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Upscaling and case study design: Influence on the environmental impact assessment of high-temperature heat pumps using LCA

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Abstract

Existing high-temperature heat pumps were investigated by means of life cycle assessment with thermal outputs of 0.19, 0.66, 1.2 and 10 MW. Scale up was performed linearly, due to a better fit than other methods presented in the literature. It was shown that the electricity consumed during the usage phase has a greater impact in the majority of damage categories rather than manufacturing or the production/leakage of the working fluid. The European grid mix was compared to the French and Spanish one, showing that a low-carbon power source is vital. Finally, a benchmark with other common steam sources was done in terms of global warming potential, showing the substitution of fossil-based steam sources is the biggest lever when implementing heat pumps for better sustainability.

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1. Introduction

When it comes to assessing sustainability of technologies and their development, life cycle assessment (LCA) is an apt tool to assess environmental impacts on a multidimensional level. Hence, heat pumps (HPs) are no exception and have been the target of several studies. [1] – [4] However, most studies only target residential HPs and/or low temperature systems with larger, high-temperature systems being more of an exception. When it comes to the roll-out of “green” technologies, investors and policy makers face a “hen-or-egg” type of question. Subsequently, potential investors want reliable information concerning economic & environmental implications, this data is hard to generate as hands-on cases are hardly found. While there are already profound approaches for other technologies such as for power-to-gas [5], [6], biorefineries [7], [8], or chemical conversions [9], High-Temperature Heat Pumps (HTHPs) are lacking in this area.

While it is common in LCA-modelling to omit the material needed for the plant as impacts are mostly of a minor nature, this notion will be put to the test in this study, as modelling of a material balance will be investigated. Caduff et al. [10] developed a scale-up framework of domestic HPs based upon exponential power laws. The applicability of this framework will be tested for commercial HPs, with its data being based upon results of IEA Task Annex 58. [11] Data gaps were filled by literature research and discussions with experts on the field. The final results were objected to an LCA with the functional unit to produce 1 GJ of steam.

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2. Materials and methods

2.1 LCA

LCA has been described numerous times in literature, thus for an introductory reading, the authors would like to refer the reader to the following standard works. [12], [13], [14]. Yet, LCA will be performed following ISO 14044, with its 4 phases being:

- Definition of Goal and Scope
- Life Cycle Inventory (LCI) analysis
- Life Cycle Impact Assessment (LCIA)
- Interpretation and Discussion

2.1.1 Definition of Goal and Scope

The goal of the LCA case study in this paper is the modelling of a HTHP, located in Europe producing steam from low-temperature heat sources, mainly water. The four cases have an output of thermal energy of 0.19, 0.66, 1.2 and 10 MW. The cases are exemplarily conducted for France, Spain and the EU-28, which means the respective electrical grid is considered. The system boundary is cradle-to-gate, as no assumptions about the steam usage are made, with the functional unit of 1 GJ of steam produced. The system entails the production of the machinery and the usage phase, which is assumed to be 15-30 years. The machines are all assumed to operate 8000 hours per year and the End-Of-Life operations were not modelled in this study.

2.1.2 Life Cycle Inventory (LCI) analysis

The life cycle inventory is mostly based upon the Ecoinvent process “Heat Pump Production, brine-water, 10kW”. [15] Other inputs came from manufacturers of the featured HPs and the literature. Details are discussed in the respect section in the results part of this work.

2.1.3. Life Cycle Impact Assessment (LCIA)

The damage impacts will be assessed by the CML-method [13], utilizing the standardized midpoint categories shown in Table 1.

Table 1: Midpoint categories used in this study as introduced by Guinée et al. [13]

Impact categories within the CML method	Unit
Global warming potential (GWP 100 years)	[kg CO ₂ -Equiv.]
Ozone layer depletion potential (ODP, steady state)	[kg R11-Equiv.]
Acidification potential (AP)	[kg SO ₂ -Equiv.]
Eutrophication potential (EP)	[kg Phosphate-Equiv.]
Photochemical ozone creation potential (POCP)	[kg Ethene-Equiv.]
Human toxicity potential (HTTP inf.), Terrestrial ecotoxicity potential (TETP inf.)	[kg DCB-Equiv.]
Freshwater aquatic ecotoxicity potential (FAETP inf.), Marine aquatic ecotoxicity potential (MAETP inf.)	[kg DCB-Equiv.]
Abiotic depletion (ADP)	[kg Sb-Equiv.]

