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External Costs of ORC Working Fluids for Geothermal Applications

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ABSTRACT

This study presents a detailed assessment of the external costs caused by power generation through geothermally driven ORCs with different working fluids. In current operating geothermal applications, ORC working fluids of the hydrocarbons (HC) and hydrofluorocarbons (HFC) groups are dominating. More recently, new working fluid groups have been developed, which are in the hydrofluoroolefines (HFO) and hydrochlorofluoroolefines (HCFO) group. The HFO R1234yf and R1234ze(E) as well as the HCFO R1233zd(E) and R1224yd(Z) are especially promising low-GWP alternatives to the HFC R134a and R245fa. Nevertheless, the evaluation and legal handling of HCFOs with an ODP slightly above zero is controversial. For instance, the German Environment Agency intends to prohibit the application of R1233zd(E), due to its ODP of 0.00024. However, R1233zd(E) has several favorable aspects, such as a very low GWP and no flammability and toxicity (safety classification of A1). A case-study for a hypothetical geothermal system with a brine temperature of 138°C and a flow rate of 122 kg/s is carried out. For the four investigated impact categories global warming, acidification, eutrophication and ozone depletion, external costs between 0.16 €ct/kWh$_{el,net}$ and 1.7 ct/kWh$_{el,net}$ are obtained. For the monetarization factors with the highest probability, the external costs caused by the high-GWP refrigerants R245fa and R134a are 0.69 €ct/kWh$_{el,net}$ and 0.83 €ct/kWh$_{el,net}$ respectively. All derived external costs for the investigated low-GWP working fluids are significantly lower and are in a range between 0.29 and 0.30 €ct/kWh$_{el,net}$. This proves, that the very small ODP by R1233zd(E) and R1224yd lead to no significant increase of the external costs. Thus, a general prohibition of potentially promising refrigerants with a very small ODP appears not be justifiable based on the presented results.

1. INTRODUCTION

While there is a common consensus that geothermal energy has a tremendous potential for environmentally friendly power generation (Resch et al., 2008), renewable technologies such as geothermal energy must be still evaluated and optimized with respect to their environmental impact to provide the most ecologically compatible power generation possible. In the case of power generation by geothermal Organic Rankine Cycles (ORCs), this applies mainly for the used working fluid. As highlighted by Martín-Gamboa et al. (2015) and Heberle et al. (2016), the choice of the ORC's working fluid can have a significant impact on the environmental performance of the geothermal project. Especially the global warming potential (GWP) of the working fluid candidates affects the CO_2 equivalent of the produced electricity significantly. For geological conditions in Germany and an assumed annual refrigerant leakage rate of 2%, the CO_2 equivalent per produced kWh net electricity is 97 gCO_{2eq}/kWh$_{el,net}$ for the common high-GWP fluid R245fa, while with the low-GWP working fluid R1233zd(E) the CO_2 equivalent is only 22 gCO_{2eq}/kWh$_{el,net}$ (Heberle et al., 2016). Thus, the thermodynamic investigation and optimization of geothermal ORC with low-GWP working fluids, as in Le et al. (2014) and Yang and Yeh (2016), is of high relevance. Particularly the hydrofluoroolefines (HFOs) R1234yf and R1234ze(E) as well as the hydrochlorofluoroolefines (HCFOs) R1233zd(E) and R1224yd(Z) are promising low-GWP alternatives for the currently commonly used hydrofluorocarbon (HFC) R134a and R245fa. While high-GWP working fluids will increasingly be substituted by low-GWP working fluids, it is questionable which category of working fluids has the best characteristic and should therefore be used in the future (Ciconkov, 2018). Since no group of working fluids has advantageous characteristics in all relevant categories (i.e. ozone depletion potential (ODP), effect on the cycle efficiency, flammability, toxicity, costs) the choice of the fluid constitutes a tradeoff (Calm, 2008). In this regard, the evaluation and legal handling of HCFOs with an ODP slightly above zero is particularly controversial. The position of the German Environment Agency (UBA), which intends to ban working fluids with an ODP above zero (e.g. R1233zd(E) with an OPD of 0.00024) (European Commission, 2017), constitutes one example of this ongoing discussion. The UBA recommends a strict ban of ozone depleting substances due to the potential environmental damage. However, it thereby bases its recommendation on a general valuation and not on numerical evaluations of the environmental impact of the different low-GWP working fluid types.

There are several tools to assess the environmental impact of power generation processes numerically. The most common ones are the Life Cycle Assessment (LCA) and the concept of external costs (Voss, 2001). The LCA investigates the environmental impact of the assessed technologies for different impact categories (e.g. global warming or eutrophication) associated with the complete lifetime of the process or product ("cradle to grave"). The strength of this method is, that equivalents for all considered impact categories are derived as a result, which allows a detailed evaluation of the environmental impact. However, it might be challenging to derive clear recommendations for actions, if technologies exhibit different rankings in the evaluated impact categories**.** The external costs represent the costs caused by the investigated technology that are not accounted for by the producers and consumers (Eyre, 1997). This mainly refers to environmental and health costs, which are caused by the producers, but not covered by the prices paid and as such must be borne by the society. Thus, on the one hand the method provides comprehensive numerical results, which allow a clear ranking of different considered systems. However, on the other hand the assessment of the external costs is accompanied by a high level of uncertainty, since the exact external costs of an impact category (i.e. one ton of CO_2) cannot be determined. Voss (2001) presents a detailed theoretical discussion of the different advantages and drawbacks of both concepts. While there are several existing

LCAs about geothermal power generation (cf. Bayer et al. (2013); Heberle et al. (2016); Martín-Gamboa et al. (2015)), no studies on the impact of the selected working fluid for geothermal power generation on external costs exists.

