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Proceedings of the 7th International Seminar on ORC Power Systems

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Potential for surplus-heat-to-power conversion in current and future aluminium production process with off-gas recycling

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ABSTRACT

Increased utilization of industrial surplus heat can make significant contributions towards reaching energy efficiency and emissions reduction goals. The off-gas from metal production smelters can contain large amounts of thermal energy, and conversion to electric power often appears an enticing prospect. However, the practical potential for exploitation can be significantly reduced from plant processes that are designed considering surplus heat as a waste product to get rid of. This typically makes the heat accessible only at reduced temperatures.

The HighEFF research centre for industrial energy efficiency has studied technologies, applications, and cases for surplus heat utilization since its start in 2016. Heat-to-power conversion has been explored in several cases provided by the partner industries from – among others – Norwegian aluminium manufacturers. Centre research activities also include novel production processes and modifications, which has side effects providing very different conditions and constraints for energy recovery. One such process modification is off-gas recirculation, mainly developed to increase concentration of CO_2 in the off-gas to improve conditions for CO_2 capture in the future, but which also will alter off-gas temperature and recoverable heat as a side effect. This could improve the potential for energy recovery.

In this work, the potential for energy recovery is evaluated and compared in four cases – one representing a current aluminium process, and three future process scenarios with flue gas recycling. The simulated heat-to-power conversion is done by applying an organic Rankine cycle (ORC) optimization model to each case. The results indicate significant benefits to energy recovery in the recycling cases. In the case with the highest recycling rate and flue gas temperature, the potential for electric power production increases by 270 % compared to the present-day case. In addition, the reduced work of the main exhaust fans in the recycling cases brings further energy savings on the system level equivalent to 25–50 % of the ORC power output, further increasing overall energy efficiency. From this, some potential synergies between process design, heat-to-power, and thermal integration of other technologies such as CO_2-capture are discussed.

1 INTRODUCTION

Waste heat recovery from industry processes has the potential to save vast amounts of energy globally. Primary metal production industries are promising targets for such heat recovery, as they create large amounts of high-temperature off-gas among other waste heat sources. However, this off-gas is commonly not easily managed, and is usually treated purely as a waste product. In Norway, aluminium production makes up the largest part of the metal industry, certainly in terms of energy use and waste heat. The largest plants can reject around one TWh/y of waste heat through the off-gas alone, which is so far not utilized to any significant extent. One problem is the relatively low temperature. Despite the electrolysis process operating at around 1000 °C, excessive draft air into the cell dilutes the produced off-gas to a temperature in the range of 150 °C, which considerably reduces thermodynamic potential and usability. The gas also contains various components and contaminants, and it can likely be cooled down to 80-90 °C without causing issues with condensation or downstream gas treatment. So not only is the temperature fairly low, only parts of the thermal energy in the off-gas is recoverable.

HighEFF is a Norwegian Centre for Environment-friendly Energy Research (FME), on the topic of industrial energy efficiency. Norwegian metal production consumes around 25% of the national electric power production, and with strong interest in process improvements and efficiency, the largest industrial companies are all partners in HighEFF. The research of HighEFF has explored both incremental improvements of current and existing processes, as well as evaluation of new, alternative processes. Several measures are needed to take metal production into the low-emission future. One potential step on this way is to recycle flue gas, replacing draft air going into the smelter process. Off-gas recycling promises to increase both energy efficiency and CO_2 concentration to improve conditions for CO_2 capture. This is relevant for several different smelting processes. One off-gas recycling concept for aluminium plants has been patented by GE (Wedde, 2011), and is currently being deployed in an industrial demonstrator. HighEFF research (Solheim and Senanu, 2020) studied the relations between recirculation and draft air rates on gas composition, energy balance, and other important aspects connected to such a concept.

The recycled off-gas must be cooled down before re-entry to the electrolysis cell, to control the heat balance. This cooling could be used for a waste heat recovery system rather than a plain heat sink, and since the latter would be needed anyways, the additional cost to the off-gas recycling loop may not be excessive. Solheim and Senanu (2020) predicted that off-gas recycling can increase the temperature of the off-gas, potentially improving the conditions for heat recovery for power production. In this paper, we study how the potential for surplus heat to power conversion may change as the core process evolve, when the process has been adapted for CO_2 capture by implementation of flue gas recycling.