2.2. Modelling of scaling laws

In the past, researchers found that the cost and material balance of scaling up process equipment does not show linear behavior, as in fact they follow a power law, as presented in Equation 1. With C being the cost/material need of interest, a being the normalization factor, X the capacity/scale of interest and b the scaling factor. If this factor is 1 the relationship is linear, however empirical data did show a value of 0.6 being best suited for many different applications.

Equation 1: The power law found for scale up of process equipment.

$$C = a * X^b \quad (1)$$

As mentioned in the introduction, Caduff et al., [10] applied this approach to HPs and biomass boilers. They tried to correlate HP's mass, working fluid use and coefficient of performance (COP) to the respective masses, by transforming Equation 1 logarithmically, as shown in Equation 2. In this case i is the property of interest, mass, COP, or working fluid, while a & b are scaling factors.

Equation 2: Equation 1 transformed logarithmically to allow for linear regression.

$$\log(i) = \log a_i + b_i \log(X) \quad (2)$$

3. Results and Discussion

3.1.1. Scale-Up of the HP

As in the original manuscript by Caduff et al., [10] the regressions for COP and the mass of working fluids showed unconvincing correlation, those were omitted for further analysis. For the material balance, the regression slope for the water/water HP was chosen. Two other additional slopes were drawn, based upon the standard-deviation in the 95 % confidence interval. Thus, the following slopes were plotted, as shown in Table 2.

Table 2: Linear regressions found by Caduff et al., [10] and the case studies on our study.

Slope Name	$\log(a_i)$	b_i	X (P / MW)
Low	0.73	0.48	0.19; 0.66; 1.2; 10
Mean	0.75	0.55	0.19; 0.66; 1.2; 10
High	0.78	0.64	0.19; 0.66; 1.2; 10

As linear scale up is a popular tool in LCI generation a linear scale up was plotted as reference too [16]. Table 3 shows the heat pumps of Annex 58 and their respective masses.

Table 3: HP case studies used to compare real-life scaling data; all data taken from IEA Annex 58.

Machine Name / Manufacturer	Thermal Power / MW	Mass / kg
Steam Generation HP / Fuji Electric	0.03	850
CO ₂ Air Heater Heat Pump / Eco Sirocco Mayekawa Mf	0.1	1750
ThermBooster / SPH Sustainable Process Heat GmbH	0.3	4000
Steam Grow Heat Pump / SGH120 / KOBELCO Compressors	0.37	4250
SkaleUP / Skala Fabrikk AS	0.45*	4200
130°C Hot Water Supply Heat Pump ETW-S /Mitsubishi Heavy Industries Thermal System	0.627	6500
Hydrocarbon Heat Pump / HS-compressor / Mayekawa Europe NV	0.75	13750
Micro Steam Recovery Compressor MSRC160L / KOBELCO Compressors Corporation	0.8	2700
Hydrocarbon Heat Pump / FC-compressor / Mayekawa Europe NV	1.0	20000
HoegTemp UHT heat pump / Enerin AS	1.0	10000

*0.3 MW Heating & 0.15 MW Cooling

The results of the linear regressions in Table 2 and the data presented in Table 3 are plotted in Figure 1. Apparently, the fitting done in the work by Caduff et al., [10] was futile in the case at hand, as the HTHP mass data follows a linear trend line in the closest manner. Thus, linear trendlines are explored further in the right part of Figure 1. In this comparison, a good fit for masses of HPs up to 0.7 MW was found, which quickly deteriorates as higher masses are also included. This finding is confirmed by the fact that for HPs with a power output > 1 MW their masses are not outlined and are commonly described with phrases such as “depends heavily on the installation and the parameters at the specific site”.

