Applied Energy 102 (2013) 1448–1457

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Thermoelectric generators for efficiency improvement of power generation by motor generators – Environmental and economic perspectives

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HIGHLIGHTS

- ▶ TEGs can save costs and reduce environmental burden in a wide range of conditions.
- ▶ Reduction of the environmental burden is still possible under worse conditions.
- ▶ Under the same conditions steam expanders produce bigger amounts of electricity.
- ▶ Steam expanders are more eco-efficient in the upper performance range.
- ▶ TEG production plays only a small role for the overall assessment.

ARTICLE INFO

Article history:
Received 27 February 2012
Received in revised form 8 August 2012
Accepted 3 September 2012
Available online 6 October 2012

Keywords:
Thermoelectric generator
Motor generator
Exhaust energy recovery
Costs
Environmental impacts
Eco-efficiency

ABSTRACT

The use of waste heat from exhaust gas of internal combustion engines in power plants and CHP plants is considered a promising application field for thermoelectrics (TE). Some recent studies have provided important knowledge on the energy efficiency of current and future thermoelectric generators (TEGs). The focus of these studies has been primarily on the precise modelling of power units and their operation, i.e., the quantification of power production by TEGs. One of the studies additionally assessed the costs and the CO_2 emissions of fuel combustion, without equipment and fuel supply. Until now, there was no life cycle-related analysis considering TEG and power unit manufacture, environmental impacts beyond climate change and competing technologies for waste heat utilisation. In order to fill this gap, the present study applies the life cycle approach, takes account of a variety of environmental impacts and costs and compares TEGs with the competing steam expander technology. The results show that, under many conditions, TEGs in power units can save energy costs and reduce the environmental burden, i.e., they are eco-efficient. With additional expenditure, energy savings and environmental benefits can be achieved even under disadvantageous conditions. However, in the upper power range the performance of steam expanders in terms of electricity production and eco-efficiency is better. The reduction costs of greenhouse gas emissions and environmental impacts as eco-efficiency indicators show identical patterns. Under reasonable operating conditions, i.e., sufficient capacity utilisation of a TEG (lowest value set in the study on hand: 50%), the impacts from the manufacturing of the TEG play only a small role in the overall assessment.

1. Introduction

Although thermoelectrics (TE) as a physical phenomenon has been known for 190 years, there are still no well-established, widespread TE applications for power generation in households or industry. Intensive research into materials aimed at improving thermoelectric performance and providing cost and environmental benefits has been triggered off particularly by advances in nano-structuring of semi-conducting materials. The use of waste heat from mobile and stationary energy conversion processes to optimise power generation (cars: substitution of the alternator; power plants and combined heat and power production: power production plus), but also to optimise combustion in simple wood stoves (electric-driven fans for air supply) are considered promising fields of application. However, some competing technologies are obviously in an advanced stage of development, at least for power production applications. Therefore, future TE technology should not only be better than present TE technology but must also be competitive to, for example, steam expanders. A skeptical view on the competitiveness of TE is taken in [1].

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http://dx.doi.org/10.1016/j.apenergy.2012.09.007

1.1. Present state: technology, application, assessment

Most of the thermoelectric modules commercially available are designed for temperatures up to 300 °C based on Bi_2Te_3. HiZ Technology [2] states for its modules of Bi_2Te_3 an efficiency of 4.5%. The same modules are used in current studies on system integration of TE generators (TEGs), e.g., by Karri et al. [3]. However, according to [3], the specifications are not completely achieved. Kumatsu indicates an efficiency of 7% and more for a newly developed module based on the same material class [4] (according to the press release "World's Highest Efficiency Thermoelectric Generation Modules"). Materials and modules operating at higher temperatures and with higher efficiencies already exist in laboratories but do not seem to be feasible in practice yet. Already in 2005, Kaibe et al. (Komatsu) reported about cascade modules from alloys of silicon with magnesium, manganese and other metals as well as Bi_2Te_3 with an efficiency of 12% at 550 and 30 °C, respectively (hot and cold sides) [5], and they expected to achieve an efficiency target of 15% at 580 and 30 °C, respectively, by the year 2007. As a tendency, efficiencies of 5–10% seem to be realisable in the short term; 10–15% are considered practicable in the medium term.

Taking a look at steam expanders in comparison: Geschermann [6] says that aggregates from 100 to 1500 kWel are technically mature. They achieve efficiencies (steam-power) of up to 15%. According to the manufacturer, the fuel savings of engine-driven generators are in the range of 6–11% [7].

The thermoelectric use of waste heat from internal combustion engines (ICEs) in cars and engine-driven power plants and CHP plants is discussed particularly intensively. Two recent studies analysed in detail the implementation of TEGs in CHP plants Chen et al. [8], in power units driven by internal combustion engines, and in cars Karri et al. [3]. Both papers include a short review of previous studies on related aspects of TEGs, revealing that these studies generally focus on selected aspects rather than on system integration. In both studies [3,8], complex models are applied to calculate heat quantities and temperature differences available for TE power production; from these parameters TE power production and effective energy savings are derived.

Chen et al. [8] analyses the application of TEGs in exhaust gas systems and in heat exchangers and cooling systems. Each of the three configurations has a different temperature range. The TE materials are not specified by name but, in practice, different TE materials would be used. Physical TE parameters (Seebeck coefficient, heat conductivity, resistance) were assumed to be equal for all temperature ranges. The TEG efficiencies were set to 15%, 5% and 1% (high, medium and low temperature). The energy saving through a TEG in the exhaust system was 0.75% (= efficiency of power generation from 40% to 40.3%); the saving from the use of waste heat in the cooling system at medium and at low temperature was in both cases 1.25% (efficiency improvement of 0.5% each).

In [3], the application of TEGs in exhaust systems of cars (not discussed here) and engine-driven power units is analysed under different operating conditions. Two types of TE modules and materials are studied: commercially available modules by HiZ based on Bi_2Te_3 and future modules based on quantum-well SiGe materials, which are under development at HiZ. The tested Bi_2Te_3 TEGs were less powerful than expected from the manufacturer's information. Therefore, TE parameters were corrected. In the power unit, an efficiency of almost 1% was achieved for the Bi_2Te_3 modules, whereas 9.5% were reached for the SiGe modules. While the energy saving through conventional Bi_2Te_3 TEGs was 0.3%, that achieved by the SiGe TEG was 3%.