The organic Rankine cycle is an attractive heat-to-power conversion method in waste heat recovery, due to its relatively low temperature requirement, and to its high efficiency and mature technology. Natural working fluids such as hydrocarbons are attractive to consider for several reasons, such as environmentally safety, long-term predictability, performance, and cost. **606**

Several approaches to heat recovery in aluminium electrolysis have been studied previously. Li et al. (2023) have performed a review on different types of waste generated by this process, including surplus heat. Barzi et al. (2018) have designed an ORC system recovering heat from the side walls of the cell, rather than the off-gas. Here, the temperature is higher, but the amount of heat is lower than in the off-gas (Li et al., 2023). Zhao et al. (2016) have performed a detailed exergy analysis of the aluminium production, mapping out the size of exergy losses throughout the process. The study highlights several potential targets for increasing the energy efficiency of aluminium production, not only in the electrolysis. However, the electrolysis process is the most energy intensive, and from this process the off-gas is the main sink for surplus heat.

Power generation from surplus heat in aluminium electrolysis smelters has been studied extensively (Ladam et al., 2016; Nosek et al., 2017). Yet, to the best of our knowledge, previous heat-to-power studies do not consider how core process improvements may affect the off-gas as a heat source. The potential changes in chemical and thermodynamical off-gas conditions have been studied, however, for the introduction of off-gas recycling. Senanu et al. (2022) have studied the amount of CO, HF and SO_2 in recycled aluminium off-gas. The off-gas composition is important to engineering, both for health, safety, and environment reasons, as well as for equipment wear. For example, SO_2 can form sulphuric acid which harms machinery. Therefore, Solheim (2022) has estimated the sulfuric acid dew point in aluminium off-gas. This imposes a lower threshold on the off-gas temperature, which is crucial for heat recovery applications.

Given this background, the scope of this current work is to estimate the potential energy savings from surplus heat-to-power in aluminium production with off-gas recycling. Heat source conditions are calculated from the off-gas properties identified by Solheim and Senanu (2020). Based on these heat source conditions and component constraints, two different ORC layouts are optimized for maximum power production.

2 METHOD

The simulations performed in the scope of this work consist of two steps: First, the boundary conditions for the waste heat recovery (WHR) system are determined. This is done for all three cases representing potential future off-gas recycling scenarios. Then, an organic Rankine cycle is optimized for each case, considering selected cycle layout and working fluid options.

2.1 Determination of boundary conditions

The model of the recirculation loop consists of two main components: The aluminium electrolysis cell and the WHR heat exchanger. This heat exchanger is connected downstream of the cell, so that all the off-gas from the cell is fed through it. Then, most of the off-gas is routed in a loop back into the cell, while a small portion is sent out of the loop to the gas treatment center (GTC) for filtration.

In practice, fresh air is drawn passively into the cell due to underpressure. The flow rate is mainly determined by how air-tight the cell can be constructed. In our model, we assume that draft air is drawn into the cell at a rate that gives a fixed CO_2 concentration of 10 % in the off-gas, by volume. The baseline case has a CO_2 concentration of 1 %, as given by Solheim and Senanu (2020).

After heat recovery, a small portion of the extracted off-gas is diverted to gas treatment while the rest is reintroduced to the cell. The flow rate going to gas treatment corresponds to the flow rate of draft air, plus the gas that is generated from the electrolysis process. The concept is sketched in Figure 1.

