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Estimating the global waste heat potential

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The process chain of energy conversion from primary energy carriers to final energy use is subject to several losses. Especially in end use, vast amounts of converted energy occur as waste heat, which is often released to the environment. In terms of raising energy efficiency and reducing the energy consumption, such waste heat needs to be used. To date, some studies or investigations about industrial waste heat of selected countries have been carried out, but other sectors like commerce were not considered. Therefore, this work presents a novel top-down approach for the estimation of waste heat potential of the most common sectors of end use (transportation, industrial, commercial and residential) including electricity generation on a global scale. It also deals with the temperature distribution of this unused energy. The evaluation reveals that 72% of the global primary energy consumption is lost after conversion. In further detail, 63% of the considered waste heat streams arise at a temperature below 100 °C in which electricity generation has the largest share followed by transportation and industry.

Contents

1. Introduction

Energy efficiency is considered as one of the key instruments to restrain growing global energy demands and therefore to abate greenhouse-gas emissions [1,2]. Following the path from primary

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energy carriers to energy services, there are basically two conversion steps in between: fuel transformation or electricity generation and conversion through devices. For example oil is refined to petroleum product and injected in a car engine to provide motion while coal is burnt in a power plant to generate electricity which is used for lighting. Within both steps, all conversion processes are subject to considerable losses. Cullen and Allwood estimated that 63% of the global primary energy consumption is lost during combustion and heat transfer processes [3].

The major loss can be identified in general as waste heat. Such waste heat needs to be recovered for specific purposes in order to raise process efficiencies [4]. However, the challenge is that it occurs in different ways and situations which determine its usability. This includes aspects like continuous or discontinuous availability, temperature ranges, the means of heat transfer (radiation, convection or conduction), type and composition in case of fluid or even location between source and sink. For instance there is a flue gas stream at a particular temperature, but the presence of sulfur trioxide could initiate dew point corrosion (forming of sulfuric acid) during heat recovery. Leaving these obstacles at first aside, there is a huge potential of waste heat along the various ways of energy use worldwide.

This paper presents an approach for the estimation of global waste heat potential for electricity generation and the four common sectors of final energy consumption based on conversion efficiencies. Different temperature levels of waste heat are taken into account. All results are visualized in Sankey diagrams.

2. Literature review

There is only few data available about particular waste heat potentials. Beginning from the year 2000, the first studies or reports seem to be published by Pellegrino et al. [5] in 2004 and the Pacific Northwest National Laboratory (PNNL) [6] in 2006, both dealing with opportunity analyses in the U.S. industry sector. They identify energy losses as percentage share in up to 16 branches and quantify them via the respective energy use. These findings were integrated into the well-known report by the U.S. Department Of Energy (DOE) [7] about waste heat recovery in 2008. It states that 20–50% of the energy consumed during industrial manufacturing processes is lost as waste heat with about 60% being released as low-grade waste heat at a temperature below 230 °C (450 °F) [7].

In 2009 two more studies with focus on the industry sector were published: Enova [8] presents a survey for Norway and Svensk Fjärrvärme [9] an estimation for Sweden. While Svensk Fjärrvärme lists different potentials in terawatt hours including a comparison to former values [10], Enova also provides a distribution of temperature ranges where 37% of the waste heat has more than 140 °C and almost half of the remaining 63% occurs at 40–60 °C [8].

Later Pehnt et al. [11] adapted the results of the Enova study to German industry by applying ratios between untapped waste heat and referring final energy consumption to the corresponding branches in Germany.

A differentiation of waste heat potentials, but with orientation towards higher temperatures, has been performed for the U.K. manufacturing industry, too. It was presented by Hammond and Norman [12] in 2012 (see also [13]).

All the above mentioned publications concentrate on industrial waste heat potentials. Looking into other sectors, there is a flow chart (published on a yearly basis) by the Lawrence Livermore National Laboratory (LLNL) [14] which covers electricity generation, the industrial, commercial and residential sector as well as transportation. The most recent chart indicates the estimated U.S. energy use of 2013 and it distinguishes between energy service and rejected energy in end use. In total the energy loss reaches a share of almost 61% [14]. Such a value represents waste heat regardless of its quality and is calculated by the assumption of overall conversion efficiencies for each sector: 80% for industry, 65% for commercial and residential sector and 21% for transportation. But there are no accessible details for these ratios. Other countries (e.g. [15]) and especially the International Energy Agency (IEA) [16] also provide similar flow charts. However, the only indicated loss representing conversion and transportation losses is derived nearly completely from electricity generation (see also [44]).

Therefore, in this paper a global approach for all sectors with insight into conversion efficiencies and a waste heat temperature distribution is performed.

Besides the determination of lumped amounts of waste heat occurring within different sectors of end use, there are also approaches which focus on the conditions of individual conversion devices and/or selected process chains. Such studies often cover both energy and exergy flows – the latter being visualized in so-called Grassmann diagrams – thus providing more insight into intensity, location and type of losses during conversion [44,45,50]. Waste heat thereby can be identified as a sum of different types of conversion loss.

On a global scale Cullen and Allwood [3] investigated 14 representative conversion devices (mainly engines and burner units regardless their sectoral division) as well as electricity generation and associated them with ten loss mechanisms. The application of exergy efficiencies – calculated directly or by 'quality factors' for energy efficiency – intends the quantification of potential energy savings, but waste heat was not addressed in concrete terms. Analyses of Hinderink et al. [46] evaluated major pathways in process industry. The development of the total physical work potential (= exergy) entering and leaving the respective processes had been calculated. Internal and external exergy losses due to process step inefficiencies and material/heat release to the environment (referring to waste heat) were combined to an overall exergy loss. Process heat having been recovered by the generation of superheated steam was indicated as 'steam credit'. Hence, a comparison of important production processes by thermodynamic means is possible, however the amount of occurring waste heat remains inaccessible.

In contrast to global and generalized considerations and apart from the industry sector, Yucer and Hepbasli [47] performed a thermodynamic analysis of a single building (heated by a conventional boiler) using exergy analysis method. Their study reveals that 80% of feed exergy (fuel input) is destructed during water heating. Both authors specified and extended their findings in a second study [48]. Exergy losses were splitted into three types whereby surface loss and a flue gas stream represent the waste heat being rejected from the boiler. Both together have a share of less than 1% referring to exergy input. In addition, an economic evaluation of all exergy streams by cost coefficients plus capital investment had been carried out in order to make the conversion process comparable not only from a technical point of view.

Balta et al. [49] made an assessment of different heating applications for buildings and investigated energy and exergy flows from primary energy transformation to the environment. It outlines high loss rates of both energy and exergy (on average 51% and 86% respectively) during primary energy transformation and heat production which can be minimized through systems driven by renewable energy sources (e.g. solar collector or geothermal energy – see also [50]). Hepbasli [45] published a comprehensive review of 20 studies about the evaluation of heating and cooling systems in buildings. Most of the studies focus on particular system performances by exergetic process efficiency or a 'sustainability index' as a function of it.

Such exergy analyses emphasize on the input side and the gradual depletion of exergy within a process chain, system or unit. As a deduction one can clearly identify weak points for improvement, for example a switch towards low valued energy sources (=less exergy demand) in case of heating and cooling. Considering waste heat potentials, the focus lies more on the output side of established processes. Energy conversion takes place with specific products and some waste heat. In this paper, the objective is a quantification of waste heat so that it has to be fully covered by energy flows. With respect to exergy, a quality factor is then applied to the respective waste heat streams in order to also evaluate its physical work potential.