Against this background, this study aims to assess the external costs for four different low-GWP working fluids (R1233zd(E), R1224yd(Z), R1234yf, R1234ze(E)) in geothermal driven ORCs and compares them with currently used working fluids (R245fa, R134a). Therefore, the four main impact categories climate change, ozone depletion, acidification, and eutrophication are assessed. Based on the external costs caused by these impact categories, the overall external costs of the produced electricity are evaluated. Thus, this work presents numerical results on the environmental and social damage caused by different working fluids and provides thereby a significant contribution to the current debate about the future handling of low-GWP working fluids.

2. WORKING FLUIDS

The currently dominant working fluids for ORC systems are refrigerants from the class of hydrofluorocarbons (HFC), such as R245fa and R134a (Park et al., 2018). For example, almost two thirds of the installed geothermal ORC plant capacity in Germany is based on these type of fluids (Eyerer et al., 2017). The other plants are operated with HC such as isopentane (R601a) and isobutane (R600a). The HFC fluids, however, have a significant GWP and thus a high environmental impact in the case of fluid leakage.

In recent years, a new generation of working fluids has been developed, combining the advantages of zero or near zero ODP and low GWP with similar thermodynamic properties as the traditional HFC working fluids (Liu et al. (2014); Braimakis et al. (2016)). From the classes of HFO and HCFO, possible low GWP alternatives for R245fa are R1233zd(E) and R1224yd(Z) (Molés et al., 2014), while R134a can possibly be replaced by the HFOs R1234yf or R1234ze (McLinden et al., 2014). The replacement possibility is supported by similar thermodynamic properties, non-toxicity, non- or mild flammability and similar thermal stability. In table 1, some relevant properties of currently dominating fluids and there potential alternatives are summarized. There, the major advantage of the modern HFO and HCFO fluids becomes obvious. While R245fa and R134a have GWP values of more than 1000, the novel fluids can reduce this value by three orders of magnitude.

Table 1: Properties of the investigated working fluids (ASHARE (2016); AGC Chemicals (2017); Solomon et al. (2016);Tokuhashi et al. (2018); Wallington et al. (2015))

	Fluid	GWP	ODP	Atmospheric life time (ALT)	ASHARE Safety Class
HFC (for comparison)	R245fa	1030	0	7.7 years	B1
	R134a	1430	0	13.4 years	A1
HCFO	R1233zd(E)	7	0.00024	26 days	A1
	R1224yd(Z)	<1	0.00012	21 days	A1
HFO	R1234yf	4	0	10.5 days	A2L
	R1234ze(E)	4	0	16.4 days	A2L

Due to the high GWP of the HFC fluids, recent legislative acts aim to reduce the production and consumption of these fluids. At an international level, the Kigali Amendment (United Nations, 2016) to the Montreal Protocol (United Nations, 1989) is the most relevant regulation, which will deliver a cut of 85% in the GWP-weighted quantity until 2036. On an European level, the F-Gas regulation (EU) 517/2014 (European Union, 2014) is the relevant framework for the reduction of high GWP fluids. Thereby, the F-Gas regulation follows a twofold approach to reduce fluorinated greenhouse gas emissions: First, by reducing the leakage from existing systems and second, by replacing high GWP fluids by cost-effective alternatives with less environmental impact.

Next to the common high-GWP working fluid R245fa and R134a, four low-GWP working fluids are compared within this work. These are the two HCFOs R1233zd(E) and R1224yd(Z) as well as the two HFOs R1234yf and R1234ze(E). Several studies investigated these working fluids as potential promising substitutes for high-GWP fluids.