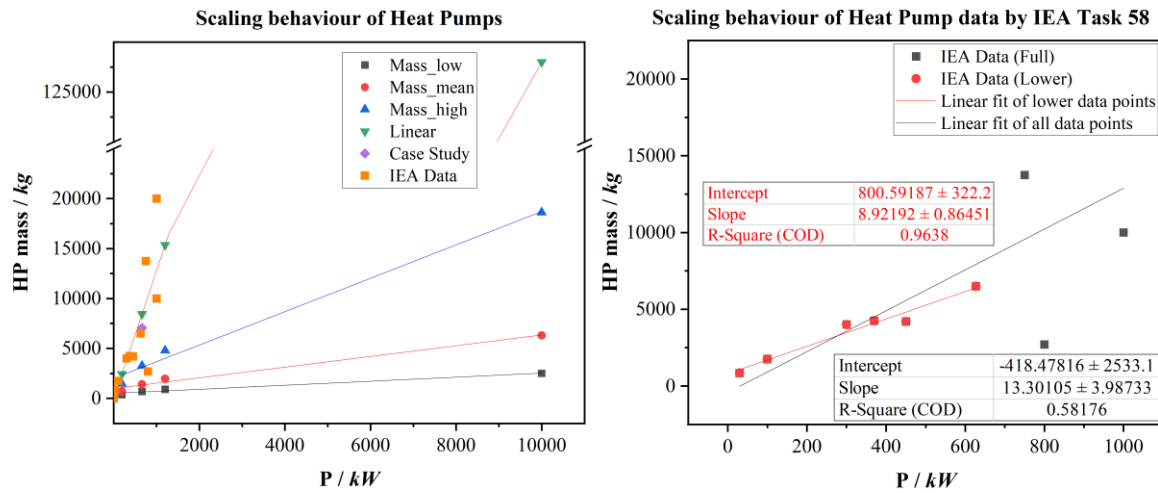


Figure 1: The left part of the figure shows the scaling results by Caduff et al., also considering the boundaries of the confidentiality interval, in comparison with the HP data collected in IEA Annex 58 (Task) 1. The right part of the figure shows only the IEA data and two fits, one encompassing the entire data set, the other one only the ones with lower outputs.

3.1.2. Life Cycle Inventory

The LCI was compiled for four HTHPs. In Table 4 the four different case studies are presented. Almost all items were modelled after the Ecoinvent database and the “Heat Pump Production, brine-water, 10kW” dataset, applying a linear scale-up [15]. However, the LCI entailed a part containing the working fluid and the power consumed/generated. Those results are found in Table 4 and Table 5. Due to the limited availability of steam-generating heat pumps on the market not all heat pumps in Table 4 can produce steam on their own. This applies to cases 1 – DryFiciency Wienerberger and 3 - Combitherm. To overcome this issue the COPs of these water-to-water heat pumps were considered and for steam production a flash tank was connected downstream. The internal mechanism of a flash tank only evaporates a relatively small portion of water at the flash valve. The percentage of the mass flow that is converted into steam depends on the pressure difference the fluid experiences at expansion. This added resistance requires more power to pump the sink stream. To take these effects into account circulation pumps were included in the calculation. Their electrical power consumption is estimated based on similar heat pump configurations that use flash tanks. The reference application was based on the design power of the pump. Therefore, the presented estimates for circulation pump power in Table 4 can be seen as an upper bound. The COPs for case studies 1 and 3 include the extra power consumption of the circulation pumps. Documentation of the different HTHP models is given in the citations.

Table 4: LCI data containing energy inputs and outputs as well as additional data.

	Case Study 1 [17]	Case Study 2 [18]	Case Study 3 [19]	Case Study 4 [20]
Model Name / Manufacturer	Dryficiency Wienerberger	SGH 165 Kobelco	Combitherm	Industrial HP Siemens Energy
Power Output / MW	0.19	0.66	1.2	10
Useful life / a	15	15	15	30
Runtime / h*a ⁻¹	8000	8000	8000	8000
Heat source in / °C	91	70	45	115
Heat source out / °C	88	65	40	105

Heat sink in / °C	131	/	112	105
Heat sink out / °C	160	/	120	/
Temperature of steam produced / °C	145*	165	105*	150
Circulation Pump / MWh*a ⁻¹	160*	0	480*	0
Circulation Pump / MWh (total life)	2400	0	7200	0
Upgrading / MWh*a ⁻¹	691	2112	4364	19048
Upgrading / MWh (total life)	10364	31680	65455	571429
COP (Steam generating HP)	1.79	2.5	1.98	4.2
Heat Output / GJ*a ⁻¹	5472	19008	34560	288000
Heat Output / TJ (total life)	82.08	285.12	518.40	4320
Documentation	[17]	[18]	[19]	[20]

* Expert's estimate

Table 5: LCI data pertaining to working fluid use and leakage.