3. Approaches for acquisition of waste heat potentials

According to Brueckner et al. [17], the methodology for analyses of waste heat potentials can be categorized into surveys and estimations. The data collection and application of input parameters is thereby realized top-down or bottom-up (or a combination of both) depending on whether a process, a sector or a region is under investigation [17]. Furthermore, approaches can be subdivided by accuracy into rough, medium and high precision methods. Brueckner et al. outline a more detailed literature review (cf. chapter 2) with emphasis on all the mentioned categories.

Based on such differentiation, the approach in this work is a top-down, medium precise estimate (use of literature data, coefficients and estimations).

As for the definition of the waste heat potential itself, there are three gradations in the following order [3]: theoretical, technical and economic potential. The target potential for this work is the theoretical potential which is only constrained by thermodynamic efficiency limits.

4. Estimating the global waste heat potential

4.1. Data collection and methodology

By decision for a top-down approach, the focus lies on the input side of conversion processes downstream to final energy consumption. For the global estimations of energy flows, the only reliable data source is provided by the IEA. Their most recent Sankey diagram – referred to as 'world' – covers the whole chain from primary energy carriers to energy end use per sector in the year of 2012. All streams and blocks in the chart are defined and sectors are also subdivided into units which, in turn, are described or classified by the International Standard Industrial Classification Of All Economic Activities (ISIC) [18]. The chosen segmentation is shown in Table 1. In the following considerations the blocks 'refineries' (oil to petroleum), 'other transformation' of fuels (mainly coal refinement) as well as 'non-energy use' are not included.

The next step is to determine the energy balances for each block and the major processes within. The challenge is to meet a scientifically acceptable compromise for the input parameters between the global evaluation as a whole and the processes individually. Cullen and Allwood [3] already addressed that issue during their global investigation of theoretical efficiency limits for energy conversion devices. The acquired data has been mainly taken from Nakicenovic et al. [19] (regional and global exergy and energy efficiencies) and adjusted to present stages of development. Then, the conversion devices were associated with the respective fuel. This methodology is adopted for the approach of waste heat potentials.

Table 1
Chosen segmentation for global approach.

Sector/Block	ISIC or description
Industry	
Iron and steel	Group 241; class 2431
Chemical and petrochemical	Divisions 20, 21
Non-ferrous materials	Group 242; class 2432
Non-metallic materials	Division 23
Transport equipment	Divisions 29, 30
Machinery	Divisions 25, 28
Mining and quarrying	Divisions 7, 8; group 99
Food and tobacco	Divisions 10–12
Paper pulp and print	Divisions 17, 18
Wood and wood products	Division 16
Construction	Divisions 41–43
Textile and leather	Divisions 13–15
Non-specified (industry)	Divisions 22, 31, 32
Residential	
Residential	Residential buildings
Commercial	
Commerce and public services	Divisions 33, 36–39, 45–47, 52, 53, 55, 56, 58–66, 68–75, 77–82, 84 (excluding class 8422), 85–88, 90–96, 99
Agriculture and forestry	Divisions 1, 2
Fishing	Division 3
Non-specified (other)	Not elsewhere specified
Transportation	
Road	Any road vehicle
Rail	Rail traffic
Pipelines	Operation of pipelines
Ship	World marine bunkers, domestic navigation
Aircraft	World aviation bunkers, domestic aviation
Non-specified (transport)	Not elsewhere specified

The distribution of energy inputs like coal, natural gas, oil products, electricity – derived from the IEA statistical data – is determined for each block per sector. Based on balance coefficients which depend on the devices, the energy output can be interpreted as energy service and losses. In this work, the losses are further divided into exhaust and/or effluent losses representing the heat source and other losses.

Every balance factor (either efficiency η_i or loss μ_i) is calculated by its respective energy stream as defined in Eq. 1 (first law of thermodynamics). Fig. 1 indicates the implemented energy balance.

$$\mu_i \quad \text{or} \quad \eta_i = \frac{\text{Energy output (stream i)}}{\text{Energy input (block)}} \tag{1}$$

The waste heat appears in all three mentioned types of loss. Only waste heat bound to fluids is considered as concentrated waste heat streams which can be directly transferred. Radiation especially at high temperatures is disregarded at other losses due to simplicity and low availability. For this reason, each of the following waste heat potentials refers solely to exhausts and/or

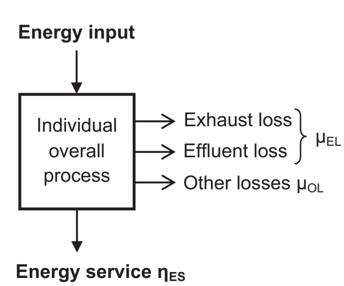

Fig. 1. Defined energy balance per process.

Table 2
Input and output streams of energy balance.

Input/Output stream	Description
Energy input	Fuel, heat, electricity
Energy service	Motion, heat, cooling, light, sound
Exhaust loss	Exhaust/flue gas, vapor
Effluent loss	Coolant (water, air, …)
Other losses	Radiation, convection, conduction, friction, electrical resistance, transmission

effluents. Table 2 contains further explanation for the inputs and outputs.

All blocks of final energy consumption as listed in Table 1 were then investigated according to the energy balance of Fig. 1. The chosen balance factors are presented in the following text subdivided by the given sectors.

4.2. Overall assumptions

In all sectors and blocks, information about detailed links from fuels to specific devices is seldom available. Hence, only the main conversion devices per fuel can be considered, so that the balance factors refer to the corresponding overall processes. As for the shares of losses, there is often a dearth of data, especially concerning burner units. In these cases, other losses are assumed to be 10% and the share of effluent losses is set to 5%.

Speaking of electricity consumption, if not specified otherwise, the distribution is mostly generalized into four major end use devices without ranking: motor, compressor, heater or cooler and lighting.

Another simplification was needed for the energy input indicated as 'heat', which appears in almost every block. Since there is no data available, the supply of such heat (process steam and district heating) is handled uniformly. A calculation has been carried out, where an efficiency of 87% for the heat exchanger [3] and a loss of 10% during transport [36] is taken into account.

4.3. Data of industrial sector

All parameters of the blocks in the industrial sector are listed in Table A1. Most of the data was extracted from [3,7]. There is a detailed data base especially for the heavy industry (see DOE report [7]) in general and some branches regarding the electricity consumption (see studies [26–28]). Several assumptions had to be made for the blocks 'transport equipment', 'machinery', 'food and tobacco', 'construction', 'textile and leather' and 'non-specified' because only few data were available at the time of this investigation.

4.4. Data of residential sector

The energy needs of the residential sector can be broken down into two forms of energy utilization: fuel for heating and cooling purpose and electricity for household devices. The latter was derived from a survey about the residential electricity consumption in the United States (see [30]). The exhaust temperatures of the heating are averaged between the ones of regular, low-temperature and condensing boilers (collected from technical data sheets).

All input parameters of the residential sector are listed in Table A2.

4.5. Data of commercial sector

The major share of energy consumption in the commercial sector is linked to the block 'commerce and public buildings'. Similar to the residential sector, a survey about commercial buildings in the United States (see [29]) has been applied to electric energy consumption.

All other parameters, as shown in Table A3, are again mainly taken from [3,7].

