional to heat generation and distribution, the variant mNetzSo contains the component geothermal storage (aquifer). The calculation of the respective network was based on a plastic-coated tube and polyethylene pipe for the probe of the geothermal storage.

4 Results and Discussion

The different heat supply options differ only slightly by comparison (Fig. 1). The variant V6 geothermal performs a slightly higher value because of the relatively high cumulative energy demand (CED) for non-renewable energy sources due to the load current, despite otherwise low emissions with 0.0137. In addition, the lower added value and the higher heat price compared to biomass have a negative impact on the assessment. Due to the increasing electricity generation from renewable energy sources such as solar, wind, hydro, and combined heat and power and rising fuel prices, particularly for biomass, this effect is reversed in a medium term [3].

The variant V3mNetzSo with 40 % solar coverage performs worse than the variants with a smaller solar percentage due to the comparatively high CED for the production and the high investment costs. The evaluation changes accordingly through the use of advanced production engineering and rising prices for mineral oil [3].

The evaluation benefits from the subsidies for combined heat and power. Emissions are weighted higher than wastewater load and land use. Therefore, biogas performs well by comparison. The best result is achieved by the variant V2aBG in the large coverage area Speichersdorf with a value of −0.01916 [3]

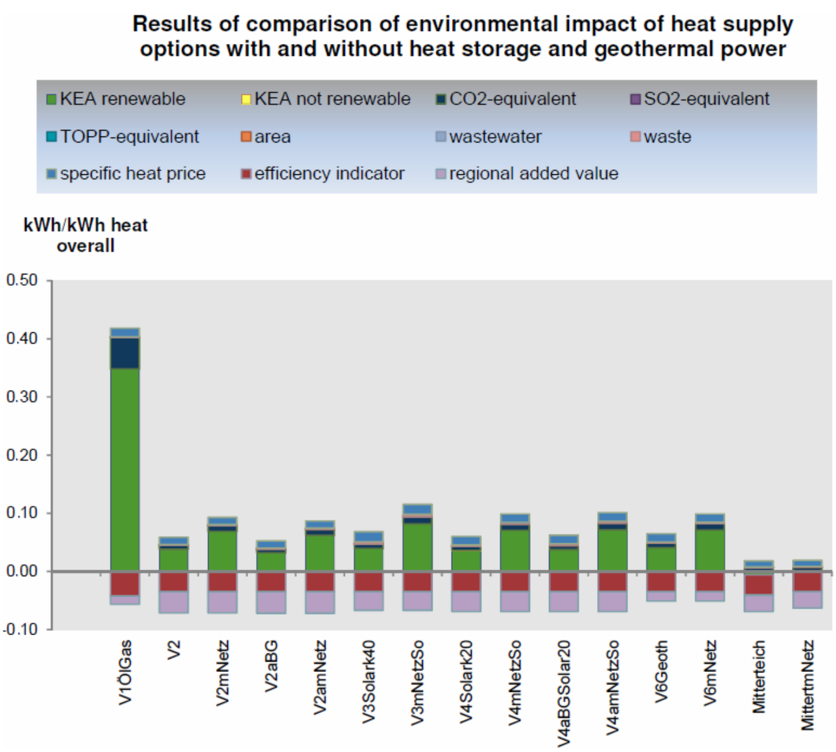

Figure 1. Results of the comparison of the environmental impacts of the heat supply options with and without heat storage and geothermal power [3], based on [4].

Due to the relatively small CED for the manufacture of boilers and the low amount of emissions, the environmental aspects of variant V2 with biomass and fuel oil for peak load are comparatively positive. In combination with its high added value and the present low heat price this variant achieves a very good result of −0.0127 [3].

With 174 € MWh^{-1} the variant V3Solark40 has the highest specific heat price. For all the other variants, however, this indicator is below the reference scenario's value of 149 € MWh^{-1} [3]. Both environmental and economic reasons suggest the implementation of district heat supply options. Overall, the reference scenario has the most negative environmental impacts, while the variant Mitterteich has the least of all compared types.

The results also demonstrate that the heat distribution network, in particular the thermal insulation, have significant environmental effects and thus influence the sustainability. The geothermal polyethylene pipe is less significant compared to the heat distribution network, but still has a strong impact. Therefore, variants with power probe and grid give the worst results. For this reason, local heat networks should only be built with mixed customer structures of medium and large customers.

Due to its low heat demand, the supply of existing pure single-family houses is not recommended. This effect is even more dramatic in the supply of new buildings. Nevertheless, when large networks are implemented with low heat demand density, heat generation should definitely be from renewable energy sources [3].

The balance indicator "avoided environmental impacts" indicates the percentage of environmental impacts that can be avoided in comparison to the reference scenario (Fig. 2). Because of the scaling between −1 and 1, results with more than 100 % can be achieved due to the credit of the negative values. Therefore, in the reference scenario 0 % of the environmental impacts are avoided and the most sustainable option Mitterteich achieves 114.08 %. Basically, the evaluations of the variations in the supply area 1 Speichersdorf do not differ greatly.

The grid and geothermal storage contribute to 13 % of the environmental impact of variant V3Solark40. In variant V6Geoth, the environmental impacts increase by 9.45 % on account of the heat distribution network. In the variants V2, V4, and V6, the same heat network is calculated for the large coverage area Speichersdorf. The share of environmental impacts of geothermal storage in the variant V3Solark40 is 3.55 %. In the variants 4aBGSolar20 with 20 % solar heat and the smaller geothermal storage, the proportion of the network and the heat storage is 10.71 %. In the variant Mitterteich, the heat network has a small impact of only 1.58 % due to the high consumer density and the short network [3].