In the case of R245fa alternatives, for example, Moles et al. (2016) compared the novel fluid R1233zd(E) with the HFC R245fa in a commercial ORC module. They varied the heat source temperature in the range of 140°C and 160°C and concluded that R1233zd(E) leads to a lower power output compared to R245fa due to the lower density of R1233zd(E). Datla and Brasz (2014) also investigated R1233zd(E) as a possible replacement for R245fa. They used an ORC system with a 75kW variable speed turbo-generator. From their experiments, they reported a 8.7% higher thermal efficiency when the system is operated with R1233zd(E) compared to R245fa. An increase in thermal efficiency has also been reported by Yang et al. (2018) when R1233zd(E) is used instead of R245fa. Besides R1233zd(E), the novel HCFO R1224yd(Z) has only recently become commercially available (AGC Chemicals, 2017). Before its commercialization, it has been investigated by Eyerer et al. (2019a) in order to prove the possibility of a drop-in replacement of R245fa. Therefore, the operation conditions of an 1 kW ORC test rig with a scroll expander have been varied in terms of working fluid mass-flow rate, condensation temperature and expander rotational speed. The heat source temperate was kept constant to a value of 120°C during all experiments. With this experimental campaign, the system performance was compared for R1224yd(Z), R1233zd(E) and R245fa. From this comparison, it can be stated that the highest power output is still obtained with the high-GWP fluid R245fa. The maximum power output with R245fa is 9% higher compared to R1233zd(E) and 12% higher compared to R1224yd(Z). In terms of thermal efficiency of the ORC system, R1233zd(E) leads to approximately 2% higher values compared to R245fa. In contrast to that, the thermal efficiency of R245fa and R1224yd(Z) is equal over a wide range of operation conditions.

The two R134a alternatives R1234yf and R1234ze(E) has for instance be investigated by Molés et al., (2017) in a numerical analysis. They modeled a standard ORC as well as a recuperative architecture and analyzed the cycle performance for each of the three fluids with various evaporating and condensing temperatures of 60–90°C and 10–40°C, respectively. They reported a higher power out with R1234ze(E) as working fluid compared to R134a for both architectures. However, R1234yf leads to both, lower power output and lower thermal efficiency compared to R134a. In another numerical study, Le et al., (2014) investigated the application of low-GWP fluids in supercritical ORCs with standard and regenerative architecture. They assumed 150°C as heat source temperature and a heat sink temperature of 15°C and compared eight different fluids, containing R134a, R1234yf and R1234ze(E). They found that R1234yf leads to the highest power output.

3. SIMULATION OF THE POWER PLANTS

A thermal water flow rate of 122 kg/s and a wellhead temperature of 138°C is assumed, which represents the average conditions of the existing commercial geothermal projects in Germany, which are mainly located in the South German Molasse Basin (Eyerer et al., 2019b; Schifflechner et al., 2019a). The chosen ambient temperature is 10°C, which represents the average German air temperature. For the analysis of the thermodynamic performance, a simple one-staged subcritical ORC is simulated with the software EBSILON Professional 14.0. The fluid properties are calculated with REFPROP 10.0 (Lemmon et al., 2018). An isentropic efficiency of 80% is assumed for the ORC turbine and the working fluid pump (Schifflechner et al., 2019b). The auxiliary power for the brine pump is 1.2 MW, representing the average power demand of the installed pumps in commercial geothermal projects in Germany (Eyerer et al., 2019b) . The assumed electricity demand of the fans for the air cooling is 0.15 kW per kg/s of air (Schlagermann, 2014).

Analogous to Eyerer et al. (2019b), the thermodynamic performance is assessed by the net system $\eta_{el,sys,net}$ and the net process efficiency $\eta_{el,process,net}$. The system efficiency is referring the electrical net power to the maximal available heat flow for the hypothetical case that the brine would be cooled down to environmental conditions, while the process efficiency only consider the actual heat flow, which is transferred towards the ORC plant.

$$\eta_{el,sys,net} = \frac{P_{el,net}}{\dot{Q}_{max}} = \frac{P_{el,gross} - P_{brine,pump} - P_{aux,PP}}{\dot{m}_{brine} \cdot (h_{in} - h_{ref})} \tag{1}$$

$$\eta_{el,process,net} = \frac{P_{el,net}}{\dot{Q}_{PP}} = \frac{P_{el,gross} - P_{brine,pump} - P_{aux,PP}}{\dot{m}_{brine} \cdot (h_{in} - h_{inj})} \tag{2}$$

Regarding the environmental impact caused directly by the investigated working fluids, the leakage rate and the recovery rate are the most important parameters. Yet, for both parameter, no exact values of existing geothermal plants are published. This work presumes a recovery rate of 90% as well as an annual leakage rate of 1%. According to the F-Gas regulation (EU) 517/2014 (European Union, 2014), an annual leakage of 1% is defined as the maximum leakage rate for systems with a charge of more than 100 kg. However, to investigate the impact of leakage rate on the results, a sensitivity analysis is carried out within a range of 0.5 and 2%/a. Furthermore, the assumed project lifetime and annual operational hours are 25 years and 7475 h/a respectively (Eyerer et al., 2019b). The functional unit is one kWh of net electricity. Table 2 summarizes the input parameter for the model.

Table 2: Summary of the model parameter

Parameter	Value
Brine temperature	138°C
Brine flow rate	122 kg/s
Annual leakage rate	1%
Recovery rate	90%
Annual full load hours	7474 h/a
Project lifetime	25 a
Assumed drilling depth per well	3910 m
Isentropic efficiency turbine	80%
Isentropic efficiency working fluid pump	80%
Auxiliary power brine pump	1.2 MW
Auxiliary power air condenser	0.15 kW per kg s^{-1} air flow
Functional unit	1 $kWh_{el,net}$

4. CALCULATION OF THE EXTERNAL COSTS

The analysis of the external costs follows the methodology described in Roth and Ambs (2004) and Pombo et al. (2016). The calculation of the equivalents per kWh net electricity for the different impact categories is based on the model presented in Heberle et al. (2016). In the next step, the derived equivalents are multiplied with the corresponding monetization factor, which indicated the caused costs of the different impact categories. Within this work, the West-European monetization factors from the Belgium research institute OVAM are used for the calculation of the external costs (OVAM, 2015). Since the monetarization factors are postulated for the year 2014, the annual inflation rates of the Euro zone are used for adjustment (Eurostat, 2019).