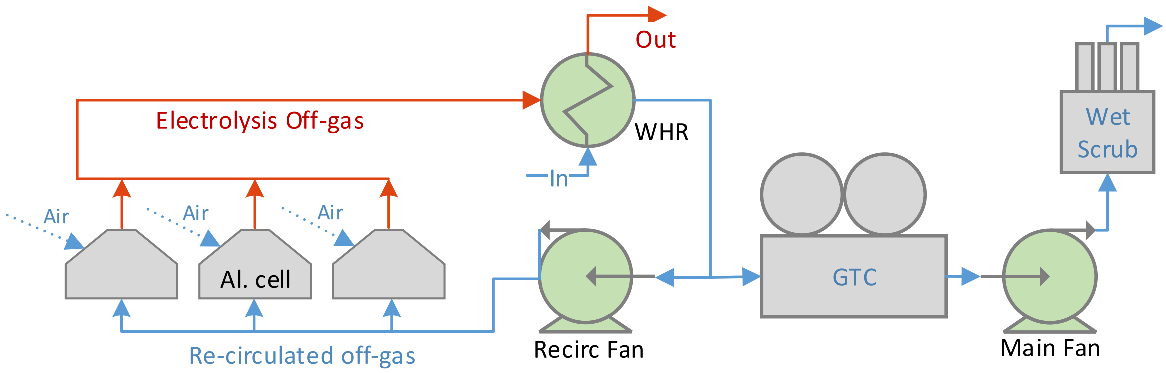

Figure 1: An illustration of the production cycle, including the off-gas recycling loop, the waste heat recovery heat exchanger and the gas treatment centre.

The case conditions are calculated based on a generic and simplified aluminium production gas system, representing a cluster of modern Hall-Héroult (Haupin and Frank, 1981) electrolysis cells, with conditions as described by Solheim and Senanu (2020). In the base case (no recirculation), the system uses 100 000 Nm^3/h draft air, and produces off-gas at 150 °C and a volumetric CO_2 content of 1 %. Other gaseous compounds produced in the cell are not considered. The baseline case is calculated for these conditions, and assuming the gas is cooled to 80 °C in the WHR before gas treatment. The case specifications that are used to compute the ORC boundary conditions are presented in Table 1.

In the cases with recirculation, the gas flowing into the cell is a mixture of the cooled off-gas at 80 °C and fresh draft air at 10 °C. The gases are assumed to be perfectly mixed, so that the temperature and composition are homogeneous inside the cell. The temperature of the off-gas going into the WHR heat exchanger is directly linked to the recirculation flow rate through the heat balance. This again determines the ratio between air and off-gas at the cell inlet. We assume further that the heat transferred to the off-gas from the cell is proportional to the temperature difference between the gas mixture in the

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cell and the cell bath temperature. The cell bath is assumed to hold 975 °C. In the case definitions, we specify the off-gas temperature as it leaves the cell. From this, the total flow rate is then determined.

The total off-gas pressure loss from the cell to the stack (including GTC and wet scrubber), is assumed to be 5000 Pa, independent of flow rate. In other words, the pressure loss remains unchanged also in recycling cases with very reduced gas flow in this part of the system, and calculated fan work savings could therefore be considered conservative estimates. Note that the electrolysis cell produces aluminium and CO_2 at a constant rate. Hence, since the concentration of CO_2 is fixed at 10 %, the mass flow to the GTC must be the same in all recycled cases. Thus, the saved fan work at the GTC will be identical for these cases.

Table 1: Case specifications for the off-gas.

Case name	**Baseline** *150-80*	**Recirc 1** *150-80*	**Recirc 2** *200-80*	**Recirc 3** *250-80*	**Unit**
T_{in}	150.0	150.0	200.0	250.0	°C
T_{out}	80.0	80.0	80.0	80.0	°C
Total pressure drop	5.0	5.0	5.0	5.0	kPa
CO_2 content	1	10	10	10	%

2.2 Cycle optimization

Consider now the ORC cycle. A generic organic Rankine cycle is defined within a simulation and optimization framework for thermodynamic cycles, previously described by Skaugen et al. (2015). Here, the gradient-based optimization algorithm NLPQL (Schittkowski, 1986) is used to identify the optimal operating conditions for the ORC. The objective function of the optimizer is maximum net power, defined as the electrical power output of the turbine generator, when the pump and fan power demand are subtracted. Two cycle configurations are considered, one with an internal recuperator and one without. These are illustrated in Figure 2. Note that the evaporators in these cycles are same as the WHR heat exchanger from Figure 1. 608