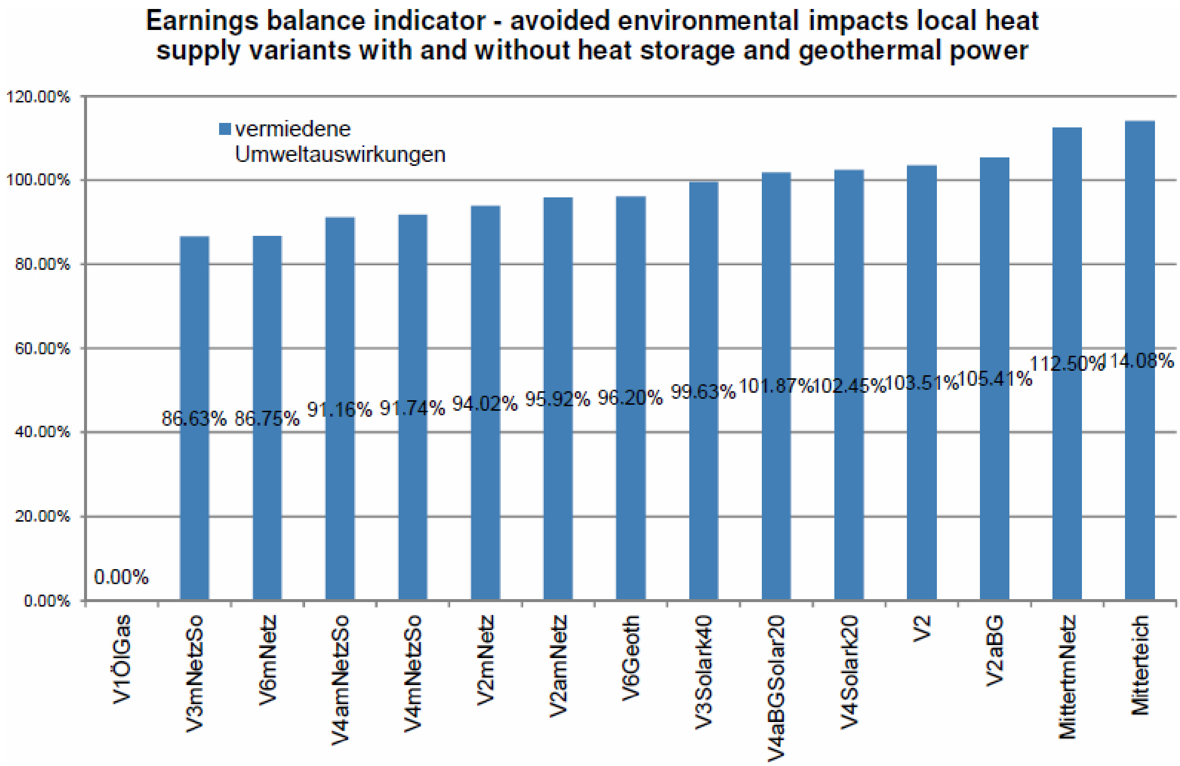

Figure 2. Presentation of comprehensive income with balance indicator “avoided environmental impact” [3], based on [4].

The impact of individual projects on sustainable development in the region is demonstrated by the indicators CO_2 equivalent and regional added value (Tab. 2). For this purpose, data from the Climate Action Plan of the district Tirschenreuth [5] in the sector domestic use are compared to the district heating supply variants.

Table 2. Reference result output indicator CO_2 emissions of heat supply variations on the region Tirschenreuth [3] – based on climate protection concept Tirschenreuth and GEMIS [4].

	[t]	[%]
Total CO_2 emissions[a)]	357 828	100
V2	2450	0.68
V2aBG	2486	0.69
V3Solark40	2396	0.67
V4Solark20	2453	0.69
V4aBGSolar20	2419	0.68
V6Geoth.	2386	0.67
Mitterteich	455	0.13

[a)] Similar residential use Landkreis Tirschenreuth 2008.

The project Mitterteich in Tirschenreuth itself already contributes to a saving of 0.13 % of CO_2. The realization of a project similar to Speichersdorf in the district of Tirschenreuth would lead to CO_2 savings between 0.67 % and 0.69 % for similar residential use, depending on which version will be implemented [3].

The indicator “regional added value” demonstrates how much capital and therefore purchasing power remains in the region and contributes to prosperity (Tab. 3) through the implementation of a district heating project. Depending on the supply variation, between 105 000 € for Mitterteich per year and up to 777 000 € for Speichersdorf per year remain in the region [3].

Table 3. Regional added value of the heat supply options 2–6 and Mitterteich [3].

	[€ MWh^{-1}]	[€]
V2	73	765 543
V2aBG	74	777 960
V3Solark40	64	672 431
V4Solark20	68	714 108
V4aBGSolar20	68	714 108
V6Geoth.	32	330 907
Mitterteich	56	105 212

5 Future Impacts

The developed sustainability indicator system serves as a planning tool for the evaluation of local heat supply options and projects. Furthermore, the individual indicators can be set in relation to almost any benchmarks such as regions, states, or other countries. With this instrument, it is calculable, e.g., which CO_2 savings single projects generate in percentage of a region. Conversely, it is a tool to determine how many projects for a heat supply from 100 % renewable energies are necessary to install. Thus, the indicator system is a useful tool also in the development of climate protection concepts.

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The authors have declared no conflict of interest.

Abbreviations

CED	cumulative energy demand
EEG	Erneuerbare-Energien-Gesetz (renewable energy law)
GEMIS	global emissions model for integrated systems
NMVOC	non-methane volatile organic compound
TOPP	tropospheric ozone precursor potential

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