As seen in Table 3, there is a wide range between the lower and upper limit of the monetarization factors. For the monetarization factor of global warming, the upper limit is four times higher than the lower limit, while for the eutrophication it is even factor nine. This represents the high uncertainty concerning the monetarization factors for the different impact categories. Therefore, the monetarization factors are varied between the lower and upper limit within the sensitivity analysis.

Table 3: Monetarization factors for each impact category for the year 2014 (OVAM, 2015)

Environmental indicator	Unit	Highest probability [€/unit]	Lower limit [€/unit]	Upper limit [€/unit]
Global warming	kg $CO_{2\,eq}$	0.10	0.05	0.20
Depletion of the stratospheric ozone layer	kg CFC-11_{eq}	49.10	25.00	100.00
Acidification of land and water sources	kg $SO_{2\,eq}$	0.43	0.22	0.88
Eutrophication	kg $(PO_4)^3{}_{eq}$	20.00	6.60	60.00

5. RESULTS AND DISCUSSION

5.1 Thermodynamic results

Table 4 summarizes the obtained results for the different investigated working fluids. The analysis reveals that R134a has the highest net power and thus also the highest system efficiency. R1234yf leads to the second highest net power. Both working fluids, R134a and R1234yf, cause the highest cooling of the thermal water down to 53°C and 45°C respectively, while for all four other investigated working fluids lead to a reinjection temperature of at least 62°C. Based on the simulation results, R134a appears to be the most favorable working fluid. However, the high achievable net power comes along with high investment demand. This refers to the size of major components such as the turbine and heat exchangers (see Heberle et al. (2016)), since for R134a the transferred heat between the brine and working fluid as well at the condenser is around 30% higher than for R245fa. Therefore, the highest achievable net power has not necessarily the lowest Levelized Costs of Electricity (LCOEs). The net power of R245fa is only slightly higher than for its low-GWP alternatives R1233zd(E) and R1224yd(Z) (2.5% and 1.3%, respectively). While for R1233zd(E) the transferred amount of heat is 3.4% lower than with R245fa, the application of R1224yd(Z) results in 2.5% higher heat flow. The analysis of the process net efficiency reveals that for all working fluids, the efficiency is within a range of between 5.1 and 6.7%. Eyerer et al. (2017) present a model function for the net process efficiency based on the performance of the existing geothermal plants in Germany. For a wellhead temperature of 138°C, a net process efficiency of 4.9% is obtained, which is slightly lower than the simulation results. However, it must be considered that the applied simulation model focused on the optimization of the achievable net power and not on the economic performance. Thus, it is reasonable that slightly higher efficiencies are obtained than for real commercial projects.

Table 4: Results of the simulations

Working fluid	$\eta_{el,sys,net}$ [%]	$\eta_{el,process,net}$ [%]	P_{gross} [MW_{el}]	P_{net} [MW_{el}]
R245fa	3.60	6.60	4.23	2.36
R134a	4.04	6.61	4.92	2.65
R1233zd(E)	3.51	6.66	4.17	2.30
R1224yd(Z)	3.57	6.42	4.18	2.33
R1234yf	3.72	5.10	4.68	2.44
R1234ze(E)	3.68	5.64	4.42	2.42

5.2 Environmental impact and external costs

Figure 1 visualizes the results for the calculation of the external costs. Firstly, it highlights the significant difference between the high-GWP working fluids and the low-GWP working fluids. The external costs for the high-GWP refrigerants R245fa and R134a are 0.69 €ct/$kWh_{el,net}$ and 0.83 €ct/$kWh_{el,net}$, respectively. These external costs are around more than twice as high as for all four low-GWP refrigerants, which are in a range between 0.29 and 0.30 €ct/$kWh_{el,net}$. This highlights that the choice of high-GWP refrigerants such as R134a is despite its favorable thermodynamic performance not justifiable from environmental and social perspective. Even if the difference between the external costs for R134a and the low-GWP working fluids appears to be not so large for one kWh (0.54 €ct/$kWh_{el,net}$), the choice of a low-GWP working fluid saves external costs of more than 2 million € over the whole project lifetime. The lowest external costs are achieved with R1234yf, which can be mainly explained by the fact, that it achieves the highest net power of all investigated low-GWP working fluids (see Table 4). The analysis reveals also that the impact of the ODP of the HCFOs R1233zd(E) and R1224yd(Z) is not visible in the results, since the share caused by the ODP on the overall external costs is only 0.0002% for R1233zd(E). Thus, it can be concluded that the choice of a low-GWP working fluid with respect to minimal external costs depends not on the question if the ODP is slightly above zero or exactly zero, but rather on the thermodynamic performance of the working fluid for the planned application. Furthermore, the analysis of the external cost's compositions shows that most of the costs are caused by the CO_2 equivalent. The GWP of R134 causes around 0.58 €ct/$kWh_{el,net}$, even for the low-GWP fluids remain some base costs through global warming of around 0.22 €ct/$kWh_{el,net}$. These external costs are not caused by working fluid leakages, but are representing mainly the CO_2 emissions during the drilling and construction of the power plant. Thus, while the choice of a low-GWP refrigerant reduces despite the external costs significantly, but to reduce the external costs further both efficiency increases and improving the environmental impact of the drilling. In addition, the present analysis highlights that the geothermal power generation by ORC can compete with the external costs caused by other renewable energy sources such as wind and solar (European Commission, 2014).

