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Abstract
A key step towards higher energy efficiency in the industry is the capture, conversion and utilization of surplus heat. To be able to determine which heat recovery technology is optimal for a given application, a set of design criteria are needed. In this memo, design criteria are discussed for a selection of heat sources relevant for the HighEFF consortium. The state-of-the-art of heat recovery technologies for each heat source is also included. The discussion shows that coming up with a set of design criteria for a heat source can be challenging, because the properties of the heat source, the surrounding process and the intended application of the recovered heat must be taken into account. Ultimately, design criteria are required to ensure that the heat recovery system does not destroy itself or interfere with the process it is integrated in.

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1   Introduction

Several types of surplus heat sources exist in the industry. Examples are hot surfaces, slags, slurries and gas, liquid and solid material streams. A key step towards higher energy efficiency in the industry is the capture, conversion and utilization of surplus heat. As can be seen in Figure 1, surplus heat recovery is one of the three pillars of HighEFF.

| Energy efficient processing and plant operation | Surplus heat-capture, conversion and utilization | Smart industrial clusters and thermal grids |

Figure 1: The three pillars of the HighEFF centre.

A selection of technologies for heat recovery are available. When choosing the heat recovery technology for a given heat source, three main factors must be considered:

1. The characteristics of the heat source
2. The characteristics of the surrounding process
3. The intended application of the recovered heat

These factors must be considered to ensure that the heat recovery system can handle the conditions of the process it is integrated in, and that it does not interfere with the performance of the surrounding process. The intended application of the heat is also of significant importance. If the heat is to be utilized e.g. as district heating, in a heat-to-power cycle or a heat pump, it should be recovered at the highest possible temperature. This will minimize the exergy destruction in the heat recovery unit, preserving as much of the potential as possible for the downstream application. The design of a heat recovery system with small exergy losses will be different from a heat recovery solution with the sole purpose of dumping the temperature of the heat source. Exergy will not be treated in detail in this memo, but the curious reader is referred to HighEFF deliverable D4.2_2017.04, called "Thermodynamics of surplus heat-to-power conversion, for dummies".

A set of design criteria are needed to be able to determine which heat recovery technology is optimal for a given application. There can be significant differences in design criteria between heat sources. In Figure 2, three possible applications of recovered heat are shown. The heat can either be used directly, upgraded or converted to electric power. The different applications vary in efficiency and flexibility, and impose different requirements on the design of the heat capture system.
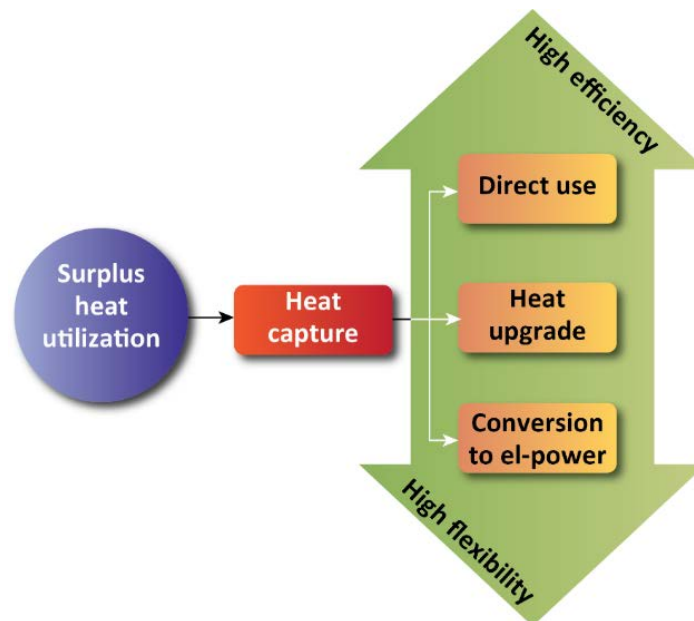
Figure 2: Possible applications of recovered surplus heat.

In this memo, the key design criteria for a selection of heat sources that are relevant for the HighEFF consortium will be discussed. Several types of heat sources have been chosen, and they are discussed in section 2. The goal is to give an indication of how one should proceed to come up with relevant design criteria for novel surplus heat recovery concepts. In 2017, the work in WP4.2 has been mainly focused on the thermodynamic potential of surplus heat sources. This memo considers practical challenges of heat recovery concepts, and is therefore a useful supplement to the work. Combining thermodynamic and practical considerations gives an indication of the realistically exploitable potential of surplus heat sources. This can help determine which industrial surplus heat sources should be focused on in HighEFF in the coming years.