4.6. Data of transportation sector

According to [24,39], more than half of the energy consumed in a car is lost as waste heat. The determined balance factors derived from [3] differ between gasoline and diesel fueled engines, but there is no differentiation of performance classes. Nevertheless, these parameters are adapted to all internal combustion engines for this approach. Exhausts and effluents (coolant) are both estimated to have an equal share within the waste heat streams based on findings of Shu et al. [40].

Besides all means of transportation, there is also a block called 'pipeline transport', which stands for the energy demand for supportive operational recompression of natural gas. The respective compressor is either driven by electricity or a gas turbine/engine and the occurring heat is usually rejected as waste heat. A simulation partially based on [37] has been carried out in order to determine the overall efficiencies of the compression process.

The input parameters for the transportation sector are listed in Table A4.

4.7. Data of electricity generation

As for the efficiency factors of electricity generation, the World Energy Council (WEC) [34] provides a good database for average global process efficiencies per type of power plant. The parameter for 'other losses', also specified by the WEC, represents losses via auxiliaries, transmission and distribution. Some efficiency factors were taken from the IEA [1] and only one (hydro) had to be estimated.

The shares of waste heat streams were determined by simulation work and the respective temperature levels were derived from [35]. Both data was uniformly adopted for all thermal power plants. Renewable energy sources like solar, tide and wind are considered to have no waste heat.

Table A5 shows the mentioned parameters of electricity generation.

The explained input parameters have been applied to all blocks of the global IEA Sankey diagram [16] in terms of the presented

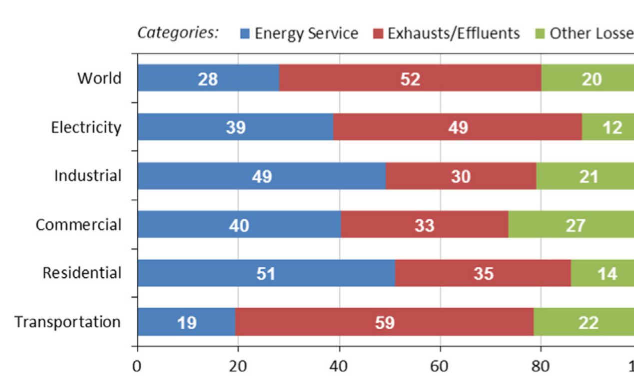

Fig. 2. Sectoral shares of balance factors.

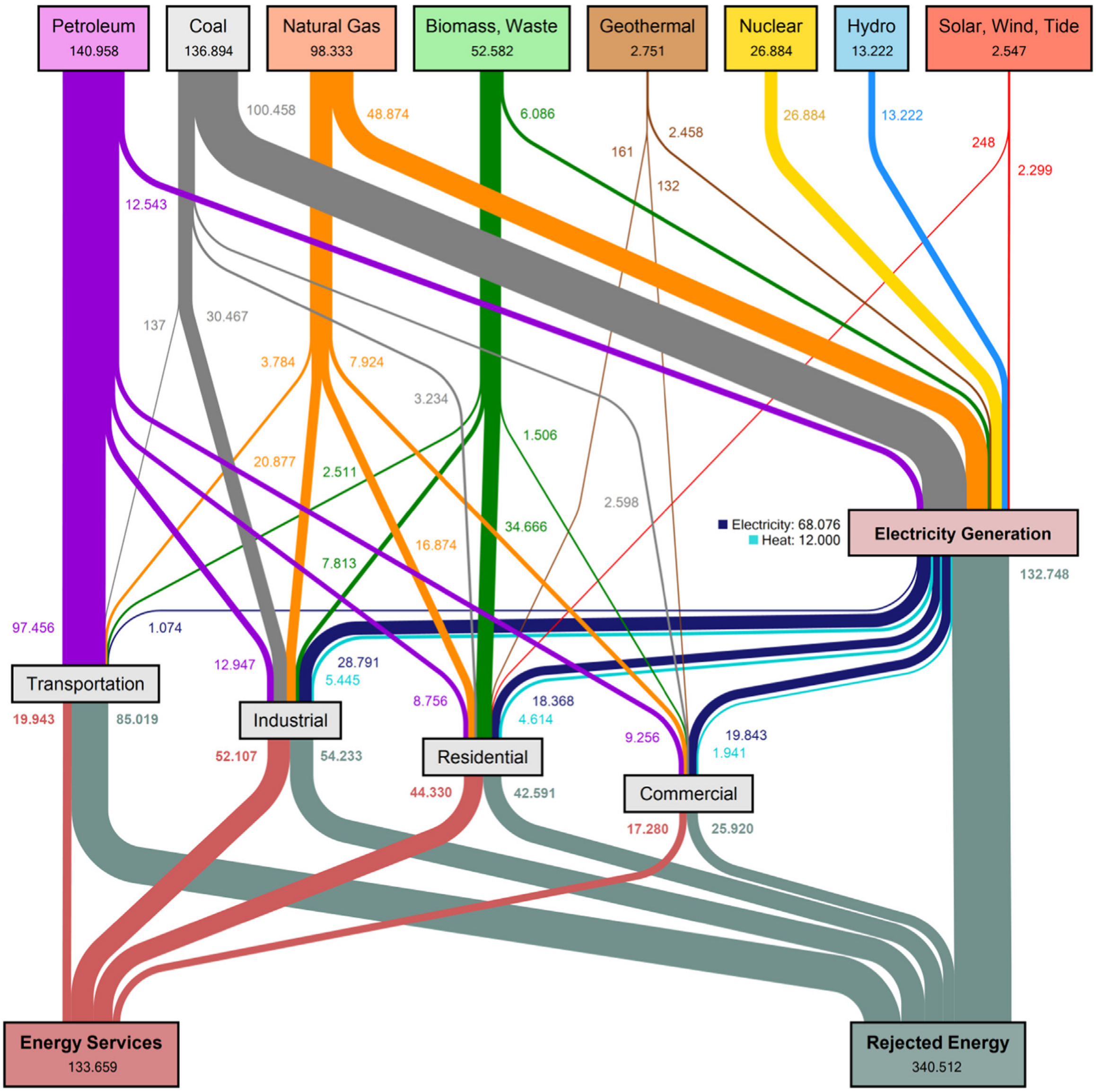

Fig. 3. Estimated world energy use of 2012 in PJ – excluding fuel processing and non-energy use (total consumption of primary energy carriers: 474.171 PJ).

energy balance (cf. Fig. 1, Table 2). All results are discussed in the following chapter.

5. Discussion of the results

5.1. Investigation evaluation

At first, the overall end use efficiencies per sector give a good overview of the results. Based on the investigation of this work, energy service has a share of 49% for industrial, 40% for commercial, 51% for residential and 19% for transportation sector. These values are clearly below the assumptions of LLNL – only the conversion factor of transportation has a similar range. As for electricity generation, the energy service (including heat) reaches 39%. Further information about the exhausts/effluents and other losses is illustrated in Fig. 2.

The share of exhaust and effluent losses in transportation sector is noticeably high, but can be explained by the dominance of the block 'road' within transportation (according to [16] it has a proportion of 75% and the average efficiency for the corresponding energy service lies at 18%, cf. Table A4). Within electricity generation, high losses occur through steam condensation and emitted flue gas.