The results of the sensitivity analysis for the annual leakage rate are summarized in Table 5. As expected, the leakage rate has a significant impact on the external costs for the high-GWP fluids, while for the low-GWP fluids the external costs increases only slightly. An assumed increase of the leakage rate from 0.5%/a to 2.0%/a result in a change of the external costs for R134a by 102% from 0.62 €ct/kWh to 1.25 €ct/kWh. For the low-GWP working fluids, the external costs per kWh increase by maximal 0.01 €ct/kWh when comparing an annual leakage rate 0.5%/a with 2.0%/a. Thus, it can be concluded that the assumed leakage rate has no significant impact when it comes to a comparison between low-GWP refrigerants.

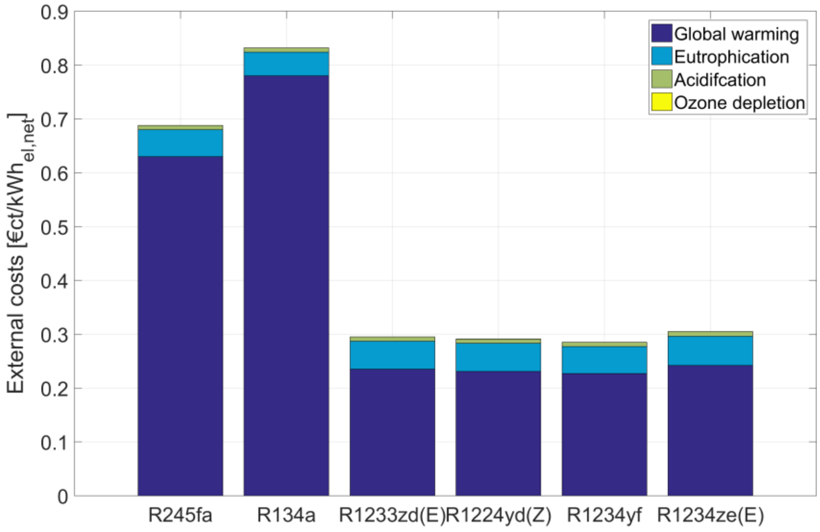

Figure 1: External costs of one kWh produced net electricity for the investigated working fluids.

Table 5: Sensitivity analysis of the annual leakage rate

	Annual leakage rate			
Working fluid	**0.5%/a**	**1.0%/a**	**1.5%/a**	**2.0%/a**
R245fa	0.54 €ct/kWh	0.69 €ct/kWh	0.84 €ct/kWh	0.98 €ct/kWh
R134a	0.62 €ct/kWh	0.83 €ct/kWh	1.04 €ct/kWh	1.25 €ct/kWh
R1233zd(E)	0.29 €ct/kWh	0.30 €ct/kWh	0.30 €ct/kWh	0.30 €ct/kWh
R1224yd(Z)	0.29 €ct/kWh	0.29 €ct/kWh	0.29 €ct/kWh	0.29 €ct/kWh
R1234yf	0.28 €ct/kWh	0.29 €ct/kWh	0.29 €ct/kWh	0.29 €ct/kWh
R1234ze(E)	0.29 €ct/kWh	0.30 €ct/kWh	0.30 €ct/kWh	0.30 €ct/kWh

As discussed in Section 4, the determination of the external costs for the different impact categories comes along with a high level of uncertainty (see Table 3). Thus, Figure 2 presents the obtained external costs for the assumed upper and lower monetarization factors for the investigated impact categories according to (OVAM, 2015). Since the external costs are dominated by the impact category global warming and the upper limit for the corresponding monetarization factor is four times higher than the lower limit, also the external costs are around four times higher calculated with the upper limit than for the lower limit. When a high monetarization factor is assumed for the costs caused by global warming, the impact of the working fluid's GWP increases significantly**.** Assuming the lower limit, the external costs for R134a are 0.24 €ct/kWh$_{el,net}$ higher than for the low-GWP refrigerants. In case of the upper limit for the monetarization factor, the difference increases up to 1.05 €ct/kWh$_{el,net}$. The higher the costs to be caused by global warming are assumed, the stronger the need for a rapid transition from geothermal ORCs to low-GWP refrigerants becomes. This refers not only to geothermal ORCs that will be built in the future, but also to the potential drop-in replacement of high-GWP working fluids, as discussed for example in Eyerer et al. (2019a) or Yang and Yeh, (2016).