2 Discussion of design criteria for selected heat sources

In this section, a selection of heat sources are presented and discussed. Different types of heat sources have been chosen, to show how the design criteria depend on the characteristics of the heat source. The heat sources considered in this section are representative of what is found in HighEFF-relevant industries. A clean gas stream, dirty (particle-laden) gas stream, hot surface and molten metal is considered. In the discussion, the state-of-the-art of heat recovery technologies for each heat source is also included.

2.1 "Clean gas" - Gas turbine exhaust

The exhaust from a gas turbine is around 500°C and has a low concentration of solid particles. According to [1], the particle concentration is below 25 ppm on a volume basis, and the exhaust is therefore considered a clean gas. Its composition is shown in Table 1. Filtered off-gas from e.g. aluminium electrolysis and ferrosilicon production will have comparable properties to a gas turbine exhaust, and could probably also have been used as examples of clean gases.

Table 1: Typical composition of a gas turbine exhaust stream. Values from [1].

Compound	Value	Unit
N_2	66 - 72	vol%
O_2	12 – 18	vol%
CO_2	1 - 5	vol%
H_2O	1 - 5	vol%
NO_x	22-240	vol ppm
SO_x	Trace – 100	vol ppm
CO	5 – 330	vol ppm
Unburned hydrocarbons	5 - 300	vol ppm
Particles	Trace - 25	vol ppm

Clean gases have low risk of scaling/fouling, which enables the use of extended surface heat exchangers to recover the surplus heat. The technology for recovering heat from clean gases is mature and proven for several applications. Extended surface heat exchangers can be designed in such a way that an increase in pressure drop is compensated by an increase in the heat transfer rate. A commonly applied extended surface heat recovery technology for clean gases is finned tube heat exchangers. An example of such heat exchangers is shown in Figure 3.
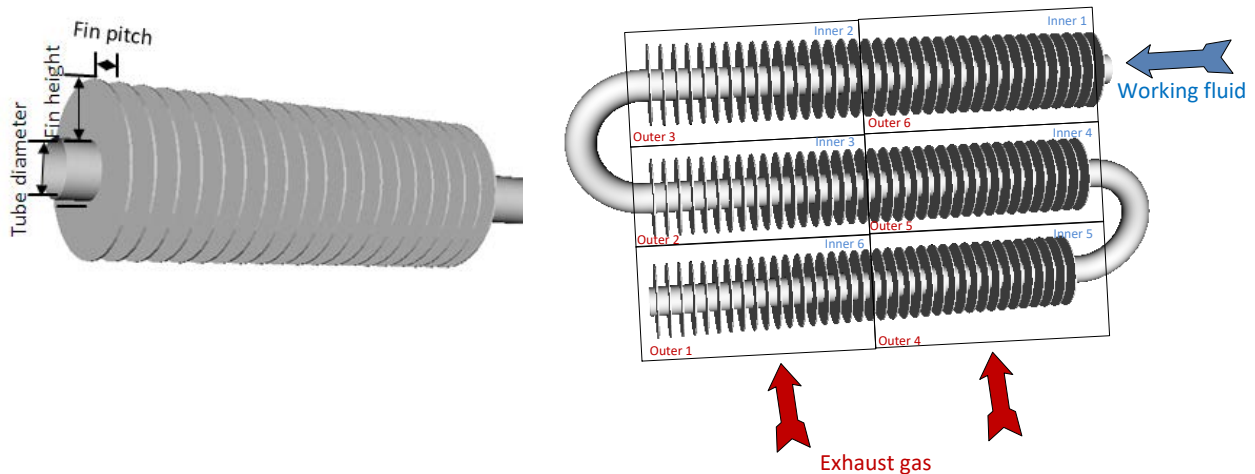

Figure 3: A finned tube (left) and section of a finned tube heat exchanger (right).

In a memo from the project SFI Metal Production [2], finned tube heat exchangers were treated in some detail. For such heat exchangers, many parameters can be varied to adjust the pressure drop and heat transfer coefficient. This is a general characteristic of extended surface heat exchangers; their performance can be tailored to match the requirements of the heat source and the surrounding process. In Table 2, taken from [2], the effect of different parameters on the heat transfer coefficient and pressure drop of finned tube heat exchangers is shown. This gives an indication of how many parameters can be varied in the design of extended surface heat exchangers.