Vining [1] contains a comparison of efficiencies of TEGs and thermal engines as a function of their power. Homm et al. [9] derive semi-quantitative criteria for the selection of TE materials and apply them to important material classes.

Even if [3,8] present very important information on the energy balance of TEGs in application systems, there is a lack of knowledge on life cycle related impacts of TEGs (i.e., considering the manufacturing), knowledge on impacts outside the technosphere (except for the analysis of CO_2 emissions from combustion in [8]), and comparative knowledge on competing technologies or concepts. Some of these issues (e.g., life cycle aspects) are addressed by Patyk [10], a study dealing with comprehensive sustainability aspects, including e.g., global and intergenerational social impacts. Using a simplified approach, it was shown in [10] that

- in a life cycle perspective, the application of TEGs for use in CHP plants is energy-efficient since the energy consumed in manufacturing is balanced by the additional power produced;
- on the global scale, the application of TE in CHP plants will produce only a relatively small benefit.

The latter results when applying the Greenpeace world energy scenario [11]. Although the "[r]evolution scenario" is extremely efficiency-oriented, the CHP share in the overall power production (e.g., 13% in 2020) and, hence, the benefits of TE implementation in CHP systems remain limited.

1.2. Goal of the study

In spite of the limitations described in 1.1, there is no reason to neglect the application field of engine-driven generators and CHP. In a number of countries, CHP already play an important role or their share in power production is planned to be increased by the national, regional or local governments (e.g., the German Federal Parliament decided in May 2012 supporting measures for achieving the goal of 25% CHP in the overall power production in 2020 [12]). However, in most cases CHP is energy- and cost-efficient only if operation is controlled by heat demand. On the other hand, electricity as an energy carrier is becoming ever more important in the future, as discussed in [13] under the heading "Towards an electricity-powered world". Hence, the efficiency of electricity generation is a precondition for a sustainable energy system. Moreover, engine-driven generators may be relevant to decentralised power generation, e.g., from biogas or as alternative to fuel cells in hybrid systems using hydrogen as energy storage. Therefore, improving the efficiency of electricity production with ICE generators (with or without heat production) is an important sector-specific approach to energy saving – provided that advantages can also be achieved for sustainability aspects such as life cycle related environmental profiles (beyond CO_2 emissions) and costs of efficiency technologies.

Therefore, this study tries to answer the following questions:

- What is the eco-efficiency (combined assessment of environmental profile and costs) of TE considering the production of the generator and relevant environmental impacts beyond CO_2 emissions?
- How does the eco-efficiency of TEGs compare to that of the competing "steam expander" waste heat utilisation technology?
- How do the results depend on the plant size?
- What are the environmentally relevant weak points of TEGs?

1.3. Systems under study

This study investigates electricity generation with *generic* natural gas engine-driven power units (PUs) of four different capacities (10, 100, 1000, and 10,000 kWel) using waste heat from the

exhaust gas in *generic* TEGs or steam expanders for efficiency improvement. The overall effect of different size dependencies of efficiencies, costs, etc. of the different aggregates and their components can be demonstrated by analysing different plant capacities. Engine-driven PUs without waste heat recovery for additional power production serve as reference systems (base PUs). The term "generic" means that the plants (base PUs, TEGs and steam expanders) are not defined by specifications of certain real plants but by values based on the studies discussed above, which are considered to be typical at present or achievable in the future for the relevant parameters of the study at hand. The technical systems are shown schematically in Fig. 1.

Base PUs: The base PUs consist of engine (incl. catalyst), generator, and electric and electronic devices, e.g., for controlling.

Thermoelectric generators: Two virtual TEGs with different efficiencies (feasible in the short-term or in the mid-term) are analysed. Both are based on tellurium and silicon as TE materials and are installed in the exhaust gas flow and cooled in the counterflow.

Steam expanders: Steam expanders are compact steam engines making use of advances in the construction of combustion engines. So obviously they are based on a very old concept. Nevertheless, their use is not widespread and is particularly uncommon in engine-driven generators, CHP plants, etc. Generally, heat from exhaust gas and from cooling water can be used. The steam expander can be coupled to the same generator as the internal combustion engine (preferred according to a manufacturer) or to a separate one. However, environmental and cost data for the steam expander can be derived without specifications for system implementation. Fig. 1 shows the concept with a common generator.

In all three systems – without waste heat recovery for power generation, with TEG, with steam expander – the residual waste heat can be used for space heating and hot water for process or domestic use. However, these modes of operation are not considered here. Costs and environmental impacts of the construction and operation of the plant are completely assigned to power production.

2. Assessment: Methodology, data generation, modelling

The assessment comprises life cycle-related environmental profiles and costs of the technologies used in the described systems, which are combined in the eco-efficiency assessment. The following sections describe the methodological fundamentals (Section 2.1), the specifications for these studies (Section 2.2), and the generation of technical and economic input data (Section 2.3).

2.1. Methodology

2.1.1. Eco-efficiency

Eco-efficiency as a summarising assessment of ecological and economic properties of products, processes, and technologies can be defined and presented in different ways [14–17]. For the issues analysed here, it is convenient to have the reduction costs (also abatement costs) defined by the quotient of the cost difference and the environmental-burden difference of a variant and a reference system.

2.1.2. Environmental life cycle assessment (LCA)

Life cycle assessments (LCAs) are compilations and interpretations:

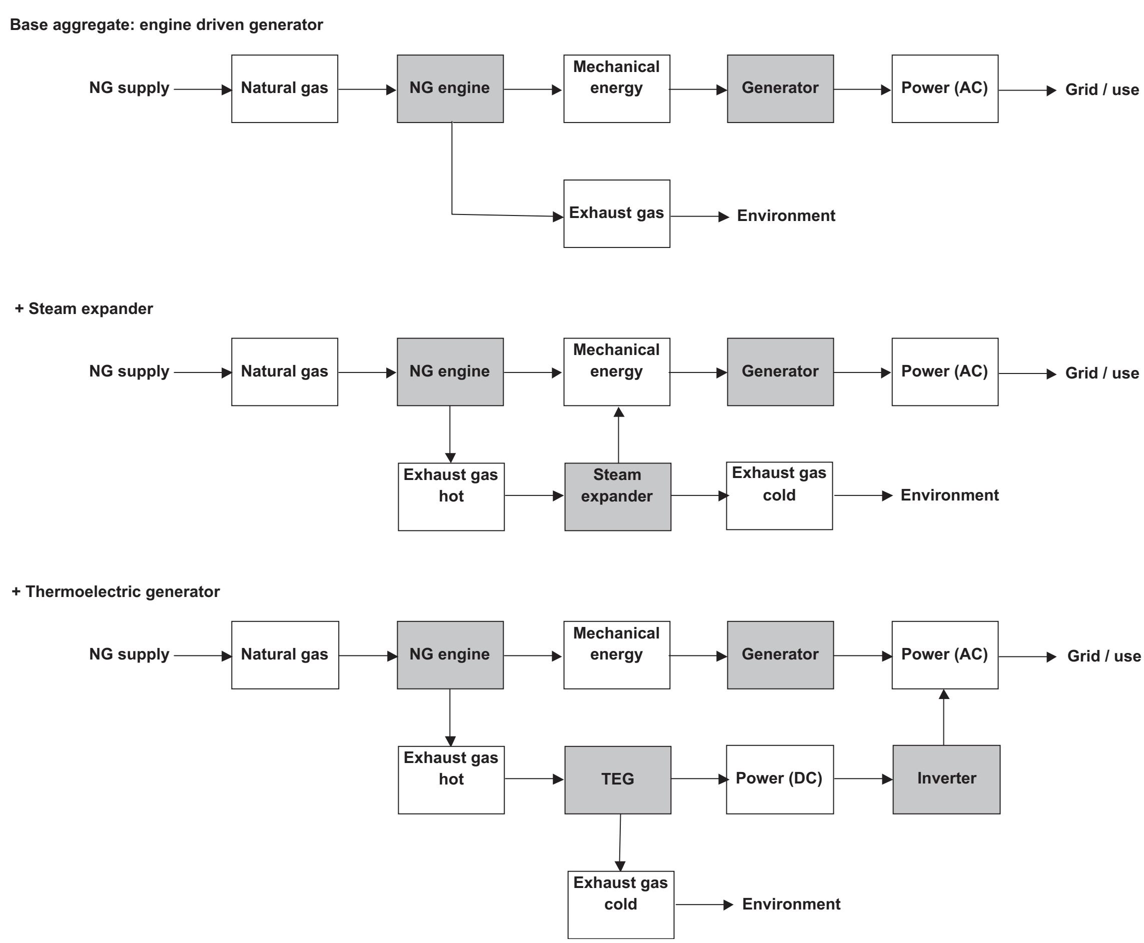

Fig. 1. Schematic representation of the analysed systems.

1. Of inputs and outputs between the technosphere and the environment and
2. Of potential environmental impacts of a product or product system
3. Along the total product life cycle.

If, as in this study, technologies are to be assessed, they are represented by their products. The procedure for conducting life cycle assessments is largely defined by ISO standards 14040/44 [18,19]. According to these, an LCA involves four phases:

1. Definition of goal and scope: questions to be answered, functional unit and system boundaries, among others.
2. Life cycle inventory analysis: building of a material flow model; compilation of energy, material, and emission data.
3. Life cycle impact assessment: calculation of environmental impacts from emissions. Optionally: reference e.g., to the overall impacts in a country, weighting of relevance of different impacts, aggregation of impacts in a single score indicator.
4. Life cycle interpretation: quality of results, evaluation, conclusions and recommendations with regard to the goals defined in (1).

In practice, simplifications of the processes considered, estimation of input data (guidelines are given e.g., in [20]) and limitations of the environmental impact categories analysed are common and usually unavoidable for methodological and practical reasons. Details on the LCA method are given in the electronic annex.

2.1.3. Cost assessment

Generally, investment and operating costs, including all overheads, should be covered over the whole life cycle as in the case of LCA (plant construction, site, auxiliaries and energy consumption, waste disposal, salaries, insurances, etc.). Depending on the technology or product under study, focusing on a selection of the mentioned cost types is common practice.

2.2. Scope and procedure of the study

Goal: Eco-efficiency assessment of TE in engine-driven generators, focusing on the questions already posed in the introduction (1.2):

1. How does the eco-efficiency of TEGs compare to that of the competing "steam expander" waste heat utilisation technology?
2. How do the results depend on the plant size?
3. What are the environmentally relevant weak points of TEGs?

The systems studied are displayed in Fig. 1.

Functional unit: The calculations related to the questions 1, 2 and 3 refer to "1 kW h electricity", additional those related to question 3 to "1 power plant" (analysis "Shares of TEG production in the entire aggregates") and to "1 TEG" (analysis "Shares of materials and components in the TEG production"), respectively.

System boundaries (Fig. 2): Construction and operation of the plants including fuel supply are covered by the calculations. Disposal of the plants is not considered explicitly. The plants mainly consist of metals and are largely recycled. The corresponding processes of dismantling and recycling are assigned to the reuse of the recycled materials, according to a common procedure ("polluter pays" principle; see e.g., [21]).

Reference time: Due to the current TEG development status, the reference time lies in the future. It makes no sense to precisely define a reference year. However, the period of 2015–2020 seems plausible regarding the definition of parameters for central processes (e.g., efficiencies of TE modules). Irrespective of this fact, energy and material flow data are taken from a database with different reference periods, as is common practice.

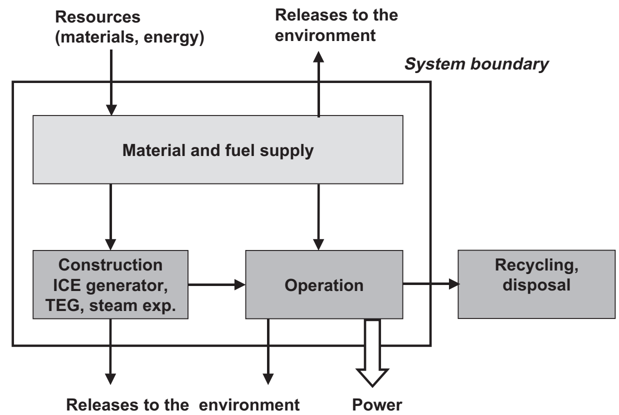

Fig. 2. System boundaries: processes covered in the analysis.

Geographic reference: Europe. This reference only applies strictly to the natural gas consumed in operation and electric power used in the manufacturing processes. The supply of fuels for power production and construction materials of the plants under study are considered by extending the reference location to the supplying countries outside Europe. Beyond that, many energy and material flow data taken from a database have different or no specific references. Irrespective of this fact, they are used as surrogate data, as is common practice. The results are largely valid on a global scale.