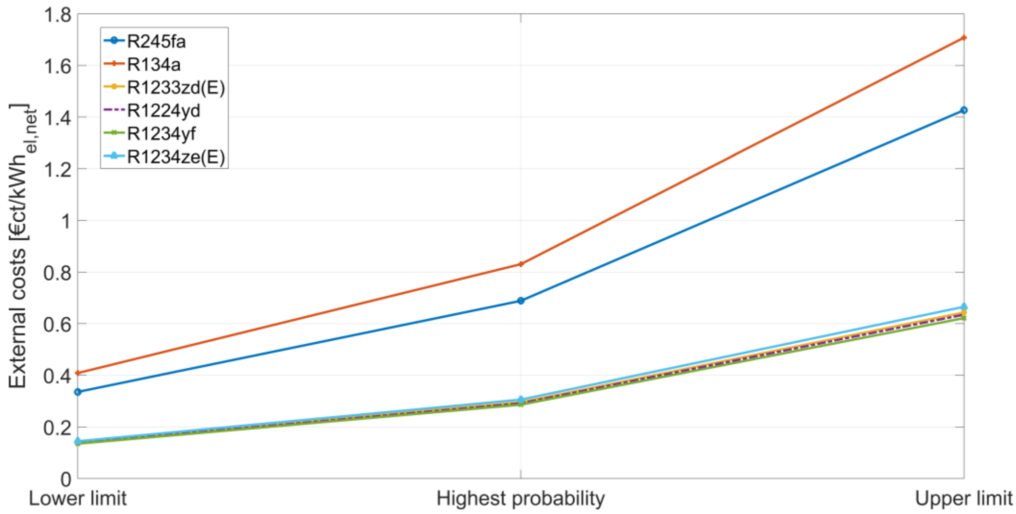

Figure 2: External costs of one kWh produced net electricity for different monetarization factors.

6. SUMMARY AND OUTLOOK

This study presents a detailed assessment of the external costs caused by power generation through geothermally driven ORCs with different working fluids. For the four investigated impact categories global warming, acidification, eutrophication, and ozone depletion, external costs between 0.16 €ct/kWh$_{el,net}$ and 1.7 ct/ kWh$_{el,net}$ are obtained. For the monetarization factors with the highest probability, the external costs caused by the high-GWP refrigerants R245fa and R134a are 0.69 €ct/kWh$_{el,net}$ and 0.83 €ct/kWh$_{el,net}$, respectively. All derived external costs for the investigated low-GWP working fluids are significantly lower and are in a range between 0.29 and 0.30 €ct/kWh$_{el,net}$. This proves, that the very small ODP by R1233zd(E) and R1224yd lead to no significant increase of the external costs. Thus, a general prohibition of potentially promising refrigerants with a very small ODP appears not be justifiable based on the presented results. Admittedly, in the present case study, the application of the zero ODP R1234yf would lead to even slightly lower external costs than for the R1233zd(E) and R1223yd. Thus, it might be concluded that HCFOs with an ODP slightly above zero are not necessary, sine lower external costs can be derived with zero ODP refrigerants. However, this generalizing conclusion is not justified due to several reasons. Firstly, the presented results are only valid for the investigated case study with an assumed brine temperature and brine flow rate of 138°C and 122 kg/s, respectively**.** Thus, the performance of the thermodynamic process with different low-GWP refrigerants could vary significantly for other geothermal conditions (e.g. brine temperature or CHP configuration) or even different fields of applications such as high temperature heat pumps**.** Secondly, in further analysis also the achievable LCOEs by geothermal power generation with the different working fluids should be taken into account. Since the external costs of the low-GWP working fluids varies only marginal, the potential tradeoff between the electricity price as well the caused external costs should be evaluated. As shown in Table 1, the atmospheric lifetimes of the HFOs and HCFOs are rather short. The present analysis proves that the ODP of the HCFOs would not cause any significant external costs, even if they would damage the ozone layer within their short atmospheric lifetime. However, the potential damage of the main decomposition products (mainly referring to hydrogen fluoride (HF) and Trifluoroacetic acid (TFA)) is also a critical ongoing discussion. The detailed literature review about the current state of knowledge on possible environmental influences of degradation products of HFO refrigerants by Goldberg and Burkholz (2017) comes to the conclusion, that the potential environmental damage by TFA is mostly classified as negligible and also HF appears to be no relevant issue. However, despite this conclusion an enhanced incorporation of the possible external costs caused by the degradation products should be considered in further studies. In summary, this work presents an important contribution for the discussion about the advantages and drawbacks of HFOs and HCFOs in geothermally driven ORCs. Based on the presented methodology, a future advancement referring to the model's level of detail, more investigated refrigerants as well as different field of applications (e.g. high temperature heat pumps) might allow a general statement about the advantages and drawbacks of a fourth generation of refrigerants.