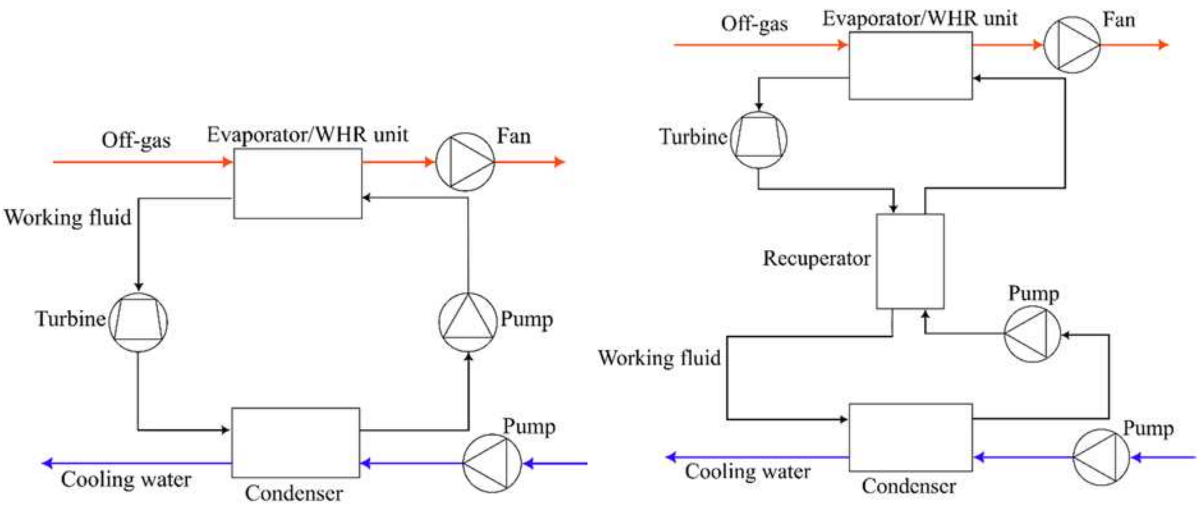

Figure 2: The modelled cycle configurations, with the simple cycle on the left and the recuperated cycle on the right.

The operating conditions of the cycle are defined by the flow rates of each fluid, as well as their pressure and temperature levels between each component. Each case definition fully specifies these for the off-gas. For the heat sink, constant temperatures and ambient inlet pressure is assumed. This leaves four degrees of freedom for the optimizer in the recuperated cycle, and three in the simple cycle. The remaining variables follow from component specifications. Table 2 shows these variables for the heat exchangers, along with an overview of specified or calculated temperatures. In addition to these specifications, the pressure level at the expander inlet is limited to a maximum of 50 bar.

Table 2: Specifications for the heat exchangers in the model.

Specification	**Evaporator**	**Recuperator**	**Condenser**	**Unit**
Cold fluid pressure drop	100	50	100	kPa
Hot fluid pressure drop	1	7.5	1	kPa
Cold fluid inlet temperature	*calc*	*calc*	10	°C
Cold fluid outlet temperature	*calc*	*calc*	20	°C
Hot fluid inlet temperature	150-250	*calc*	*calc*	°C
Hot fluid outlet temperature	80	*calc*	*calc*	°C
Minimum temperature difference	20	10	5	K

The heat exchangers are modelled with a lower limit on the minimum temperature difference between its two fluids. This temperature difference is estimated by discretizing over the transferred heat, assuming a linear pressure drop distribution. Both pumps, as well as the off-gas fan and the expander are modelled assuming isentropic processes corrected by an isentropic efficiency, set to 0.85 for the expander and 0.75 for the rest. The power consumption or production of these components is calculated using a motor/generator efficiency of 0.95.

We assume constant pressure losses over the heat exchangers in the optimization model. This is less realistic than a detailed pressure drop model over each individual component but preferred to ignoring pressure drop entirely. The efficiency of working fluids with low operating pressures could be severely overestimated if pressure drop is fully neglected.