2.2.1. Environmental impacts and indicators, aggregations

All impact assessments are done in accordance with the ReCiPe 2008 method [22] and based on the cumulated energy demand (CED). This includes:

- Shares of individual processes in the impacts from the production and use of TEGs: energy demand, climate change (greenhouse effect), acidification, eutrophication, and human toxicity.
- Comparative LCA: energy demand, climate change, human toxicity, and aggregated environmental impacts (perspective, i.e., value choice, for evaluating the aggregated impacts: "hierarchist").
- Comparative eco-efficiency assessment: climate change and aggregated environmental impacts (perspective "hierarchist"; the two other perspectives according to ReCiPe 2008 are applied in sensitivity analyses; for details see the electronic annex).

Cost assessment: For the calculation of investment costs, purchase prices of the engine-driven generators, TEG modules and other components (heat exchangers, inverters) and steam expanders are recorded. Since the study on hand analyses sustainability aspects, no discounting is carried out in the basic scenario. Discounting is by no means compulsory: with respect to the sustainability goal "intergenerational justice" [23], the higher weighting of the availability of goods and capital at present as compared to the future is at least questionable and, e.g., according to Hampicke [24], should be refrained from. To accommodate common practice, discounting at an interest rate of 7% per year is done as sensitivity analysis.

Operating costs comprise maintenance, fuel and labour costs (incl. overhead).

Eco-efficiency assessment: As eco-efficiency indicators, greenhouse gas (GHG) and environmental burden reduction costs related to the basic options are calculated. Using these indicators, the most important environmental problem on a global scale – climate change – as well as overall environmental impacts (incl. toxic effects, etc.) are analysed. The reduction costs are calculated as follows (example GHG; formula valid for emission reduction only; for overall impacts analogous formulas using the points of the totals according to ReCiPe instead of GHG emissions):

$$\text{GHG reduction costs}(v,s) = -(\text{cost difference}(v,s)/\text{GHG reduction}(v,s)) \tag{1}$$

$$\text{cost difference}(v,s) = \text{electricity costs}(v,s) - \text{electricity costs}(\text{base PU},s) \tag{2}$$

$$\text{GHG reduction}(v,s) = \text{GHG emission}(v,s) - \text{GHG emission}(\text{base PU},s) \tag{3}$$

where v = variant (base TEG, opt. TEG, steam expander); s = size (10, 10, 1000, 10,000 kWel base PU)

Modelling: Calculations were done with an integrated Excel tool (including functions to support data generation for plant and process specification, a database of material flow data and impact indicators, combination of the different data categories).

2.3. Generation of technical and economic input data

The following points are essential for the data generation. The subject of the study is not the most exact modelling of real TEGs or materials. Direct reference to the TE base parameters electric and thermal conductivity and Seebeck coefficient as well as complex calculations as in [3,8] are not required here. The subject is rather to assess the eco-efficiency of the technology "TEGs for use of waste heat in power units" on two possible levels of development, in different power ranges, and compared to a competing technology. For that, it is sufficient that important parameters, especially efficiencies and their relations to each other, of generic facilities are set correctly with respect to their orders of magnitude. This is done by directly taking data from other studies, by own estimates based on other studies that include detailed modelling or measuring of TEGs and materials, as well as by some own calculations (e.g., in terms of size or temperature scaling).

The overall lifetime of all aggregates is assumed to be 20 years, and the annual operating time is defined to be 7884 full load hours (90% capacity utilisation). For a sensitivity analysis, 4380 full load hours (50% capacity utilisation) are assumed.

2.3.1. Engine-driven generators – base PUs

Four base PUs with an electric power of 10, 100, 1000 and 10,000 kW are considered.

2.3.1.1. A: Generator manufacturing and construction (Table 1). The environmental impacts of manufacturing and construction of the four base units (engine, generator, catalyst, controls) are assessed by using data for CHP plants from the energy and material flow database ecoinvent [25], which are scaled to the electric power ratings defined in this study. The costs are calculated with an empirical formula as a function of the electric performance, which was derived from a market overview for CHP plants [26].

2.3.1.2. B: Generator operation (Tables 1 and 2). Overall efficiencies of power generation (lower heating value of the natural gas => electric power) are assigned to the four power units. This is based on market surveys, information provided by the manufacturer, and studies including data and formulas for efficiencies, costs and weights as a function of the power [26,27]. Data on the environmental impacts of the operation and the natural gas supply in Europe are directly taken from ecoinvent. For calculating fuel costs, the price of natural gas for industrial users in Germany 2009 (9 €/GJ) is used [28]. Labour costs are based on wages in the electricity generation sector (75,000 €/(a * person); 10 MW: operator at plant; 1 person/shift, 5 persons/a incl. holidays, etc.; smaller plants: remote control, slightly higher specific input) [29].

Table 1
Cost data of base aggregates, TEGs and steam expanders.

Base aggregate	kWel	10	100	1000	10000
Base aggregate					
Invest	€	20,400	95,400	446,300	2,087,300
Maintenance	€	2000	9500	44,600	208,700
General overhaul	€	4900	21,200	92,500	403,800
Total equipment	€	27,300	126,100	583,400	2,699,800
Fuel (natural gas)	€	183,100	1,533,300	12,838,900	107,509,100
Labour	€	29,300	117,200	937,500	7,500,000
Total	€	239,700	1,776,600	14,359,800	117,708,900
Steam expander					
Invest	€	5800	25,800	113,300	491,600
Maintenance	€	600	2600	11,300	49,200
General overhaul	€	1400	5700	23,500	95,100
Equipment	€	7800	34,100	148,100	635,900
Base TEG					
Invest TEG	€	500	4300	36,000	301,200
Invest inverter	€	30	200	1200	7200
Maintenance	€	30	200	1800	15,100
General overhaul	€	100	500	3700	29,100
Total equipment	€	660	5200	42,700	352,600
Opt. TEG					
Invest TEG	€	500	4300	36,000	301,200
Invest inverter	€	100	400	2500	14,400
Maintenance	€	30	200	1800	15,100
General overhaul	€	100	500	3700	29,100
Total equipment	€	730	5400	44,000	359,800

References and assumptions: see Section 2.3.