Table 2: Effect of increasing the value of different parameters on the heat transfer coefficient and pressure drop of finned tube heat exchangers. Taken from [2].

Parameter	Effect on gas side heat transfer coefficient	Effect on gas side pressure drop	Effect on liquid side heat transfer coefficient	Effect on liquid side pressure drop	Other significant effects
Tube diameter		Increase ↑	Decrease ↓	Decrease ↓	
No. of tube rows		Increase ↑			Area ↑
No. of tubes per row*	Decrease ↓	Decrease ↓	Decrease ↓	Decrease ↓	Area ↑
No. tube passes per row**			Increase ↑	Increase ↑	
Tube pitch (Hor. + Ver.)	Decrease ↓	Decrease ↓			
Fin pitch	Decrease ↓	Decrease ↓			
Fin height		Increase ↑			Area ↑
Smooth tubes (no fins)	Decrease ↓	Decrease ↓			Area ↓
Staggered vs. inline	Increase ↑	Increase ↑			
Gas velocity (outside)	Increase ↑	Increase ↑			
Fluid velocity (inside)			Increase ↑	Increase ↑	

Positive effect

Negative effect

Minor or inconclusive effect

*@ constant tube pitch => Increased heat exchanger core height

**@ constant tubes per row => Constant heat exchanger core height, increased fluid velocity

As previously mentioned, there is little risk for particulate fouling in heat recovery systems for clean gases. However, condensation of water and sulphur-containing species can occur if the temperature drops below a critical limit. For gases where this is a potential issue, care must be taken to avoid the local surface temperatures within the heat exchanger from falling below the critical value. In practice, this typically restricts how far the exhaust gas can be cooled down.

For a gas turbine exhaust heat exchanger, pressure drop is a significant parameter. The power output and efficiency of the gas turbine is affected by the pressure drop in the waste heat recovery unit. If the pressure drop downstream of the gas turbine is large, the outlet pressure from the gas turbine must be higher, which reduces the power output. For other "clean gas" heat sources, a change in heat exchanger pressure drop is generally directly proportional to a change in exhaust fan work. This shows the importance of considering the surrounding process when evaluating or designing a heat recovery system.

2.2 "Particle laden gas" - Raw gas from aluminium electrolysis

Approximately 25% of the heat loss from an aluminium electrolysis cell is lost through the off-gas. Therefore, heat recovery from the off-gas is interesting to consider, but the characteristics of the gas makes it challenging to achieve in practice. To reduce the temperature, substantial amounts of false air is mixed with the CO_2 that is produced in the cell reaction. The raw gas that leaves the cell typically consists of 1% CO_2, and has a temperature of around 120°C, depending on the ambient temperature. A typical composition of the raw gas is given in Table 3.

Table 3: Typical composition of raw gas from aluminium electrolysis. Values from [3].

Compound	Value	Unit
O_2	20	vol%
N_2	78	vol%
CO_2	1	vol%
Ar	1	vol%
H_2O	4	g/Nm^3
Particles	640	mg/Nm^3
HF	260	mg/Nm^3
SO_2	200	mg/Nm^3

In addition to the compounds mentioned in Table 3, sulphur-containing species like SO_3 and H_2SO_4 will be present in the gas. The characteristics of particulate emissions from aluminium electrolysis cells were studied in a PhD-thesis from NTNU [4]. The particles were found to mainly consist of clean sodium fluoroaluminates in the sub-micron range. The larger and more coarse particles were found to contain most of the impurities, although they represent a minor fraction of the particles in the raw gas. The concentration of impurities in the particles was about 2.3 wt%, distributed amongst Ni, Fe, P, V, Ti, Co, Cu, Zn and Ga. Even though the gas consists mostly of O_2, N_2, CO_2 and Ar, it is the other species that have the largest effect on the design of raw gas heat exchangers. There are two main phenomena that must be accounted for: condensation of acidic components and the formation of scale on the gas side of the heat exchanger.

As mentioned in the previous section, restrictions on how far the gas can be cooled are generally required to avoid condensation of certain species. SO_3 and H_2SO_4 will condense if the local temperature within the heat recovery unit falls below the dew point of these components. Identifying the exact dew points is not trivial, and subject to discussion and uncertainty. A commonly enforced lower temperature limit is 70-80°C, but in [5], measurements carried out at Hydro Sunndalsøra indicated that the dew point in that case was lower than 40°C.