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NOMENCLATURE

Abbreviations	
GWP	Global Warming Potential
HC	Hydrocarbons
HCFO	Hydrochlorofluoroolefines
HF	Hydrogen fluoride
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefines
LCA	Life Cycle Assessment
LCOE	Levelized Costs of Electricity
ODP	Ozone Depletion Potential
ORC	Organic Rankine Cycle
ODP	Ozone Depletion Potential
TFA	Trifluoroacetic acid
Symbol	
h	Enthalpy
P	Electrical power
$\dot{m}$	Mass flow
$\dot{Q}$	Heat flow
η	Thermal efficiency
Subscript	
el,gross	Electrical gross power
el,net	Electrical net power
eq	Equivalent
inj	Injection
max	Maximal
PP	Power plant
ref	Reference conditions

REFERENCES

AGC Chemicals, 2017. AMOLEA TM 1224yd, Technical information. https://www.agc-chemicals.com/jp/en/products/detail/index.html?pCode=JP-EN-G016. Accessed 28 July 2019.

ASHARE, 2016. ASHRAE Standard 34 2016: Designation and Safety Classification of Refrigerants.

Bayer, P., Rybach, L., Blum, P., Brauchler, R., 2013. Review on life cycle environmental effects of geothermal power generation. Renewable and Sustainable Energy Reviews 26, 446–463.

Braimakis, K., Roumpedakis, T., Leontaritis A., Karellas, S., 2016. Comparison of environmentally friendly working fluids for organic Rankine cycles. In: Minea A., editor. Advances in new heat transfer fluids: from numerical to experimental techniques. Boca Raton: CRC Press; p. 377–426.

Calm, J.M., 2008. The next generation of refrigerants – Historical review, considerations, and outlook. International Journal of Refrigeration 31, 1123–1133. 10.1016/j.ijrefrig.2008.01.013.

Ciconkov, R., 2018. Refrigerants: There is still no vision for sustainable solutions. International Journal of Refrigeration 86, 441–448. 10.1016/j.ijrefrig.2017.12.006.

Datla, B.V., Brasz, J.J., 2014. Comparing R1233zd and R245fa for low temperature ORC applications. 15th International Refrigeration and Air Conditioning Conference.

European Commission, 2014. Subsidies and costs of EU energy - Final report.

European Commission, 2017. Evaluation of the Ozone Regulation - Feedback from: German Environment Agency. https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2017-3562786/feedback/F6584_en?p_id=35878. Accessed 7 June 2019.

European Union, 2014. The European Parliament and the Council of the European Union, Regulation (EU) No 517/2014 of the European Parliament and the Council of the European Union of 16 April 2014 on Fluorinated Greenhouse Gases and Repealing Regulation (EC) No 842/2006.

Eurostat, 2019. Harmonised Indices of Consumer Prices (HICPs) - Annual average rate of change (%). https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tec00118&plugin=1. Accessed 18 July 2019.

Eyerer, S., Schifflechner, C., Hofbauer, S., Wieland, C., et al., 2017. Potential der hydrothermalen Geothermie zur Stromerzeugung in Deutschland. Technical report., Geothermie Allianz Bayern & Lehrstuhl für Energiesysteme. https://mediatum.ub.tum.de/1360572.

Eyerer, S., Dawo, F., Kaindl, J., Wieland, C., Spliethoff, H., 2019a. Experimental investigation of modern ORC working fluids R1224yd (Z) and R1233zd (E) as replacements for R245fa. Applied Energy 240, 946–963.

Eyerer, S., Schifflechner, C., Hofbauer, S., Bauer, W., Wieland, C., Spliethoff, H., 2019b. Combined heat and power from hydrothermal geothermal resources in Germany: An assessment of the potential. Submitted to Renewable & Sustainable Energy Reviews.

Eyre, N., 1997. External costs: What do they mean for energy policy? Energy Policy 25, 85–95.

Goldberg, M., Burkholz, T., 2017. Literaturrecherche und Bewertung des aktuellen Wissenstandes zu möglichen Umwelteinflüssen von Abbauprodukten von HFO-Kältemitteln. Institut für Luft- und Kältetechnik.

Heberle, F., Schifflechner, C., Brüggemann, D., 2016. Life cycle assessment of Organic Rankine Cycles for geothermal power generation considering low GWP working fluids. Geothermics 64, 392–400. 10.1016/j.geothermics.2016.06.010.

Le, L., Feidt, M., Kheiri, A., Pelloux-Prayer, S., 2014. Performance optimization of low-temperature power generation by supercritical ORCs (organic Rankine cycles) using low GWP (global warming potential) working fluids. Energy 67, 513–526. 10.1016/j.energy.2013.12.027.

Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O., 2018. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology. 2018. URL http://www. nist. gov/srd/nist23. cfm.

Liu, W., Meinel, D., Wieland, C., Spliethoff, H., 2014. Investigation of hydrofluoroolefins as potential working fluids in organic Rankine cycle for geothermal power generation. Energy 67, 106–116. 10.1016/j.energy.2013.11.081.