2.3.2. TEG

Two types of virtual TEGs are considered. For each of them, a different efficiency is assumed which seem to be achievable in the short or in the medium term. For the close-to-market "base TEGs", a long-term stable module efficiency of 7.5% at hot and cold side temperatures (T_h, T_c) of 580 and 30 °C (reference temperatures) is assumed. The efficiency of the "optimised TEGs" under the mentioned conditions is supposed to be 15%.

2.3.2.1. A: TEG manufacturing and construction (Tables 1–3). Modelling is done for "unit TEGs" with a power of 1 kW at the reference temperatures (580 °C, 30 °C). The power of this unit TEG at other temperatures (T_h = a °C, T_c = b °C) is estimated applying the ratio of the Carnot efficiencies $\eta(a\,°C, b\,°C)/\eta(580\,°C, 30\,°C)$. As TE materials, equal amounts of tellurium and silicon are assumed. Hence, temperatures and materials are roughly as described in [5]. The TE material volumes per kW TEG output are estimated based on HiZ data by scaling with the efficiencies applied here. For heat exchangers, etc., HiZ data are adopted directly (HiZ personal communication 2008 and [2]). The energy consumed in manufacturing is estimated based on data from the metalworking industry (electricity consumption: 4 kW h/kg material). Data on the environmental impacts of material supply (tellurium, electronic grade

Table 2
Technical data of operation of base aggregates, TEGs and steam expanders.

Base aggregate	kWel	10	100	1.000	10.000
Base aggregate					
Engine (E)	Efficiency	31.0%	35.9%	41.5%	48.0%
Generator (G)	Efficiency	90.0%	92.9%	95.9%	99.0%
Aggregate (E + G)	Efficiency	27.9%	33.3%	39.8%	47.5%
Fuel consumption	kWchem	36	300	2513	21,044
Engine performance	kWmech	11	108	1042	10,101
Power production	kWel	10	100	1000	10,000
Heat (total)	kWtherm	25	192	1471	10,943
Heat (exhaust gas)	kWtherm	8.2	64	490	3648
Steam expander					
Efficiency (heat-power)		10.0%	12.1%	14.4%	17.3%
Power production	kWel	0.83	7.7	71	631
TEG					
TEG temperature hot side (T_h)					
IN	°C	550	510	470	430
OUT	°C	450	410	370	330
Mean	°C	500	460	420	380
TEG temperature cold side (T_c)					
IN	°C	80	80	80	80
OUT	°C	90	90	90	90
Mean	°C	85	85	85	85
TEG efficiency (at T_h, T_c above)[a]					
Carnot factor		53.7%	51.1%	48.3%	45.2%
Base TEG	Efficiency	6.2%	6.0%	5.6%	5.3%
Opt. TEG	Efficiency	12.5%	11.9%	11.2%	10.5%
Heat					
Exhaust gas	kW	8.2	64	490	3648
Converted	kW	1.6	13	109	912
DC Power (AC: −10%)					
Base TEG	kW	0.10	0.77	6.1	48
Opt. TEG	kW	0.19	1.5	12	96
Unit TEGs					
Base TEG	Number	0.1	1	8	68
Opt. TEG	Number	0.2	2	16	137

[a] Carnot factor at reference T_h (580 °C) and T_c (30 °C): 64.5%; base TEG efficiency at reference T_h and T_c: 7.5%; opt. TEG efficiency: 15%.

Table 3
Data on TEG production.

		Base TEG	Opt. TEG
Performance	kW/Unit TEG	1	1
Efficiency		7.5%	15.0%
TEG materials			
Steel, high alloyed	kg/Unit TEG	24	12
Steel, low alloyed	kg/Unit TEG	0.90	0.45
Aluminium	kg/Unit TEG	20	10
Tellurium	kg/Unit TEG	1.7	0.87
Silicon	kg/Unit TEG	1.7	0.87
Al2O3	kg/Unit TEG	0.30	0.15
Total	kg/Unit TEG	48	24
Manufacturing			
Power	kWh/Unit TEG	194	97
Costs	€/Unit TEG	4404	2202

References and assumptions: see Section 2.3.

and silicon, photovoltaic grade), the electricity used, and the inverters are taken from ecoinvent.

The costs of the TEGs are derived from prices of HiZ modules by scaling with the efficiencies applied here. The costs of other components are taken directly from HiZ. The costs of the inverters are estimated from current market prices based on an internet search [30].

2.3.2.2. B: TEG operation (Tables 1 and 2). TEG operation requires no material or energy expenditures. Maintenance costs are estimated to be half that of the base PUs (shares applied to investment costs).

In a few calculation steps, the generated electricity is estimated based on a number of set parameters.

Set parameters: Engine efficiency; share of waste heat in the exhaust gas (1/3, rest cooling water); temperature drop of the exhaust gas in the TEG; cold side temperatures; TEG efficiency (580 °C, 30 °C).

Calculated parameters:

- Exhaust gas temperature TEG inlet (= engine outlet) and heat volume: calculated from engine efficiency, share of waste heat in exhaust gas, exhaust gas volume and composition, heat capacities of exhaust gas components (common combustion calculation).
- TEG efficiency ($T_h = a$ °C, $T_c = b$ °C): calculated from TEG efficiency (580 °C, 30 °C) with Carnot efficiency (580 °C, 30 °C) and Carnot efficiency (a °C, b °C).
- Electricity generated: calculated from heat volume, temperature difference of exhaust gas inlet and outlet, and TEG efficiency.

2.3.3. Steam expander

Data generation is based on analogies to internal combustion engines and generators and direct adoption of energy related parameters.

2.3.3.1. A: Steam expander manufacturing and construction (Tables 1 and 2). The expander is represented by an engine-driven generator with the same mechanical power and corresponding electric power. The environmental impacts are calculated as described for the base PUs: The costs are assumed to be 50% higher (low production up to now). This estimation is justified by the structural similarities of ICEs and steam expanders.

2.3.3.2. B: Steam expander operation (Tables 1 and 2). Power production is estimated using data from a manufacturer of steam expanders for additional power production in CHP applications [7]. The differentiation by size classes is based on that of ICEs.

The material and financial maintenance expenditures are calculated as described for the base PUs.