	Case Study 1	Case Study 2	Case Study 3	Case Study 4
Working fluid	1336mzz (Z)	R134a + R245fa	R1233zd (E)	R1233zd (Z)
IUPAC name	1,1,1,4,4,4-Hexafluorobutene	1,1,1,2-Tetrafluoroethane & 1,1,1,3,3-Pentafluoropropane	<i>trans</i> -1-Chloro-3,3,3-trifluoroprop-1-ene	<i>cis</i> -1-Chloro-3,3,3-trifluoroprop-1-ene
Initial filling / kg	82	140	285	5000
Total leakage (life) / kg	12.3	21	42.75	1500
Total demand (life) / kg	94.3	161	327.25	6500
GWP / kg CO ₂ -eq.*kg ⁻¹ [Source]	2 [21]	1050* [22]	6 [22]	6 [22]
GWP (leakage over life) / kg CO ₂ -eq	24.6	22050	42.75	1500
ODP / kg R11-eq.*kg ⁻¹ [Source]	0 [23]	0* [23]	0.00034** [23]	0.00034** [23]
ODP (leakage over life) / kg R11-eq	0	0	0.014535	0.51

*The manufacturer told the authors that the two WF are in a secret mixture, but for the sake of calculation 100 % R245fa should be assumed.

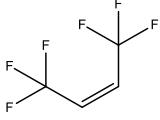
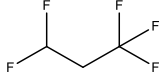
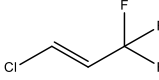
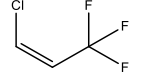
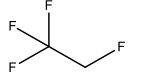
** The value was assumed to be similar for both enantiomers.

The original inventory from Ecoinvent listed significant amount of working fluid (WF) needed for the initial fillings and high losses during production and decommissioning. [15] After having talks with experts, it was concluded, that those values were too high for state-of-the-art processes. A leakage of 1 % per year and a refilling was hence assumed and modelled.

3.1.3. Transforming the inventory to the model

As discussed, the production of the HP features also the production of a WF. As R134a is not used in any of the model cases, production data had to be found for the remaining WFs. Literature shows that synthesis routes are manifold, mostly too complicated for LCA studies, as non-standard chemicals and rare-element catalysts are used. [24], [25] A process from the Ecoinvent database for R134a, was used as a proxy [26]. The reason was that literature only lists values for GWP and ODP and we wanted the other midpoint categories to be accounted for, too. Wang et al., analyzed the production of R134a and found a GWP of 15.9 kg CO₂-eq. / kg for the production of R134a. This was deemed close enough to the Ecoinvent dataset's result to confirm its validity. The chemical structures of the different WF's are shown in Table 6.

Table 6: Overview of the WFs used in the study.

Working fluid	1336mzz (Z)	R245fa	R1233zd (E)	R1233zd (Z)	R134a
IUPAC	(Z)-1,1,1,4,4,4-hexafluor-2-butene	1,1,1,3,3-pentafluoropropane	(E)-1-chloro-3,3,3-trifluoroprop-1-ene	(Z)-1-chloro-3,3,3-trifluoroprop-1-ene	1,1,1,2-tetrafluoroethane
Structure					

For the LCA, the Ecoinvent standard processes were used given in the documentation of the 10 kW HP process if not stated else. Exceptions include the supply for thermal energy, which was modelled with a Sphera process [27], or the plastic waste mixture which was assumed to be treated thermally [28]. As for incineration, steam and power are produced, substitution had to be modelled. For the thermal energy, the beforementioned process was taken; while for the grid, the grid used in the scenario was chosen. According to the country selections, the grid mixes by Sphera for the “1KV-60KV grid mix” in the EU-28, France and Spain. [29], [30], [31].

3.2. LCIA results

As a first group of results, the base cases of the four heat pumps are presented, for which the EU:28 electricity mix was used. The absolute values results are listed in Table 7, as well as percentual impacts which were normalized to the 10 MW case, case 4. They are accompanied by percentual values in relation to the 10 MW case.

Table 7: CML LCIA results for the scenarios obtained in the LCA base case.