Martín-Gamboa, M., Iribarren, D., Dufour, J., 2015. On the environmental suitability of high- and low-enthalpy geothermal systems. Geothermics 53, 27–37. 10.1016/j.geothermics.2014.03.012.

McLinden, M.O., Kazakov, A.F., Brown, J.S., Domanski, P.A., 2014. A thermodynamic analysis of refrigerants: Possibilities and tradeoffs for Low-GWP refrigerants. International Journal of Refrigeration 38, 80–92.

Moles, F., Navarro-Esbr\'\in, Peris, B., Mota-Babiloni, A., 2016. Experimental evaluation of HCFO-1233zd-E as HFC-245fa replacement in an Organic Rankine Cycle system for low temperature heat sources. Applied Thermal Engineering 98, 954–961.

Molés, F., Navarro-Esbr\'\in, Peris, B., Mota-Babiloni, A., Barragán-Cervera, Á., Kontomaris, K.K., 2014. Low GWP alternatives to HFC-245fa in Organic Rankine Cycles for low temperature heat recovery: HCFO-1233zd-E and HFO-1336mzz-Z. Applied Thermal Engineering 71, 204–212.

Molés, F., Navarro-Esbrí, J., Peris, B., Mota-Babiloni, A., Mateu-Royo, C., 2017. R1234yf and R1234ze as alternatives to R134a in Organic Rankine Cycles for low temperature heat sources. Energy Procedia 142, 1192–1198. 10.1016/j.egypro.2017.12.380.

OVAM, 2015. Annex: Update monetisation of the MMG method (2014). The Public Waste Agency of Flanders.

Park, B.-S., Usman, M., Imran, M., Pesyridis, A., 2018. Review of Organic Rankine Cycle experimental data trends. Energy conversion and management 173, 679–691.

Pombo, O., Allacker, K., Rivela, B., Neila, J., 2016. A multi-criteria approach for the assessment of housing renovation strategies. Expanding Boundaries: Systems Thinking in the Built Environment, 328–333.

Resch, G., Held, A., Faber, T., Panzer, C., Toro, F., Haas, R., 2008. Potentials and prospects for renewable energies at global scale. Energy Policy 36, 4048–4056. 10.1016/j.enpol.2008.06.029.

Roth, I.F., Ambs, L.L., 2004. Incorporating externalities into a full cost approach to electric power generation life-cycle costing. Energy 29, 2125–2144.

Schifflechner, C., Eyerer, S., Alonso Alvarez, P., Wieland, C., Spliethoff, H., 2019a. Evaluating the South German Molasse Basin's geothermal potential by means of the UNFC 2009 Classification. European Geothermal Congress 2019, Den Haag, Netherlands.

Schifflechner, C., Dawo, F., Eyerer, S., Wieland, C., Spliethoff, H., 2019b. Combined Heat and Power Generation by Enhanced Geothermal Systems: Comparison of direct and indirect concepts for water and supercritical CO2 as heat carriers. 5th International Seminar on ORC Power Systems, Athens, Greece.
Schlagermann, P., 2014. Exergoökonomische Analyse geothermischer Strombereitstellung am Beispiel des Oberrheingrabens. PhD thesis, TU Munich.
Solomon, K.R., Velders, G.J.M., Wilson, S.R., Madronich, S., Longstreth, J., Aucamp, P.J., Bornman, J.F., 2016. Sources, fates, toxicity, and risks of trifluoroacetic acid and its salts: Relevance to substances regulated under the Montreal and Kyoto Protocols. Journal of Toxicology and Environmental Health, Part B 19, 289–304.
Tokuhashi, K., Uchimaru, T., Takizawa, K., Kondo, S., 2018. Rate Constants for the Reactions of OH Radical with the (E)/(Z) Isomers of CF3CF═ CHCl and CHF2CF═ CHCl. The Journal of Physical Chemistry A 122, 3120–3127.
United Nations, 1989. Ozone Secretariat United Nations Environment Program, The Montreal Protocol on Substances that Deplete the Ozone Layer.
United Nations, 2016. Ozone Secretariat United Nations Environment Program, Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer.
Voss, A., 2001. LCA and external costs in comparative assessment of electricity chains: Decision support for sustainable electricity provision? IEA Conference Energy Policy and Externalities: The Life Cycle Analysis Approach, Paris, 15.-16. November 2001
Wallington, T.J., Andersen, M.S., Nielsen, O.J., 2015. Atmospheric chemistry of short-chain haloolefins: Photochemical ozone creation potentials (POCPs), global warming potentials (GWPs), and ozone depletion potentials (ODPs). Chemosphere 129, 135–141.
Yang, J., Sun, Z., Yu, B., Chen, J., 2018. Experimental comparison and optimization guidance of R1233zd(E) as a drop-in replacement to R245fa for organic Rankine cycle application. Applied Thermal Engineering 141, 10–19.
Yang, M.-H., Yeh, R.-H., 2016. Economic performances optimization of an organic Rankine cycle system with lower global warming potential working fluids in geothermal application. Renewable Energy 85, 1201–1213. 10.1016/j.renene.2015.07.067.