3. Results and discussion

In this section, first the composition of the environmental impacts and costs of electricity generation using TEGs, i.e., the relative contributions of the individual processes and components, are discussed. This is followed by environmental and cost-related comparisons between steam expanders and TEGs. Finally, the costs of reducing greenhouse gas emissions and environmental impacts as eco-efficiency indicators are discussed. The results of sensitivity analyses on discounting, annual operating hours, and impacts of equipment and fuel supply are summarised and discussed on the basis of GHG reduction costs. Pay-back times of energy, GHG emissions, and costs as well as absolute LCA and cost values, compositions of the results in detail and results of sensitivity analyses are available in an electronic annex.

The discussion focuses on the smallest and largest aggregates (electric power of the base PUs: 10 kW and 10 MW, respectively). As expected, the results of the two medium-sized aggregates (100 and 1000 kW) are between those of the two others, but in a different ratio.

3.1. Composition of environmental impacts and costs of electricity generation with TEGs by processes and components (weak point analysis)

3.1.1. Composition of environmental impacts

Shares of the manufacturing of the entire aggregates (incl. TEGs) in the impacts from the electricity generation: The shares increase with decreasing size of the base PUs. Virtually identical values result for PUs with base and optimised TEGs. Shares: energy consumption and climate change 0.45% (10 kW base PU) and 0.25% (10 MW), acidification about 4% and 2%, eutrophication 28% and 23%, and human toxicity about 30% (10 kW and 10 MW). Optimisation potentials of materials or manufacturing processes can therefore be found particularly in the categories of eutrophication and human toxicity. The indicator values related to the functional unit "1 kW h electricity generated" and the shares in detail are documented in *Tables* A1 and A2 of the electronic annex.

Shares of TEG production (incl. inverter) in the impacts from the manufacturing of the entire aggregates: The shares decrease with decreasing size of the base PUs. Virtually identical values result for base and optimised TEGs. Shares: energy consumption and climate change 1% (10 kW base PU) and 1.6% (10 MW), acidification about 0.4% and 0.7%, eutrophication and human toxicity about 1.4% (10 kW and 10 MW). The indicator values related to the functional unit "1 power plant" and detailed shares are documented in *Tables* A1 and A3 of the electronic annex.

Shares of materials and components in the impacts from the TEG production (Fig. 3*; base TEG for 10 kW base PU)*: The differences between the units' power ranges are very small (exception: inverter; shares at 10 kW are double that at 10 MW) The shares of individual components, materials, and processes of TEG production differ widely across impact categories. Hence, there are different approaches to mitigating the individual impacts. It is remarkable that for only one of five impact categories, human toxicity, TE materials achieve a share of more than 50% and, therefore, absolutely dominate the balance (tellurium contributes about 50%, silicon only 1%). With the optimised TEG, the share of the inverter doubles and the shares of all other components reduces correspondingly. The indicator values related to the functional unit "1 TEG" and detailed shares are documented in *Tables* A1 and A4 of the electronic annex.

3.1.2. Composition of costs

Shares of the manufacturing of the entire aggregates (incl. TEGs) in the costs of the electricity generation: The shares are between 2.5% and 12% (base PU 10 MW and 10 kW). The fuel costs dominate with 75–90% (10 kW and 10 MW). The rest are personnel costs. Virtually identical values result for aggregates with base and optimised TEGs. The indicator values related to the functional unit "1 kW h electricity generated" and detailed shares are documented in *Table* A5 of the electronic annex.

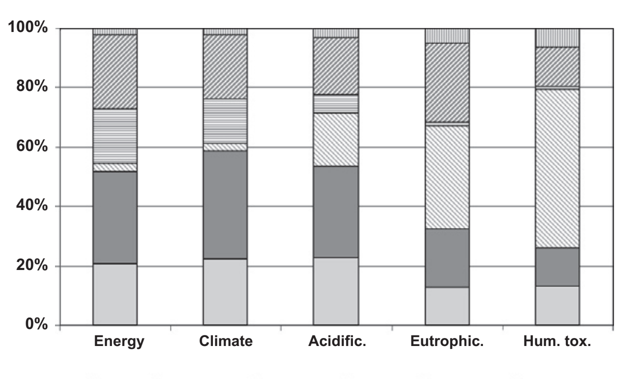

Fig. 3. Shares of materials and components in the TEG production.

Shares of TEG production (incl. inverter) in the costs of the manufacturing of the entire aggregates: The shares are between 2.5% and 12% (base PU 10 kW and 10 MW), i.e., they are inverse to the shares of the total aggregate costs in electricity generation. This is due to the cost degression of the base PUs and the consistency of the specific costs of the TEGs. The values for optimised TEGs are slightly higher (bigger inverter). The indicator values related to the functional unit "1 power plant" and detailed shares are documented in *Table* A5 of the electronic annex.

Shares of components in the costs of the TEG production: The shares of the modules are between about 65% (optimised TEG in 10 kW base PU) and 72% (base TEG in 10 MW base PU). The inverters account for 2% (base TEG in 10 MW base PU) to 10% (optimised TEG in 10 kW base PU). About 25% are allotted to the other components (heat exchangers, body, etc.). The indicator values related to the functional unit "1 TEG" and detailed shares are documented in *Table* A5 of the electronic annex.

3.2. Comparison of electricity production, environmental impacts, and costs

The results for the amount of additional electricity generated by TEGs and steam expanders as well as for specific costs, energy consumption, and environmental impacts of total electricity generation (base PU + TEG or steam expander) are shown in Fig. 4a–d. Relative differences between the results of the variants (PU with base TEG or optimised TEG or steam expander) and the data of the base PU are displayed for each size:

$$\text{relative difference}(i, v, s) = (\text{value}(i, v, s) - \text{value}(i, \text{basePU}, s)) / \text{value}(i, \text{basePU}, s)) \quad (4)$$

where i = indicator (electricity, costs, etc.); v = variant (base TEG, opt. TEG, steam expander); s = size (10, 10, 1000, 10,000 kWel base PU)

In this presentation, the base PUs form the base line (absolute values in the electronic annex). The generated electricity of the variants necessarily results in positive values. These positive values are advantageous as compared to the base. For all other quantities, positive or negative values may arise. The latter are advantageous (*lower* costs, energy consumption, GHG emissions, etc. compared to the base PU).

3.2.1. Comparison of additional electricity generation

The amount of electricity generated by the base PUs is increased by about 6–8% using steam expanders, by 0.5–1% using base TEGs, and by 1–2% using optimised TEGs (10 MW and 10 kW base PU each). Electricity generation by use of steam expanders is 5–15 times higher than that with TEGs.