By division of all streams into energy service and rejected energy, it turns out that around 72% of the global energy input (consumed primary energy carriers) is lost after conversion. For

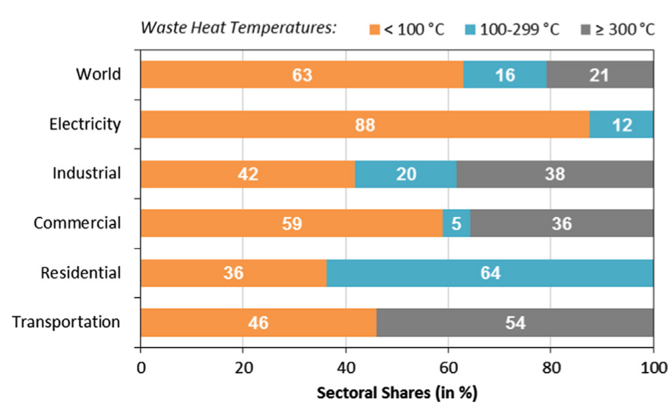

Fig. 4. Sectoral shares of waste heat distribution.

comparison only, this ratio exceeds the value of the LLNL chart, however it must be noted that different regions are evaluated. A Sankey diagram based on the segmentation of Table 1 and the presented approach has been created demonstrating the estimated world energy use in Fig. 3. As one can see, the highest amount of waste heat derives from electricity generation (39% of globally rejected energy), followed by the sectors in the displayed order.

It can also be recognized that industry and transport have the same scale but a totally different input composition and the residential sector has twice the energy demand of the commercial sector. So, a closer look at the rejected energy is of interest.

This investigation provides insight into the waste heat distribution and reveals the following sectoral shares (Fig. 4). The respective shares only refer to the exhausts/effluents fraction (cf. Fig. 2) and the waste heat temperatures for exhausts and effluents are divided into ranges below 100 °C, within 100 to 299 °C and 300 °C or more.

All sectors, especially the commercial sector, show a relatively high amount of low temperature waste heat (< 100 °C). The huge fraction of electricity generation was to be expected for thermodynamic reasons. As for the residential sector and electricity generation, there is no high temperature waste heat (≥ 300 °C). According to the theoretical approach of this investigation, no

Table 3
Comparison of waste heat distributions.

Studies	Temperature ranges ≤ 60 °C	60–140 °C	> 140 °C
Industry (global) Enova [8] Pehnt et al. [11]	15% *4.679* PJ 47% 82%	28% *8.981* PJ 16% 6%	57% *18.016* PJ 37% 12%
	≤ 120 °C	> 120 °C	–
Industry (global) Bonilla et al. [38]	43% *13.660* PJ 36%	57% *18.016* PJ 64%	– –
	< 230 °C	≥ 230 °C	–
Industry (global) DOE [7]	38% *12.144* PJ 60%	62% *19.532* PJ 40%	– –

medium temperature waste heat (100–299 °C) occurs in the transportation sector.

Speaking of the industrial sector in detail, a comparison with other approaches is possible. Table 3 shows different industrial waste heat distributions of one top-down estimation (see [11]) and three bottom-up surveys (see [7,8,38]). The deviation of the shares of these temperature ranges is significant, bearing in mind that the listed approaches cover specific countries of different industrial structure and magnitude at earlier date. Though, we can see a shift towards higher waste heat temperatures according to the global approach.

The Sankey diagram in Fig. 5 visualizes all results of the theoretical approach of this work. In addition, the diagrams in Fig. 6 provide the respective ratios with focus on the sectoral shares within the low temperature waste heat fraction.

This fraction itself is the biggest share (63%) among all exhausts/effluents (52% of inputs). Electricity generation herein

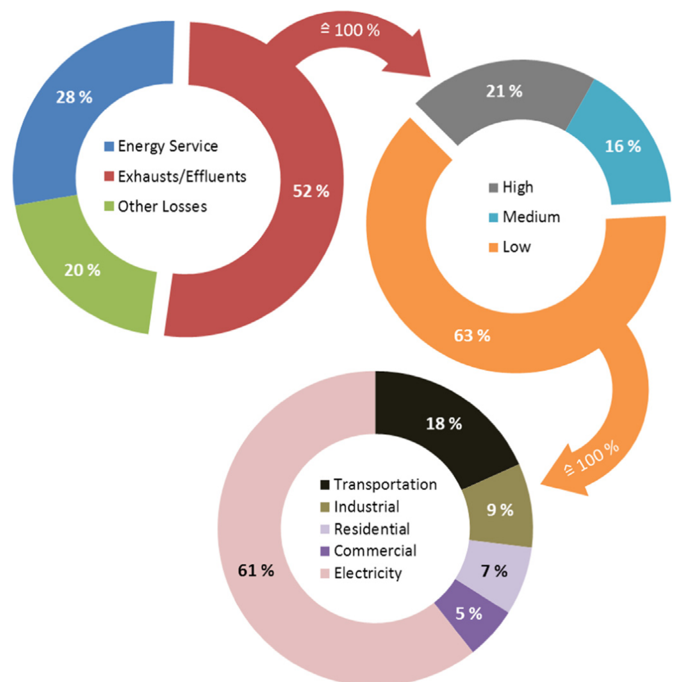

Fig. 6. Global ratios of theoretical approach results.

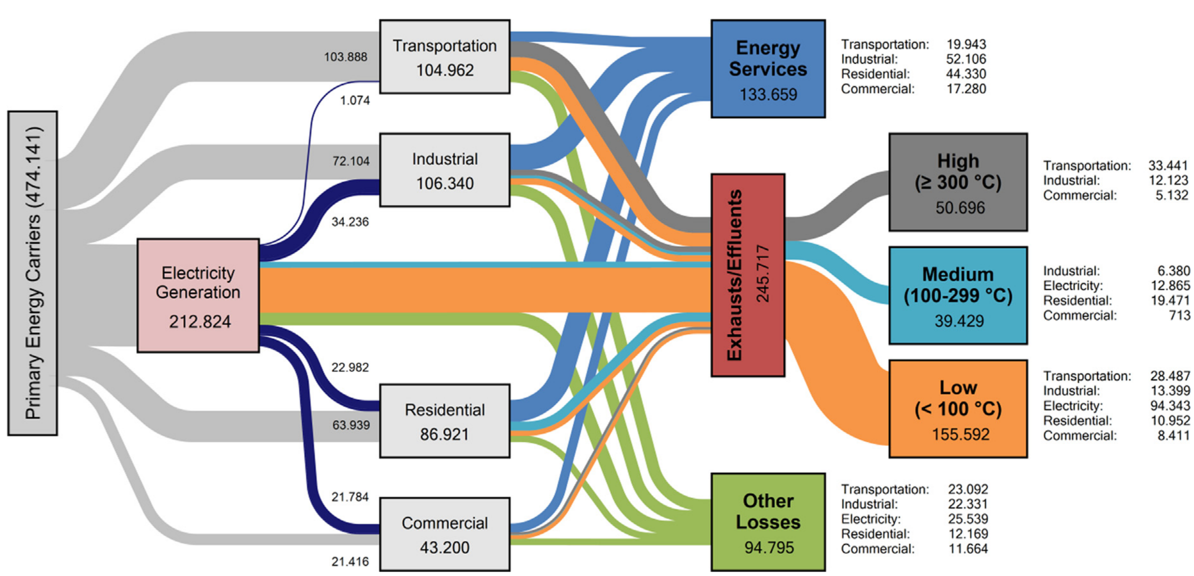

Fig. 5. Estimated global waste heat distribution of 2012 in PJ (according to theoretical approach).

has a share of 61%, which is equivalent to almost 20% of the global primary energy consumption in 2012.