For the working fluid, several hydrocarbons are considered, based on working fluid screenings for ORCs with similar temperature conditions (Bahrami et al., 2022; Yu et al., 2016). Previous work by Andresen and Hagen (2022) suggests that natural and artificial working fluids perform equally well for waste heat-to-power applications. Therefore, and because the exploration of natural working fluids is a focus of the HighEFF research centre, only natural working fluids have been included. To further narrow down the list, fluid performance in Agromayor and Nord's (2017) study on a comparable but general heat source has been considered. In the end, five working fluids were used in the ORC simulation, spanning critical temperatures from 91.1 to 152.0 °C, as listed in Table 3. While exploring five working fluids is preferable to one, this work is not intended to be an exhaustive working fluid screening. The thermophysical library REFPROP (Lemmon et al., 2013) is used to obtain the properties of these fluids, as well as for the cooling water, and for each component of the off-gas.

Table 3: The working fluids included in this study, with their critical temperature, pressure, and condensation pressure at minimum cycle temperature (15 °C).

Fluid	T_{crit} **[°C]**	P_{crit} **[bar]**	P_{cond} **[bar]**
Propylene	91.1	45.6	10.17
Propane	96.7	42.5	8.36
Isobutane	134.7	36.3	3.02
Butene	146.1	40.1	2.55
Butane	152.0	38.0	2.08

3 RESULTS

The two parts of this work – determining boundary conditions for the off-gas loop and optimizing the ORC under these boundary conditions – are presented in turn in this section.

3.1 Gas flow and heat source calculations

As described in section 2, four aluminium production off-gas scenarios have been defined. One represents the current production processes, and three represent possible future processes with off-gas recycling implemented. In this section, we describe each of the cases, with the cycle boundary conditions computed from the work of Solheim and Senanu (2020).

The baseline case, corresponding to the current state of aluminium manufacturing, is defined with the conditions presented in section 2.1, with the off-gas cooled to 80 °C before the GTC. For the three future cases, a CO_2 concentration of 10 % is assumed, along with off-gas temperatures of 150 °C, 200 °C, and 250 °C. As described, the mass flows follow from these assumptions. Table 4 shows the specifications for each case, together with resulting off-gas flow rate, the recoverable heat, the exergy content in this heat, and the estimated reduction in fan work for the GTC. Recycling the off-gas significantly increases the amount of heat available for recovery, while higher off-gas temperatures increase the exergy content of this heat while reducing the flow rate.

Table 4: Specification of conditions for the heat recovery heat exchanger, including temperatures (T), mass flows, available heat (Q) and exergy (E) for capture, as well as the impact on system fan work compared to the baseline case.

Case name	**Baseline** *150-80*	**Recirc 1** *150-80*	**Recirc 2** *200-80*	**Recirc 3** *250-80*	**Unit**
Mass flow rate	35.76	65.47	36.97	25.23	kg/s
Q_{WHR}	2534.8	4591.6	4471.7	4350.1	kW
E_{WHR}	680.7	1233.0	1385.2	1502.8	kW
Relative E_{WHR}	0.269	0.269	0.31	0.345	-
Diff. fan work (GTC)	0	-202.8	-202.8	-202.8	kW

3.2 Cycle optimization

This section presents the result of the second part of the study, namely the ORC optimization. Using the ORC model with input from the case specifications above, the cases and the working fluids have been compared. This section presents the performance of the ORC, for each case and working fluid.

Figure 3 shows the net power performance of the ORC for each case and fluid. The performance is the electrical power output of the turbine generator, subtracted the power consumption of working fluid and cooling water pumps and recirculation fan, as illustrated in Figure 2. Similarly, Figure 4 below shows the thermal efficiency of the cycles for each working fluid and case, taken as the net power production of the ORC cycle divided by the available recoverable heat in the off-gas in each case.