3.2.2. Comparison of environmental impacts

Energy consumption, climate change, and aggregated environmental impacts: Very similar values result for the indicators in all size classes and variants, which correlate with the additional electricity generation. Without exception, improvements are achieved since the additional inputs are overcompensated by the fuel saving (a negative sign (−) indicates an improvement compared to the base PU):

10 kW base PU: steam expander: −7%; base TEG: −1%; optimised TEG: −2%
10 MW base PU: steam expander: −6%; base TEG: −0.5%; optimised TEG: −1%

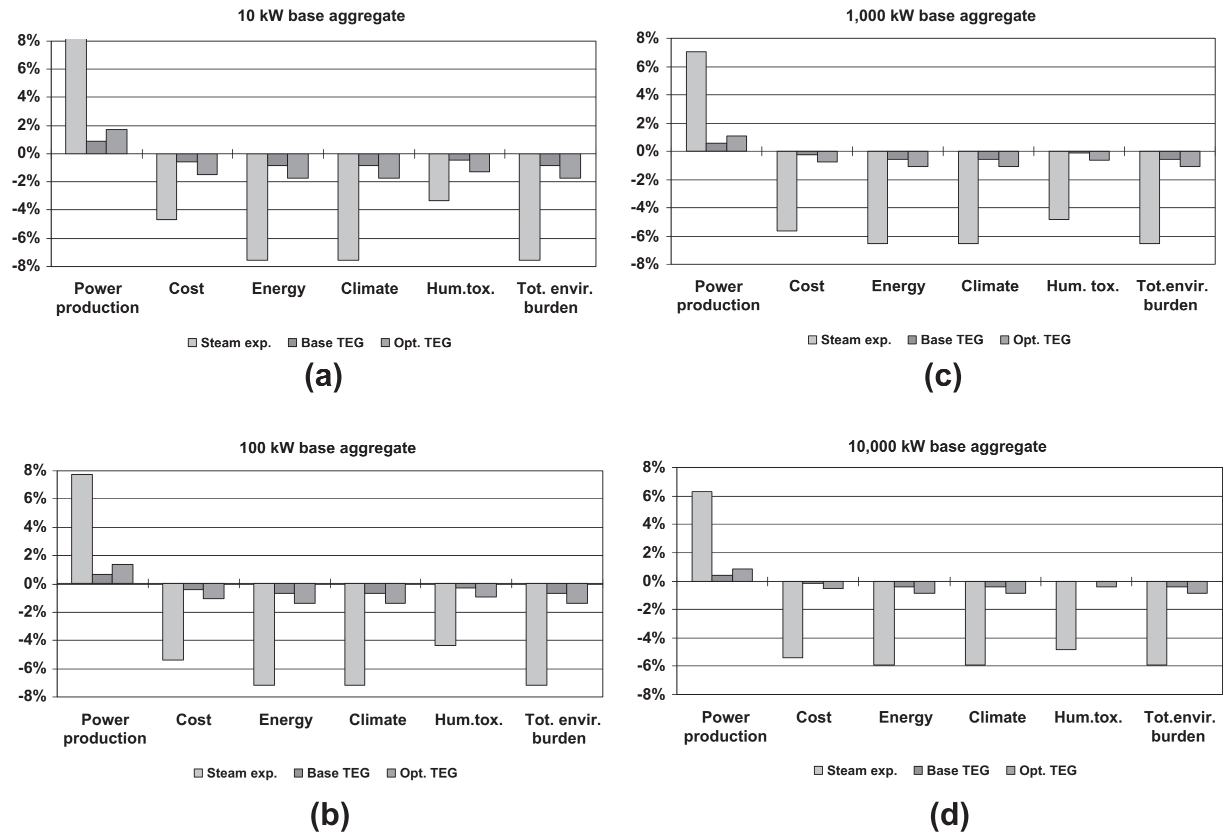

Fig. 4. Produced electricity, environmental impacts and costs of the analysed systems in comparison: relative differences related to the base PUs (4a: base PU 10 kW, 4b 100 kW, 4c 1 MW, 4d 10 MW).

Human toxicity:

10 kW base PU: steam expander: −3%; base TEG: −0.5%; optimised TEG: −1.5%
10 MW base PU: steam expander: −5%; base TEG: ±0; optimised TEG: −0.5%

The differing pattern of human toxicity is due to the fact that the production of additional equipment results in higher toxic emissions than are caused by operation.

3.2.3. Comparison of the specific costs of the total generated electricity

The electricity costs are reduced in nearly all size classes and variants, however in the case of TEGs only slightly. I.e., the fuel savings overcompensate the additional costs (a negative sign (−) indicates an improvement compared to the base PU):

10 kW base PU: steam expander: −5%; base TEG: −0.5%; optimised TEG: −1.5%
10 MW base PU: steam expander: −5%; base TEG: ±0%; optimised TEG: −0.5%

3.3. GHG and environmental burden reduction costs

Fig. 5 shows the GHG reduction costs. Under standard conditions (no discounting, 90% capacity utilisation), *negative GHG reduction costs* result for all variants and size classes. I.e., GHG reduction is associated with *cost savings*. The cost advantage with steam expanders grows with increasing size, while that with TEGs decreases (unit €/t CO_2 equivalent; a negative sign (−) indicates a saving compared to the base PU):

10 kW base PU: steam expander: −100; base TEG: −110; optimised TEG: −130
10 MW base PU: steam expander: −120; base TEG: −40; optimised TEG: −85

The reduction costs of the aggregated environmental burden [€/ReCiPe point] show the same pattern as the GHG reduction costs; i.e., the same ratios among the different variants of a certain size or among different sizes of a certain variant. Therefore, they are not displayed here but in the electronic annex (selection). This

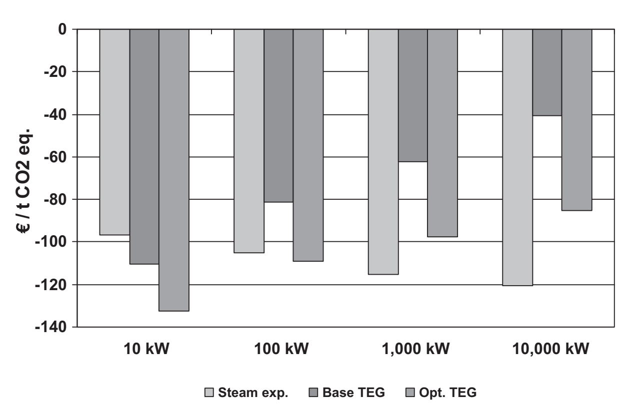

Fig. 5. Greenhouse gas reduction costs of the analysed variants.