CML-Midpoint category	Case 1	Case 2	Case 3	Case 4
Abiotic Depletion (ADP elements) [kg Sb eq.]	2.26E-05	2.08E-05	2.19E-05	1.34E-05
In %	168.82%	155.71%	163.64%	100.00%
Abiotic Depletion (ADP fossil) [MJ]	2.00E+02	1.43E+02	1.81E+02	1.70E+02
In %	117.87%	84.53%	106.42%	100.00%
Acidification Potential (AP) [kg SO ₂ eq.]	3.85E-02	2.76E-02	3.48E-02	3.25E-02
In %	118.53%	85.06%	106.92%	100.00%
Eutrophication Potential (EP) [kg Phosphate eq.]	4.38E-03	3.17E-03	3.96E-03	3.69E-03
In %	118.94%	85.99%	107.33%	100.00%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	0.15	0.13	0.14	0.09
In %	165.08%	148.21%	157.56%	100.00%
Global Warming Potential (GWP 100 years) [kg CO ₂ eq.]	18.39	13.20	16.53	15.57
In %	118.12%	84.77%	106.13%	100.00%
GWP 100 years. excl biogenic c [kg CO ₂ eq.]	1.84E+01	1.32E+01	1.65E+01	1.56E+01
In %	118.12%	84.77%	106.13%	100.00%
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	9.25E-01	6.93E-01	8.41E-01	7.42E-01
In %	124.64%	93.37%	113.31%	100.00%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	2.45E+03	1.79E+03	2.22E+03	2.03E+03
In %	120.86%	88.11%	109.35%	100.00%
Ozone Layer Depletion Potential (ODP) [kg R11 eq.]	1.12E-06	5.54E-07	6.20E-07	7.93E-07
In %	141.52%	69.90%	78.19%	100.00%
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	2.70E-03	1.95E-03	2.44E-03	2.28E-03
In %	118.38%	85.35%	106.81%	100.00%
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	2.29E-02	1.65E-02	2.07E-02	1.92E-02
In %	118.92%	85.80%	107.73%	100.00%

The results are relatively uniform throughout the impact categories. The 0.66 MW machine yields the lowest results, owing to the high COP, especially compared to 0.2 and 1.2 MW. While the 10 MW HTHP exhibits a COP of 4.2, one must not forget that this figure comes from a heat source of $> 100^{\circ}\text{C}$. Moreover, case study 1 and 3 need the circulating pump, thus higher emissions due to the power used were found. However, lower emissions due to scaling effects were not found. Moreover, the impacts were grouped into the three different stages of the life cycle of the HTHPs. The results are shown in Figure 2.

Upon reviewing the percentual contributions it becomes clear the influences are very similar among the different HTHP systems. Except for ADP elements, FAETP, and ODP, the usage phase of HPs was responsible for the majority of the impacts. The leakage was only noticeable in the case of the 10 MW case, which resulted in a 7 % contribution to ODP, which was again based on very low overall numbers. Especially for GWP, HP production and leakage's impacts were under 1 %, thus confirming the hypothesis that in energy-intensive operations the plant plays only a minor role. Interestingly enough, when comparing case studies 2 & 3, case study 2 featuring a working fluid with a GWP > 20.000 , no difference is visible to case study 3 which uses a WF with a GWP of 43, thus indicating that over the lifetime of one HP the GWP of the working fluid should not influence decision making too much.

As mandated by ISO 14044, sensitivity analysis should be used in comparative LCA in order to account for weak spots in the analysis and to further insights into the comparative model. For this, the grid mixes were changed to the Spanish and French one, as well as material balances were changed by + 50 % and reduced by - 50 %. Results for the CML midpoint categories are presented in Figure 3.