Looking at the energy service again, only 28% of the globally consumed energy is turned into 'useful' energy. This value does not fit to the global conversion efficiency stated by Cullen and Allwood (result: 11% [3]). The reasons are diverse: this investigation covers process chains of energy conversion (e.g. power plant) as well as conversion devices (e.g. engines) instead of the devices only whereby also different efficiency factors are used for the calculations. Furthermore, the overall efficiency of electricity generation in this work is higher (39% compared to 30% [3]); and no fuel loss has been considered.

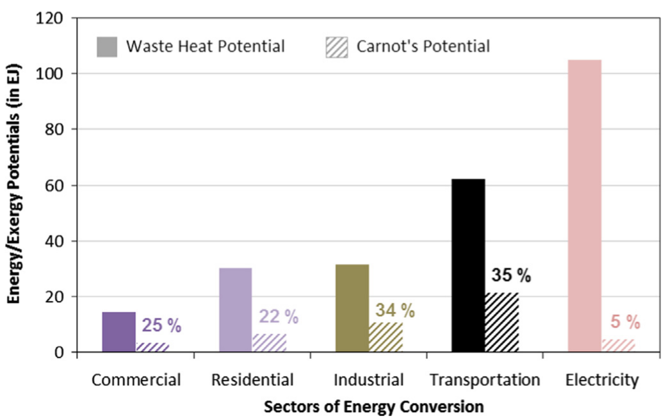

Fig. 7. Waste heat and Carnot's potential by sector.

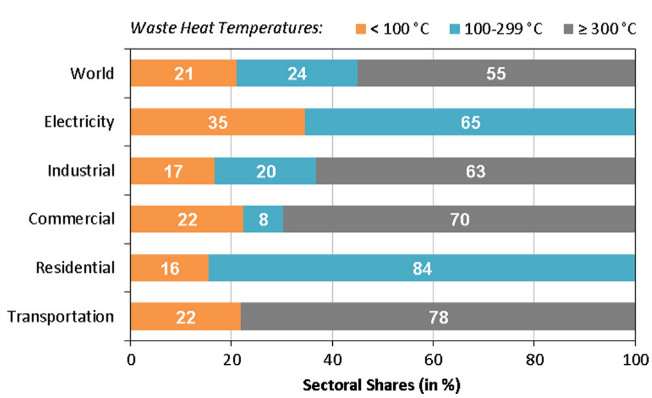

Fig. 8. Sectoral shares of Carnot's potential distribution.

5.2. Waste heat potential evaluation

So far, the amounts of waste heat have been evaluated by quantity. In terms of applicability of the rejected energy, an investigation by quality is needed. Thermodynamically speaking, energy is described as the sum of exergy and anergy, whereby exergy stands for the energy which can be totally turned into technical work. Anergy in turn is only suitable for providing the internal heat. With regard to the waste heat, its exergy content can be calculated by Carnot's theorem. This rule states that the maximum efficiency of a heat engine is determined by the two available heat reservoirs as follows. The lower temperature is defined as ambient temperature (298.15 K) in this case.

$$\eta_{\max} = \eta_C = 1 - \frac{T_{\text{low}}}{T_{\text{high}}} \tag{2}$$

Applying the Carnot factor (Eq. 2) to the waste heat amounts and their corresponding waste heat temperatures (T_{high}) gives the respective technical work potential further indicated as Carnot's potential. Fig. 7 shows the comparison by sector between the global waste heat potential and the Carnot potential as a share of it (summed up for each exhaust/effluent loss per block).

The result is clear to see: amongst all sectors the Carnot potential is low. Only waste heat from industry and transportation is still available at a comparatively good quality. Their shares reach in total 34 and 35% (see Fig. 7), which is low in general. Carnot's potential for waste heat out of electricity generation is even dropping down to 5% since the low temperature fraction is dominant (see Figs. 4 and 6).

A more differentiated assessment is possible by looking at the Carnot potential for the presented temperature ranges (Fig. 8). As expected, waste heat at lower temperature level has a significantly smaller share within Carnot's potential. For instance speaking of the commercial sector, the waste heat fraction below 100 °C explains the differences. By quantity, this temperature range has a share of 59% (energy based value, see Fig. 4), but by quality it contributes only 9% (as 22% of exergy based value, see Fig. 8). Thus, Carnot's potential provides a more precise indication for waste heat, whether it could still perform technical work or better should be used for heat transfer. Nevertheless, the conversion of exergy is again subject to further losses (cf. Fig. 1).

In Table 4 all results are displayed by number in PJ and TWh. Worldwide about 246 EJ (68 PWh) were lost as waste heat in 2012. As for the Carnot potential, it is 48 EJ (13 PWh).

Table 4
Overview of the final results.

Sectors	Units	Waste heat potentials (energy)				Carnot's potentials (exergy)			
Distribution		**High**	**Medium**	**Low**	**Total**	**High**	**Medium**	**Low**	**Total**
Transportation	PJ	33.441	0	28.487	61.928	16.906	0	4.768	21.674
	TWh	*9.289*	*0*	*7.913*	*17.202*	*4.696*	*0*	*1.325*	*6.021*
Industrial	PJ	12.123	6.380	13.399	31.902	6.833	2.169	1.844	10.846
	TWh	*3.367*	*1.772*	*3.722*	*8.861*	*1.898*	*603*	*512*	*3.013*
Residential	PJ	0	19.470	10.952	30.422	0	5.622	1.071	6.693
	TWh	*0*	*5.408*	*3.042*	*8.450*	*0*	*1.562*	*297*	*1.859*
Commercial	PJ	5.132	713	8.411	14.256	2.495	285	784	3.564
	TWh	*1.426*	*198*	*2.336*	*3.960*	*693*	*79*	*218*	*990*
Electricity generation	PJ	0	12.865	94.344	107.209	0	3.484	1.876	5.360
	TWh	*0*	*3.574*	*26.207*	*29.781*	*0*	*968*	*521*	*1.489*
Global	PJ	50.696	39.429	155.592	245.717	26.234	11.561	10.343	48.138
	TWh	*14.082*	*10.952*	*43.220*	*68.254*	*7.287*	*3.212*	*2.873*	*13.372*

5.3. Data accuracy

The parameters used in this approach often originate from literature research. Although there is an emphasis on two sources (see [3,7]), the calculations still base upon many different values including several assumptions that have been generalized to global coverage. An assessment of the accuracy of the input parameters cannot be made. This affects the results by number in detail (specific data in PJ), which have to be handled with care.

However, the calculated values provide a comprehensive explanation for the scales of the considered streams. Contrary to other evaluations, this approach gives a detailed insight into the used methods. The presented scales (rounded to the nearest EJ) and ratios are justifiable.

6. Conclusions

Waste heat appears during almost every step of energy conversion and is rejected to the environment in many cases. In order to raise process efficiencies, solutions for further use have to be found.

The presented approach is a novel estimate for the waste heat potential on a global scale. It reveals the vast amount of waste heat from common sectors of end use energy as well as from electricity generation. Fuel processing (exploration and refining) and non-energy use were excluded from any energy balancing. A special focus lies on the investigation of the waste heat temperature distribution. In addition, the calculated potentials are evaluated by their exergy content (Carnot's potential). Low grade waste heat has the major share and therefore also lowers the quality of waste heat in total.