Table 4
Greenhouse gas reduction costs in base and sensitivity analyses.

Base aggregate	kWel	10	100	1000	10,000
90% Capacity utilisation; no discounting; base case production of aggregates and natural gas					
Steam exp.	€/t CO_2 eq.	−97	−105	−115	−121
Base TEG	€/t CO_2 eq.	−110	−81	−62	−41
Opt. TEG	€/t CO_2 eq.	−133	−109	−97	−85
50% Capacity utilisation; no discounting; base case production of aggregates and natural gas					
Steam exp.	€/t CO_2 eq.	−78	−93	−111	−121
Base TEG	€/t CO_2 eq.	−102	−50	−15	24
Opt. TEG	€/t CO_2 eq.	−142	−100	−79	−57
90% Capacity utilisation; 7% interest/a; base case production of aggregates and natural gas					
Steam exp.	€/t CO_2 eq.	−3	−52	−84	−102
Base TEG	€/t CO_2 eq.	−31	43	108	184
Opt. TEG	€/t CO_2 eq.	−109	−55	−16	26
90% Capacity utilisation; no discounting; increased effort of production of aggregates and decreased of natural gas					
Steam exp.	€/t CO_2 eq.	−100	−109	−119	−125
Base TEG	€/t CO_2 eq.	−114	−84	−64	−42
Opt. TEG	€/t CO_2 eq.	−137	−113	−101	−88
50% Capacity utilisation; 7% interest; increased effort of production of aggregates and decreased of natural gas					
Steam exp.	€/t CO_2 eq.	94	4	−56	−91
Base TEG	€/t CO_2 eq.	41	180	303	447
Opt. TEG	€/t CO_2 eq.	−103	−3	71	148

Details: see Sections 3.3 and 3.4.

similarity is due to the dominating role of GHG emissions in the total environmental burden – CO_2 from natural gas combustion, methane from natural gas supply.

3.4. Data quality, sensitivity analyses

Important input data were *set* in accordance with the values found in other studies. These values are realistic targets (efficiencies and costs of TEGs) or typical values (e.g., engine efficiencies, power unit costs) which adequately describe the essential properties of the analysed technologies, especially when compared to each other. The adequacy of these data was validated by an internal review.

However, there are uncertainties about material flow data from ecoinvent when applied to modelling *future* systems (supply of natural gas, materials, etc.). The advantages of the analysed technologies are smaller if the production of the aggregates is less efficient and the supply of natural gas is more efficient than assumed. In sensitivity analyses, the inputs for TEGs and steam expanders were increased by 20%, and those for natural gas were decreased correspondingly. As a result, there are only individual disadvantages in the category human toxicity which do not substantially influence the overall environmental burden.

Future fuel costs are subject to significant uncertainties. However, in the long run, substantial price increases can be expected. These, however, are advantageous in the assessment of each of the two investigated technologies and will not lead to significant changes in the result patterns. Therefore, sensitivity analyses are not required.

The sustainability assessment does not consider discounting due to the choice of values (2.2). Hence, additional calculations should include discounting for reasons of acceptance. Even with a capacity utilisation of 50% and an annual interest rate of 7%, steam expanders in 1 and 10 MW PUs and optimised TEGs in 10 kW PUs result in cost advantages.

The same is true for the combination of capacity utilisation of 50%, discounting, less efficient production of the aggregates, and more efficient supply of the natural gas.

The variation of the value-based weighting of individual environmental impacts to calculate the total environmental burden results in different totals for the *individual variants* and different shares of individual components, materials, etc. This will not lead to changes in the result patterns of *comparisons of the variants* and reduction costs (data in the electronic annex).

Hence, the presented results – which are in accordance with expected outcomes – very likely give a realistic overall picture (rankings of technology variants and ratios of aggregate sizes) of the environmental and economic characteristics of TEGs available in the short and medium term (Table 4).

4. Conclusions

Regarding the environmental weak point analysis, it is important to note that the production of the TEGs and that of the entire plants do not play a dominant role in the overall assessment (overcompensation by reduced fuel consumption). Nevertheless, environmental optimisation of TEG production is an imperative of sustainable production and, therefore, a main task of the manufacturers of real TEGs. As cost factor, however, TEG production is more relevant.

The following conclusions can be drawn from the comparative technology assessment:

- TEGs with the specifications assumed in this study, i.e., with those of the base and optimised variants, can contribute to the reduction of environmental burdens through power generation with engine-driven generators and can thus generally contribute to a more sustainable energy system.
- However, steam expanders offer the same advantages, but with higher efficiencies, i.e., increased additional power production. If additional power production is the main criterion, steam expanders should be preferred over TEGs.
- Cost savings and reduced environmental burden result for optimised TEGs in small plants and for steam expanders in large ones even with reduced capacity utilisation and with discounting. Accordingly, with increased capacity utilisation and without discounting, the savings increase or are also found with other aggregates (e.g., base TEGs). If absolute additional power production is not the main criterion but instead the specific costs of environmental burden reduction, i.e., eco-efficiency, different optimal size ranges can be identified for the application of TEGs and steam expanders in line with [1].

In view of the foreseeably increasing electricity demand, the significantly higher efficiency of steam expanders is gaining in importance. This is particularly true when considering that fuel costs are also expected to increase. Steam expanders or other thermal engines (e.g., ORC generators) in smaller power ranges are thus becoming more advantageous. In line with the above, even significantly improved thermoelectrics tend to be inferior to the competing systems.

The results of the study on hand and those of Patyk [10] suggest the analysis of other TE applications in terms of environmental and economic characteristics. Especially fans operated in simple cooking wood stoves are a more effective TE application which is not dependent on expensive high-performance materials made from possibly rare resources [31–33]. This application has the potential of significantly reducing energy consumption and CO_2 emissions on a global scale, and of preventing numerous deaths due to smoke inhalation [34–36,10]. The considerations presented in [10] ought to be extended, detailed, and up-dated. For the engine-driven PUs analysed in this study, mainly case-specific analyses within the framework of concrete project planning are required to identify the position of a plant or its variants within the presented range of results.

Acknowledgement

I am grateful to my colleague Witold Poganietz for valuable discussions.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2012.09.007.

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