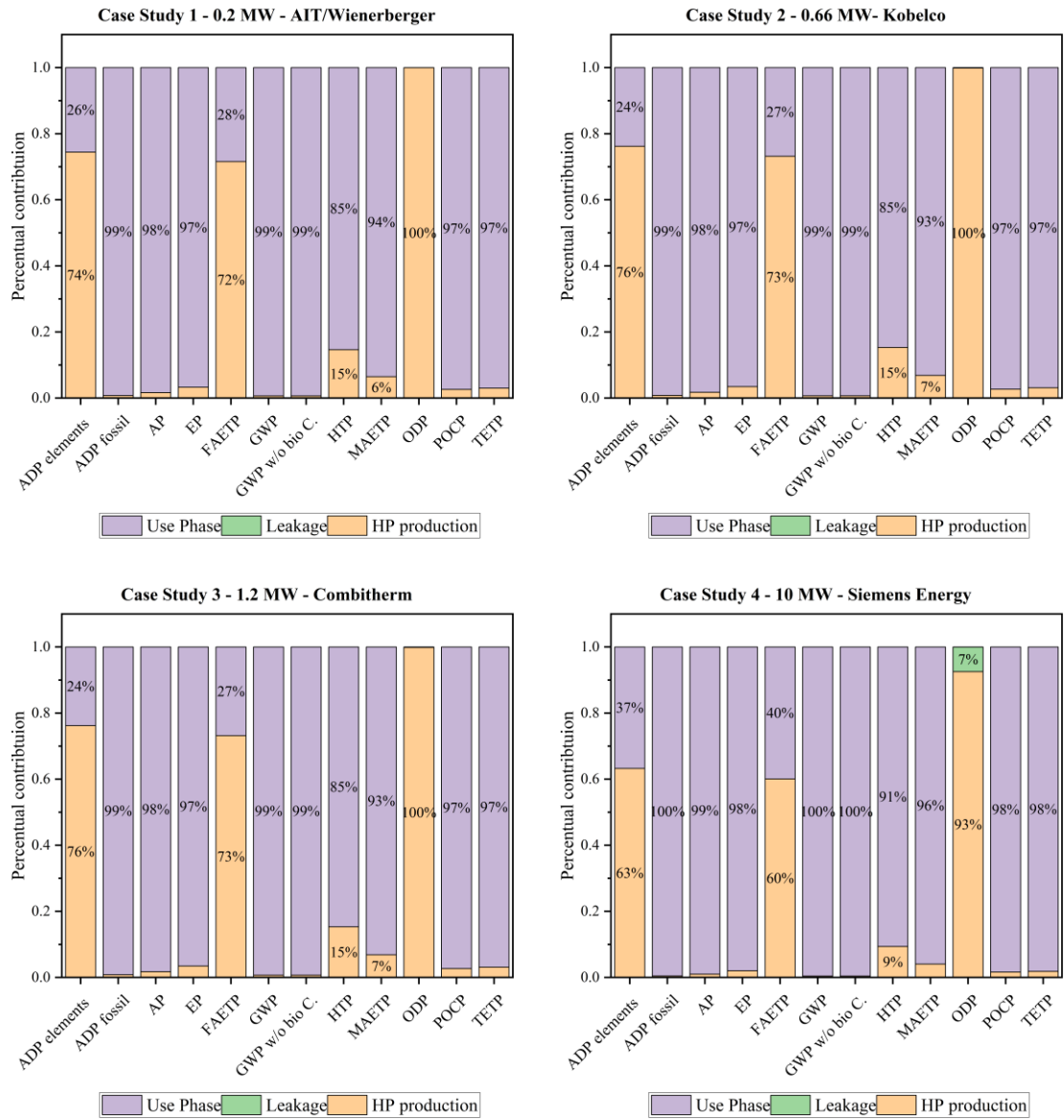


Figure 2: Percentual contributions to the midpoint categories by the three different life style changes.