It is a challenge in general to recover waste heat by integration into existing processes or to transfer and convert it for further purpose. On a technical level, additional aspects influence the usability of waste heat streams. Besides inappropriate temperature levels, there is often a discrepancy between supply and demand by time, location and quantities. Process related obstacles might be acidic components for example in a flue gas (risk of dew point corrosion) or any restriction for the operation reliability. Moreover, financial barriers like high capital investment or economic uncertainties could affect the waste heat utilization. In this context, exergoeconomic analyses of possible concepts/solutions of conversion processes help to get the optimum out of efficiency and costs.

This results in a package of measures to follow up with. First of all, unused energy services need to be identified and avoided, whereby both energy consumption and the production of waste heat are prevented. Secondly, waste heat should be directly utilized in the process chain or in the local environment nearby. Finally, there are methods like the Organic Rankine Cycle or heat pumps to harvest waste heat and exploit the exergy fraction of the remaining energy. Besides, there is a lot of research going on, especially concerning the low-grade waste heat harvesting.

From the thermodynamic point of view, the major target is to supply the end energy demand at an adequate level from the beginning. Taking the example of household heating, usually fossil fuel of high exergy content is burnt to heat water and space to temperatures of up to 60 °C and 90 °C. Such heat demand could be provided by a waste heat source below 100 °C (low exergy but high anergy content), too. Consequently, the energy and exergy loss would be minimized. This principle is known, but has not been sufficiently intensified yet. Possible solutions in this case are raising the share of combined heat and power and/or installing more solar thermal energy systems. Generally, exergy analysis based on energy flows reveals the crucial steps in conversion and should be considered as a next phase of investigation.

As for the theoretical approach, further work is required to improve the database of balance factors, conversion processes/devices and the determination of temperature levels of the waste heat streams. Yet this estimate of the global waste heat potential provides the first sound referential framework.

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Supplementary data

See Appendix Tables A1–A5

Table A1
Input parameters for industrial sector

Blocks with inputs	Conversion device(s)/unit(s) and shares	Balance factors (in %)			Waste heat streams as exhausts (G)/effluents (L)
		η_{ES}	η_{EL}	η_{OL}	
Iron and steel					
Oil and oil products	Oil burner	61 [3]	29 [B]	10 [A]	G: 95% [B], 200 °C [7] L: 5% [A], 85 °C [7]
Coal	Blast and cupola furnace	43 [B]	27 [7]	30 [7]	G: 60% [7], 450 °C [7] L: 40% [B], 85 °C [7]
Natural gas, biofuels and waste	Gas burner	64 [3]	26 [B]	10 [A]	G: 95% [B], 200 °C [7] L: 5% [A], 85 °C [7]
Electricity	Electric arc furnace	55 [20]	18 [7]	27 [B]	G: 55% [20], 1000 °C [7] L: 45% [20], 85 °C [7]
Heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Chemical and petrochemical					
Oil	Oil burner	61 [3]	29 [B]	10 [A]	G: 95% [B], 200 °C [7] L: 5% [A], 85 °C [7]
Oil products, coal	- Gasifier: 75% [E]	75 [42,43]	15 [B]	10 [A]	G: 23% [C], 150 °C [7] (all) G: 38% [C], 100 °C [E] (all)
	- Burner unit: 25% [E]	60 [C]	30 [B]	10 [A]	L: 1% [C], 85 °C [7] (all) L: 38% [C], 50 °C [E] (all)
Natural gas, biofuels and waste	- Gas burner: 50% [A] - Steam reformer: 50% [A]	64 [3] 80 [22,42]	26 [B] 10 [B]	10 [A] 10 [A]	G: 95% [B], 150 °C [7] (all) L: 5% [A], 85 °C [7] (all)

Table A1 (*continued*)

Blocks with inputs	Conversion device(s)/unit(s) and shares	Balance factors (in %)			Waste heat streams as exhausts (G)/effluents (L)
		η_{ES}	η_{EL}	η_{OL}	
Electricity	- Motors: 25% [A]	60 [3]	30 [A]	10 [B]	L: 100% [A], 55 °C [E]
	- Compressors: 25% [A]	5 [23]	80 [23]	15 [B]	L: 100% [A], 80 °C [23]
	- Heaters: 25% [A]	80 [3]	0 [A]	20 [B]	G/L: none [A]
		13 [3]	0 [A]	87 [B]	G/L: none [A]
Heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Non-ferrous metals (aluminum)					
Oil products, coal, natural gas	Melting furnace	30 [B]	60 [7]	10 [A]	G: 95% [B], 1000 °C [7]
					L: 5% [A], 85 °C [7]
Electricity	Hall-Heroult-Cell	54 [B]	1 [7]	45 [7]	G: 100% [7], 700 °C [7]
Heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Non-metallic minerals (glass, cement)					
Oil	Oil burner	61 [3]	29 [B]	10 [A]	G: 95% [B], 200 °C [7]
					L: 5% [A], 85 °C [7]
Oil products, coal, natural gas, biofuels and waste	- Glass production: 50% [A]	36 [B]	34 [7]	30 [7]	G: 100% [A], 650 °C [7]
	- Cement production: 50% [A]	49 [B]	21 [7]	30 [7]	G: 100% [A], 360 °C [7]
Electricity	Heater (electric boost)	80 [3]	0 [A]	20 [B]	G/L: none [A]
Heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Transport equipment, machinery, food and tobacco, construction, textile and leather					
Oil	Oil burner	61 [3]	29 [B]	10 [A]	G: 95% [B], 200 °C [7]
					L: 5% [A], 85 °C [7]
Oil products	- Oil burner: 34% [A]	61 [3]	29 [B]	10 [A]	G: 33% [C], 300 °C [25,41] (all)
	- Diesel engine: 33% [A]	22 [3]	58 [24]	20 [B]	G: 33% [C], 200 °C [7] (all)
	- Petroleum engine: 33% [A]	13 [3]	62 [24]	25 [B]	L: 34% [C], 85 °C [7,41] (all)
Coal	Coal furnace/burner	59 [3]	31 [B]	10 [A]	G: 95% [B], 200 °C [7]
					L: 5% [A], 85 °C [7]
Natural gas, biofuels and waste	- Gas burner: 50% [A]	64 [3]	26 [B]	10 [A]	G: 75% [C], 300 °C [25,41] (all)
	- Other engine: 50% [A]	47 [3]	43 [B]	10 [A]	L: 25% [C], 85 °C [7,41] (all)
Electricity (all)	- Motors: 50% [E]	60 [3]	30 [A]	10 [B]	L: 100% [A], 55 °C [E]
	- Compressors: 25% [E]	5 [23]	80 [23]	15 [B]	L: 100% [A], 80 °C [23]
	- Lighting: 25% [E]	13 [3]	0 [A]	87 [B]	G/L: none [A]
Heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Mining and quarrying, paper pulp and print, wood and wood products					
Oil products	- Oil burner: 34% [A]	61 [3]	29 [B]	10 [A]	G: 33% [C], 300 °C [25,41] (all)
	- Diesel engine: 33% [A]	22 [3]	58 [24]	20 [B]	G: 33% [C], 200 °C [7] (all)
	- Petroleum engine: 33% [A]	13 [3]	62 [24]	25 [B]	L: 34% [C], 85 °C [7,41] (all)
Coal	Coal furnace/burner	59 [3]	31 [B]	10 [A]	G: 95% [B], 200 °C [7]
					L: 5% [A], 85 °C [7]
Natural gas, biofuels and waste	- Gas burner: 50% [A]	64 [3]	26 [B]	10 [A]	G: 75% [C], 300 °C [25,41] (all)
	- Other engine: 50% [A]	47 [3]	43 [B]	10 [A]	L: 25% [C], 85 °C [7,41] (all)
Electricity (mining and quarrying)	- Motors: 78% [26]	60 [3]	30 [A]	10 [B]	L: 100% [A], 55 °C [E]
	- Compressors: 17% [26]	5 [23]	80 [23]	15 [B]	L: 100% [A], 80 °C [23]
	- Lighting: 5% [26]	13 [3]	0 [A]	87 [B]	G/L: none [A]
Electricity (paper pulp and print)	- Motors: 85% [27]	60 [3]	30 [A]	10 [B]	L: 100% [A], 55 °C [E]
	- Compressors: 5% [27]	5 [23]	80 [23]	15 [B]	L: 100% [A], 80 °C [23]
	- Lighting: 10% [27]	13 [3]	0 [A]	87 [B]	G/L: none [A]
Electricity (wood and wood products)	- Heater: 50% [28]	80 [3]	0 [A]	20 [B]	G/L: none [A]
	- Motors: 35% [28]	60 [3]	30 [A]	10 [B]	L: 100% [A], 55 °C [E]
	- Compressors: 10% [28]	5 [23]	80 [23]	15 [B]	L: 100% [A], 80 °C [23]
	- Lighting and other: 5% [28]	17 [3]	27 [B]	56 [3]	L: 100% [A], 35 °C [E]
Heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Non-specified					
Oil and oil products	- Oil burner: 34% [A]	61 [3]	29 [B]	10 [A]	G: 33% [C], 300 °C [25,41] (all)
	- Diesel engine: 33% [A]	22 [3]	58 [24]	20 [B]	G: 33% [C], 200 °C [7] (all)
	- Petroleum engine: 33% [A]	13 [3]	62 [24]	25 [B]	L: 34% [C], 85 °C [7,41] (all)
Coal	Coal furnace/burner	59 [3]	31 [B]	10 [A]	G: 95% [B], 200 °C [7]
					L: 5% [A], 85 °C [7]
Natural gas, biofuels and waste	- Gas burner: 50% [A]	64 [3]	26 [B]	10 [A]	G: 75% [C], 300 °C [25,41] (all)
	- Other engine: 50% [A]	47 [3]	43 [B]	10 [A]	L: 25% [C], 85 °C [7,41] (all)
Electricity	- Motors: 25% [A]	60 [3]	30 [A]	10 [B]	L: 100% [A], 55 °C [E]
	- Compressors: 25% [A]	5 [23]	80 [23]	15 [B]	L: 100% [A], 80 °C [23]
	- Heaters: 25% [A]	80 [3]		20 [B]	G/L: none [A]
	- Lighting: 25% [A]	13 [3]	0 [A]	87 [B]	G/L: none [A]
Heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]