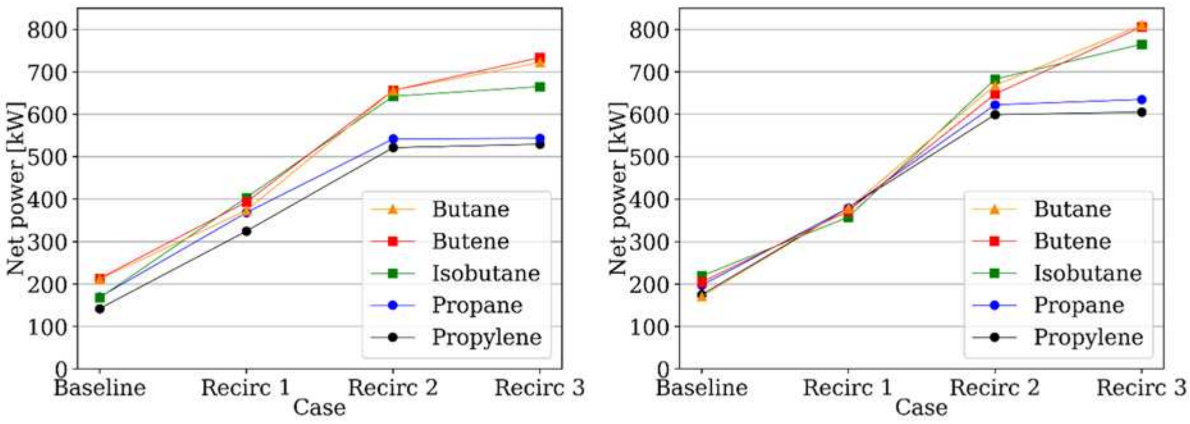

Figure 3: The net power produced by the WHR unit, for each of the four cases. The left figure shows the simple cycle, and the rightmost figure shows the recuperated cycle.

The cycle simulations indicate a significant increase in potential power output of an ORC with off-gas recycling implemented. This is as expected, as both the temperature and available energy in the off-gas is shown to increase. The simulations of the high-temperature off-gas recycling cases can reach more than three times the net power output of the baseline case.

Working fluid choice has significant impact, but mainly in the highest temperature cases. In the recirc 3 case, the maximum turbine pressure of 50 bar limits the power output for all fluids. This occurs for propane and propylene also in the recirc 2 case, which is why there is little change between the two cases for these. In the lower temperature cases, the differences are smaller – especially in the recuperated cycle. Recuperated cycles generally perform better for the explored fluids, with the exception of case Recirc 1. Here, the non-recuperated cycle with Isobutane performs slightly better. This is likely due to a very small benefit from recuperation at the lowest heat source temperature being overcome by the negative effect of additional pressure drops reducing turbine power. For a practical implementation of waste heat-to-power with an ORC in any of these cases, a full working fluid screening would be required.

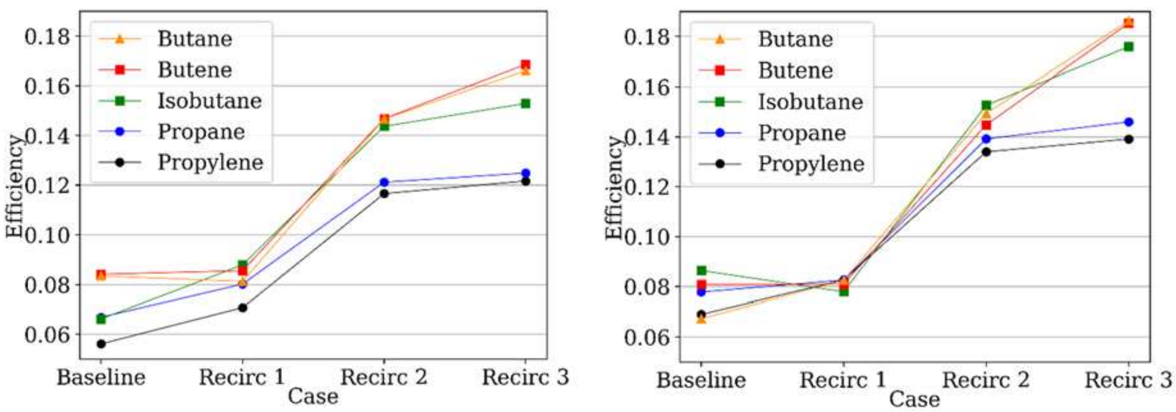

Figure 4: Thermal efficiency of the WHR unit, for each of the four cases. The left figure shows the simple cycle, and the rightmost figure shows the recuperated cycle.

Due to the severely reduced downstream (GTC) flow rates, as well as a high baseline pressure drop, the additional benefit of reduced fan work is considerable compared to the ORC net power. Note that this improvement comes in addition to the indicated threefold increase in power output potential from the present-day case to the recycling cases. This effect is independent of heat-to-power production but is another significant energy efficiency benefit of this concept.