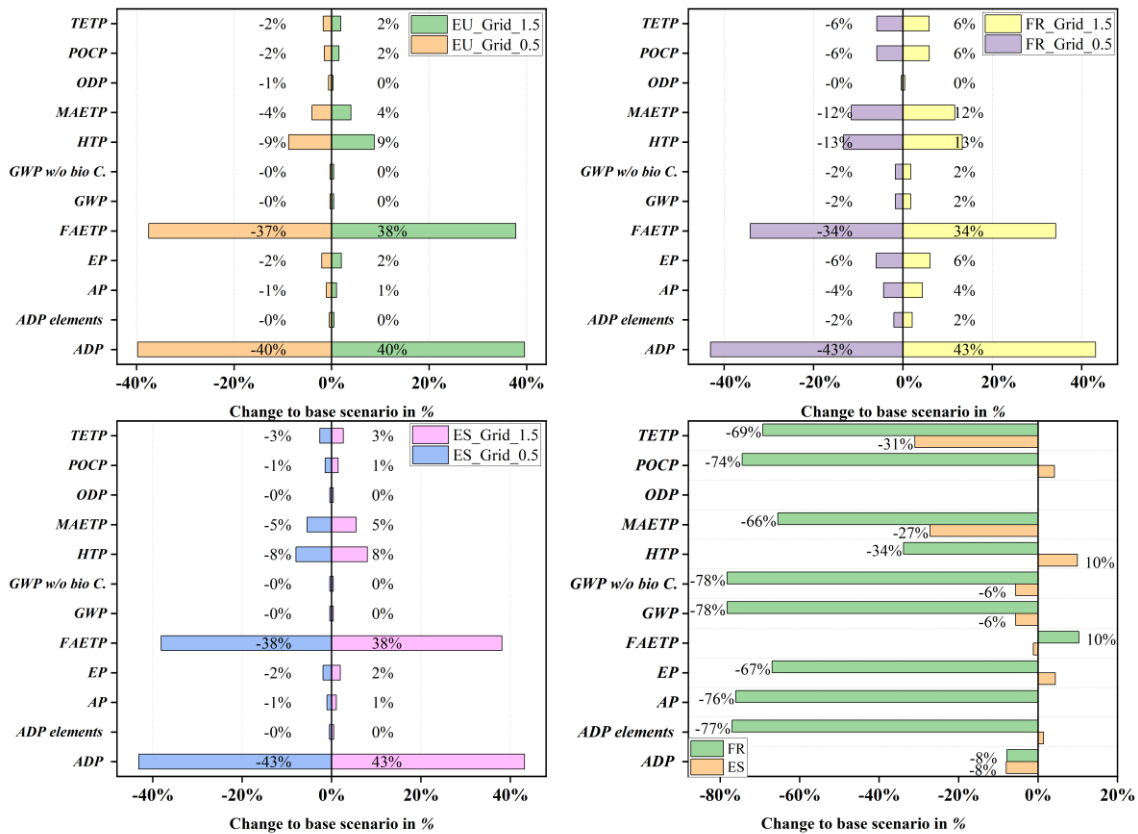


Figure 3: The results of the sensitivity analysis. The top figures and the bottom left ones indicate percentual changes in scenarios varying the three grid mixes and the material balances. The bottom right scenario features no change of material solely the grid mixes changed. Changes smaller than 5 % were not shown for reasons of readability.

The findings of Figure 3 match the ones made in Figure 2. The increased/decreased material demands altered ADP and FAETP by less than 50 %, while leaving the majority of other categories, including GWP, largely unaltered. Due to the linear scaling, the tornado chart is highly symmetrical. This once again highlights, that if GWP is the main focus of a HTHP study, the material balance plays a minor role at most. For toxicity related impacts however, the scaling effects are of interest. Acidification and eutrophication were also only influenced on a minor level. If only the electricity grid mixes were changed from the EU-28 mix to the Spanish or French one, the results turned out very different. The influence is mostly indirectly proportional to the previous analysis, as categories change more drastically. I.e., the French grid provides significant reductions of 77 % in the ADP elements category as well as -78 % for GWP, which was due to its low carbon intensity. AP and EP show similar behaviour, as they are also hardly influenced by the material balance’s scaling. The Spanish mix does provide some reductions, yet its influence is notably smaller than the French one. However, in a direct comparison, the Spanish grid provided little improvement over the French one, only in the FAETP category it yielded minuscule better results.

As it was shown, when aiming for an improved carbon balance, the usage phase provides the biggest lever. Aiming for a high efficiency and clean energy can help to significantly reduce the GWP. While this is one part of the equation, the other side in LCA is the energy provision, which will be replaced using a HTHP. Therefore, 1 GJ produced by the HTHP was compared to other steam sources such as solid biomass, biogas, light fuel oil (LFO) and natural gas. Data was obtained from Sphera’s Professional database and is presented in Figure 4, normalized to steam by LFO. [32], [33], [34], [35]