Legend: A – assumption, B – balance (energy), C – calculation (including simulation), E – estimation (trend/scale available).

Table A2
Input parameters for residential sector.

Blocks with inputs	Conversion device(s)/unit (s) and shares	Balance factors (in %)			Waste heat streams as exhausts (G)/effluents (L)
		η_{ES}	η_{EL}	η_{OL}	
Residential					
Oil products	Oil heating	61 [3]	29 [B]	10 [A]	G: 95% [B], 150 °C [E] L: 5% [A], 85 °C [7]
Coal	Coal burner	59 [3]	31 [B]	10 [A]	G: 95% [B], 150 °C [E] L: 5% [A], 85 °C [7]
Natural gas	- Gas burner: 50% [A] - Other engine: 50% [A]	64 [3] 47 [3]	26 [B] 43 [B]	10 [A] 10 [A]	G: 75% [C], 150 °C [E] (all) L: 25% [C], 85 °C [7,41] (all)
Biofuels and waste	- Biomass burner: 34% [A] - Gas burner: 33% [A] - Other engine: 33% [A]	34 [3] 64 [3] 47 [3]	56 [B] 26 [B] 43 [B]	10 [A] 10 [A] 10 [A]	G: 80% [C], 150 °C [E] (all) L: 20% [C], 85 °C [7,41] (all)
Solar/wind/tide	Conversion technologies	100 [A]	0 [B]	0 [B]	G/L: none [A]
Electricity	- Cooling: 18% [30]	46 [19]	44 [B]	10 [A]	L: 100% [A], 35 °C [7]
	- Lighting: 14% [30]	13 [3]	0 [A]	87 [B]	G/L: none [A]
	- Refrigeration: 10% [30]	46 [19]	44 [B]	10 [A]	L: 100% [A], 35 °C [7]
	- TV, PC, devices: 10% [30]	20 [3]	55 [B]	25 [A]	L: 100% [A], 35 °C [E]
	- Water heating: 9% [30]	80 [3]	0 [B]	20 [A]	G/L: none [A]
	- Space heating: 6% [30]	100 [19]	0 [B]	0 [B]	G/L: none [A]
	- Other: 33% [30]	50 [A]	25 [B]	25 [A]	L: 100% [A], 35 °C [A]
Geothermal, heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]

Legend: A – assumption, B – balance (energy), C – calculation (including simulation), E – estimation (trend/scale available).

Table A3
Input parameters for commercial sector

Blocks with inputs	Conversion device(s)/unit (s) and shares	Balance factors (in %)			Waste heat streams as exhausts (G)/effluents (L)
		η_{ES}	η_{EL}	η_{OL}	
Commerce and public buildings					
Oil products	- Diesel engine: 50% [A] - Petroleum engine: 50% [A]	22 [3] 13 [3]	58 [24] 62 [24]	20 [B] 25 [B]	G: 50% [40], 300 °C [41] (all) L: 50% [40], 85 °C [41] (all)
Coal	Coal furnace/burner	59 [3]	31 [B]	10 [A]	G: 95 % [B], 200 °C [7] L: 5% [A], 85 °C [7]
Natural gas, biofuels and waste	- Gas burner: 50% [A] - Other engine: 50% [A]	64 [3] 47 [3]	26 [B] 43 [B]	10 [A] 10 [A]	G: 75% [C], 300 °C [25,41] (all) L: 25% [C], 85 °C [7,41] (all)
Electricity	- Lighting: 38% [29]	13 [3]	0 [A]	87 [B]	G/L: none [A]
	- Cooling: 13% [29]	46 [19]	44 [B]	10 [A]	L: 100% [A], 35 °C [7]
	- Refrigeration: 12% [29]	46 [19]	44 [B]	10 [A]	L: 100% [A], 35 °C [7]
	- TV, PC, devices: 7% [29]	20 [3]	55 [B]	25 [A]	L: 100% [A], 35 °C [E]
	- Space heating: 4% [29]	100 [19]	0 [B]	0 [B]	G/L: none [A]
	- Water heating: 2% [29]	80 [3]	0 [B]	20 [A]	G/L: none [A]
	- Other: 24% [29]	50 [A]	25 [B]	25 [A]	L: 100% [A], 35 °C [A]
Geothermal, heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Fishing					
Oil products	Diesel engine	22 [3]	58 [24]	20 [B]	G: 50% [40], 300 °C [41] L: 50% [40], 85 °C [41]
Agriculture and forestry					
Oil products	Diesel engine	22 [3]	58 [24]	20 [B]	G: 50% [40], 300 °C [41] L: 50% [40], 85 °C [41]
Coal	Coal furnace/burner	59 [3]	31 [B]	10 [A]	G: 95% [B], 200 °C [7] L: 5 % [A], 85 °C [7]
Natural gas, biofuels and waste	- Gas burner: 50% [A] - Other engine: 50% [A]	64 [3] 47 [3]	26 [B] 43 [B]	10 [A] 10 [A]	G: 75% [C], 300 °C [25,41] (all) L: 25% [C], 85 °C [7,41] (all)
Electricity	- Heating: 25% [A]	100 [19]	0 [B]	0 [B]	G/L: none [A]
	- Cooling: 25% [A]	46 [19]	44 [B]	10 [A]	L: 100% [A], 35 °C [7]
	- Lighting: 25% [A]	13 [3]	0 [A]	87 [B]	G/L: none [A]
	- Engines: 25% [A]	60 [3]	30 [B]	10 [A]	L: 100% [A], 35 °C [E]
Geothermal, heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]
Non-specified					
Oil	Oil burner	61 [3]	29 [B]	10 [A]	G: 95% [B], 200 °C [7] L: 5% [A], 85 °C [7]
Oil products	- Diesel engine: 50% [A] - Petroleum engine: 50% [A]	22 [3] 13 [3]	58 [24] 62 [24]	20 [B] 25 [B]	G: 50% [40], 300 °C [41] (all) L: 50% [40], 85 °C [41] (all)
Coal	Coal furnace/burner	59 [3]	31 [B]	10 [A]	G: 95% [B], 200 °C [7] L: 5% [A], 85 °C [7]
Natural gas, biofuels and waste	- Gas burner: 50% [A] - Other engine: 50% [A]	64 [3] 47 [3]	26 [B] 43 [B]	10 [A] 10 [A]	G: 75% [C], 300 °C [25,41] (all) L: 25% [C], 85 °C [7,41] (all)
Solar/wind/tide	Conversion technologies	100 [A]	0 [B]	0 [B]	G/L: none [A]