Table 5 compares the best performing cycle ORC for each case. System power savings are included, taken as the net power production of the ORC with the difference in fan work in the GTC from Table 4 included. Each result uses the working fluid and layout with the highest net power output for each case. There are two main contributors to the increased power potential: The increased amount of recoverable heat caused by the off-gas recirculation, and the increased thermal efficiency when the off-gas temperature (and exergy content) increases.

Solheim and Senanu (2020) have also indicated an energy consumption for the electrolysis cell. Using these numbers, we can compare the ORC power output with the overall "plant" consumption. At 400 kA, and 4.05 V per 10 000 Nm^3/h draught air, the production system in this study consumes 16 200 kW electric energy for the electrolysis. The ORC recovers 6.3 % of this consumed energy in the best case, compared to 1.4 % in the baseline case, which is significant considering the huge scale of energy consumption required for aluminium production.

The respective impact of these contributions can be seen in the bottom part of Table 5, where their values relative to the base case are shown. It can be observed that the relative net power is a product of the relative values of recoverable heat and ORC thermal efficiency. Therefore, these values indicate the relative contribution of difference in heat quantity (Q_{WHR}) and heat quality (resulting in higher cycle thermal efficiency) to the relative net power for the different cases.

Table 5: Breakdown of cycle performance for each case.

	Base	**Recirc 1**	**Recirc 2**	**Recirc 3**	**Unit**
Best performing cycle option	Isobutane Recuperated	Isobutane Simple	Isobutane Recuperated	Butane Recuperated	-
Gross power output	297.8	540.7	862.9	961.7	kW
Recirculation fan work	-50.4[1]	-88.2	-49.8	-34.0	kW
Working fluid pump work	-21.0	-35.3	-118.4	-106.0	kW
Cooling water pump work	-7.4	-13.3	-12.1	-11.3	kW
Net power output	219.0	403.9	682.6	810.4	kW
Recoverable heat (Q_{WHR})	2534.8	4591.6	4471.7	4350.1	kW
ORC thermal efficiency	0.086	0.088	0.153	0.186	-
Reduction in main fan work	0	202.8	202.8	202.8	kW
System power savings	219	606.7	885.4	1013.2	kW
System power savings relative to electrolysis process	1.4	3.7	5.5	6.3	%
		Relative to base case			
Net power	1	1.84	3.12	3.70	-
Recoverable heat (Q_{WHR})	1	1.81	1.76	1.72	-
ORC thermal efficiency	1	1.02	1.77	2.16	-
System power savings	1	2.77	4.04	4.63	-

[1] For the base case, this value indicates additional *main* fan work incurred by pressure drop in the WHR

4 CONCLUSIONS

Building on previous work on off-gas recycling in aluminium production cells, boundary conditions for a heat-to-power system using the off-gas as a heat source have been defined. Then, an organic Rankine cycle has been optimized for these boundary conditions. A total of four cases were explored – one baseline case corresponding to the current standard aluminium production processes, and three cases with flue gas recycling. An ORC with and without a recuperator has been optimized for each case, and five different working fluids have been explored.

The results show a very significant increase in potential power output for off-gas recycling cases. For the cases with highest recirculation rates and heat source temperatures, the calculated power output increases more than threefold. Additionally, with off-gas recycling, power is saved due to a lower off-gas flow rate to gas treatment, and thus a reduced need for fan work. This reduction in main extraction fan work was equivalent to 25–50 % of the ORC net power, in other words a significant contribution to the overall system benefit. This strongly indicates that future aluminium production processes could have conditions that enable high-performance and competitive ORC integrations, even though heat-to-power is not the main motivation for implementing off-gas recycling in such processes.

This study leaves some possible paths for future work. An extension of this study to other processes where flue gas recycling is considered could provide further insight into the future of heat-to-power as a method of increasing energy efficiency – both in Norwegian and international metallurgical industry. Also, this work highlights that further research and industrial endeavours to implement off-gas recycling in aluminium production is useful also in terms of energy efficiency. Techno-economical assessments may also help refine optimal boundary conditions and system specifications.

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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