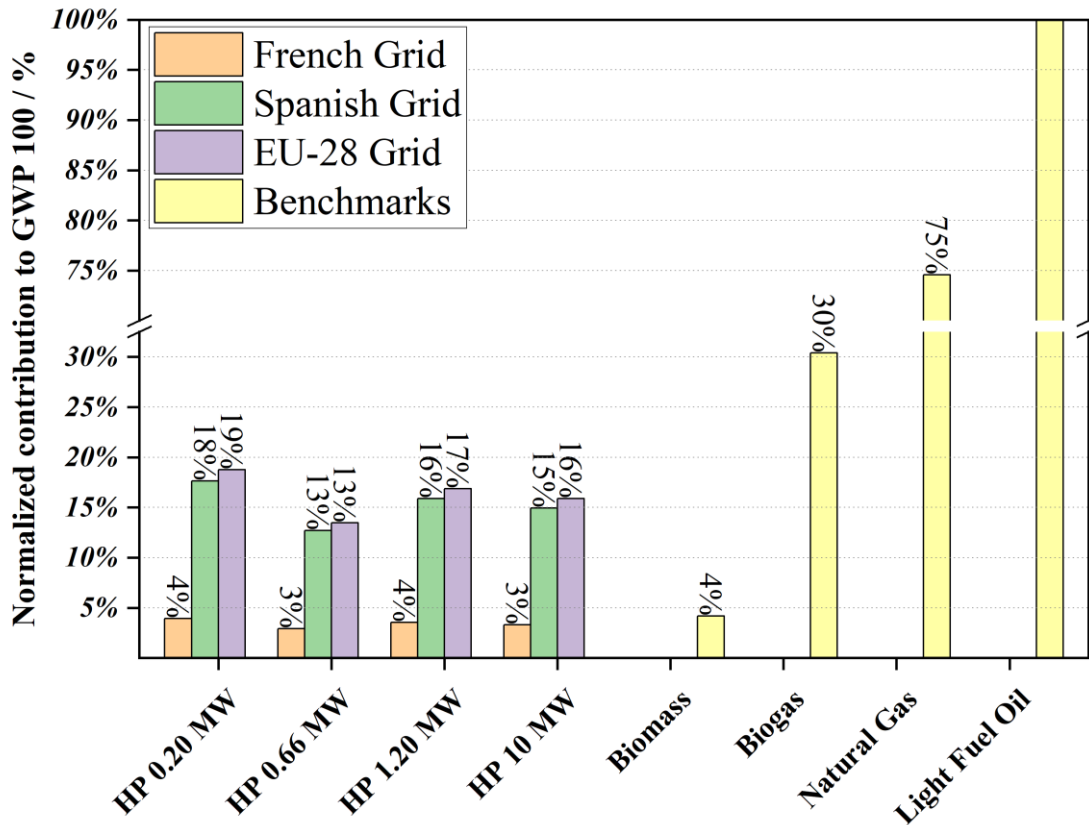


Figure 4: The results for the four HTHP cases in comparison with other established steam sources in terms of GWP.

When assessing the GWPs of the different steam generating technologies it becomes clear that the differences between the different HTHPs, their production and usage parameters are negligible when compared to the figures obtained by different steam generating technologies. This means if one of the HTHPs is implemented, the largest lever to lower the carbon balance is the technology which is replaced. The best case for example, the 0.66 MW design, powered by a French grid, replacing steam from LFO would yield a reduction of emissions by 97 %. The real case would probably be not as straight-forward, as 1:1 replacement is a very optimistic assumption, and it all comes down to the case at hand and its thermodynamic and process properties. But even replacing smaller fossil steam sources can provide significant emissions savings due to the emission's slope's sizes.

4. Conclusion, final remarks, and further outlook

While the power-laws used for scaling up equipment/cost in process engineering have come in handy many times in the past, this was not true in this case of industrial sized HTHPs. It was shown that the power-law was not applicable to the HTHP case, as the scaling behaved mostly in a linear fashion. Especially in the range between 0.1 and 0.7 MW_{th} a good linear correlation was found. However, those results were of methodological interest only as it was shown that manufacturing is not as influential as the usage when it comes to life cycle impacts, especially GWP. This was confirmed in the sensitivity analysis. The usage/choice of working fluid also was shown to be not as influential as assumed, as no considerable difference was observed between cases with a WF with high and low GWPs. Therefore, it is recommended that manufacturers should care about thermodynamic properties foremost, which are mostly met by working fluids with low GWPs in the HTHP area anyways. In the case studies, it was shown that a grid with low carbon intensity can help significantly in decreasing environmental impacts. This effect can be further amplified if carbon-intensive steam sources are replaced. If e.g., a HTHP powered by the French grid replaces steam from LFO GWP savings of over 97 % could be achieved. However, one must not forget that as of now the HTHPs can only supply lower temperature and lower pressure steam, while the fossil sources are not limited in that sense. Moreover, biogenic carbon CO₂ emissions are not further considered in this work, as no storage over long times is achieved. This is accurate for the system boundary in this case but may change drastically if different system boundary in terms of biomass is applied.

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