Table A3 (*continued*)

Blocks with inputs	Conversion device(s)/unit (s) and shares	Balance factors (in %)			Waste heat streams as exhausts (G)/effluents (L)
		η_{ES}	η_{EL}	η_{OL}	
Electricity	- Lighting: 17% [19]	13 [3]	0 [A]	87 [B]	G/L: none [A]
	- TV, PC, devices: 15% [19]	20 [3]	55 [B]	25 [A]	L: 100% [A], 35 °C [E]
	- Refrigeration: 14% [19]	46 [19]	44 [B]	10 [A]	L: 100% [A], 35 °C [7]
	- Cooling: 13% [19]	46 [19]	44 [B]	10 [A]	L: 100% [A], 35 °C [7]
	- Space heating: 11% [19]	100 [19]	0 [B]	0 [B]	G/L: none [A]
	- Water heating: 9% [19]	80 [3]	0 [B]	20 [B]	G/L: none [A]
	- Other: 21% [19]	50 [A]	25 [B]	25 [A]	L: 100% [A], 35 °C [A]
Geothermal, heat	Heat exchanger including distribution network	47 [C]	36 [C]	17 [C]	L: 100% [A], 50 °C [21]

Legend: A – assumption, B – balance (energy), C – calculation (including simulation), E – estimation (trend/scale available).

Table A4
Input parameters for transportation sector.

Blocks with inputs	Conversion device(s)/unit(s) and shares	Balance factors (in %)			Waste heat streams as exhausts (G)/effluents (L)
		η_{ES}	η_{EL}	η_{OL}	
Road					
Oil, oil products, natural gas, biofuels,	- Diesel engine: 50% [A]	22 [3]	58 [24]	20 [B]	G: 50% [40], 300 °C [41] (all)
	- Petroleum engine: 50% [A]	13 [3]	62 [24]	25 [B]	L: 50% [40], 85 °C [41] (all)
Rail					
Oil products	Diesel engine	22 [3]	58 [24]	20 [B]	G: 50% [40], 300 °C [41] L: 50% [40], 85 °C [41]
Coal	Steam engine	10 [31]	60 [31]	30 [B]	G: 100% [A], 300 °C [E]
Electricity	Electric engine	60 [3]	30 [B]	10 [A]	L: 100% [A], 55 °C [E]
Pipeline transport					
Natural gas	Gas engine/turbine and compressor	11 [C]	85 [C]	4 [C]	G: 40% [C], 300 °C [25,41] L: 40% [C], 85 °C [7,41] L: 20% [C], 45 °C [C]
Electricity	Electric engine and compressor	21 [C]	71 [C]	8 [C]	L: 70% [C], 55 °C [E] L: 30% [C], 45 °C [C]
Ship					
Oil products	Diesel engine	22 [3]	58 [24]	20 [B]	G: 50% [40], 300 °C [41] L: 50% [40], 85 °C [41]
Aircraft					
Oil products	Aircraft engine/turbine	28 [3]	52 [B]	20 [32]	G: 100% [A], 500 °C [33]
Non-specified					
Oil products, natural gas	- Diesel engine: 50% [A]	22 [3]	58 [24]	20 [B]	G: 50% [40], 300 °C [41] (all)
	- Petroleum engine: 50% [A]	13 [3]	62 [24]	25 [B]	L: 50% [40], 85 °C [41] (all)
Electricity	Electric engine	60 [3]	30 [B]	10 [A]	L: 100% [A], 55 °C [E]

Legend: A – assumption, B – balance (energy), C – calculation (including simulation), E – estimation (trend/scale available).

Table A5
Input parameters for electricity generation

Blocks with inputs	Conversion device(s)/unit(s) and shares	Balance factors (in %)			Waste heat streams as exhausts(G)/effluents (L)
		η_{ES}	η_{EL}	η_{OL}	
Thermal power station					
Oil and oil products	Plant with oil-fired boiler	35,7 [34]	52,4 [B]	11,9 [34]	G: 15% [C], 120 °C [35] L: 85% [C], 30 °C [35]
Coal	Plant with coal-fired boiler	34,3 [34]	53,8 [B]	11,9 [34]	G: 15% [C], 120 °C [35] L: 85% [C], 30 °C [35]
Natural gas	Plant with gas-fired boiler or gas turbine	40,3 [34]	47,8 [B]	11,9 [34]	G: 15% [C], 120 °C [35] L: 85% [C], 30 °C [35]
Nuclear	Plant with nuclear reactor	33,0 [1]	55,1 [B]	11,9 [34]	L: 100% [A], 30 °C [35]
Biomass power station, waste incineration					
Biofuels and waste	Plant with biomass-fired or waste-fired boiler	35,7 [34]	52,4 [B]	11,9 [34]	G: 15% [C], 120 °C [35] L: 85% [C], 30 °C [35]
Renewable energy sources power station					
Hydro	Plant with hydro turbine (run-of-river, reservoir)	80,0 [E]	8,1 [B]	11,9 [34]	L: 100% [A], 85 °C [7]
Geothermal	Rankine cycle driven by geothermal power	10,0 [1]	78,1 [B]	11,9 [34]	L: 100% [A], 30 °C [35]
Solar/tide/wind	Solar thermal plant, photovoltaic plant, tidal power plant, wind power (on-/offshore)	91,1 [B]	0 [A]	8,9 [34]	G/L: none [A]

Legend: A – assumption, B – balance (energy), C – calculation (including simulation), E – estimation (trend/scale available).

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