Scaling on the cold surfaces in an aluminium pot gas heat exchanger will reduce the heat transfer coefficient on the gas side. This reduces the cooling capacity of the heat exchanger, and can cause operational problems. Scaling is the formation of hard and strongly adhered layers on surfaces due to the reaction of chemicals [6]. In aluminium production plants, scaling appears in the form of an amorphous hard grey scale. Scaling is a complex phenomenon that is not yet fully understood, and many chemical components and operational factors influence scale formation. Heat exchangers for aluminium pot gas must be designed carefully to avoid scaling. To our best knowledge, only two concepts for such heat exchangers have been developed and documented significant operation time, by GE (previously Alstom) and NTNU/Hydro. A brief presentation of these concepts will be given.

GE has several heat exchanger concepts in their HEX series. They are all based on the same principle, where the pot gas flows on the inside of straight tubes, and the cooling medium flows on the outside. In Figure 4, a sketch of the concept and a picture of the tubes after 26 months of operation at Alcoa Mosjøen is shown. The picture shows that the heat exchanger can be operated for long periods of time without requiring maintenance.

a)   b)
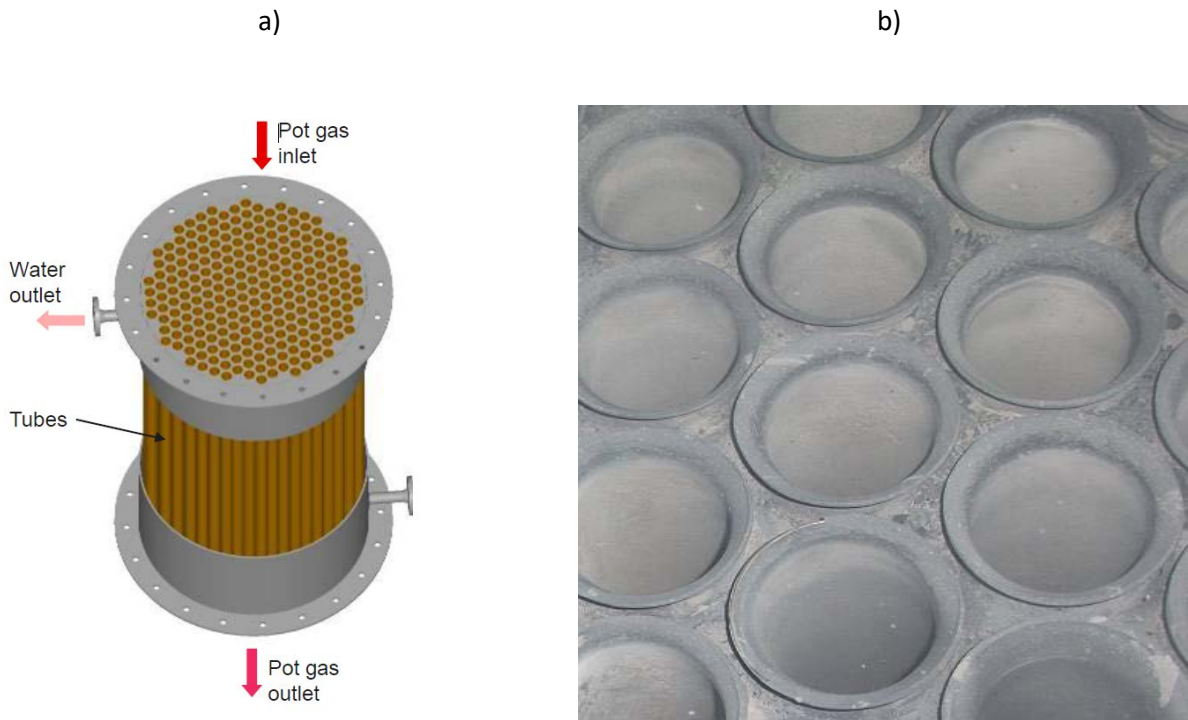

Figure 4: a) The counter-current, straight-tubed Alstom pot gas heat exchanger. b) Close-up picture of the tube inlets after 26 months of operation at Alcoa Mosjøen. (Source: Alstom/GE)

An overview of the different concepts GE delivers is given in an online document [7]. The external unit EHEX is located outside the plant walls, close to the GTC. IHEX is a heat recovery unit integrated with the dry scrubber in the GTC and MHEX is a smaller unit that can be positioned directly downstream of the electrolysis cells. GE has also developed a combined heat exchanger and fume treatment centre, called AHEX [8]. A sketch of the AHEX concept is shown in Figure 5.
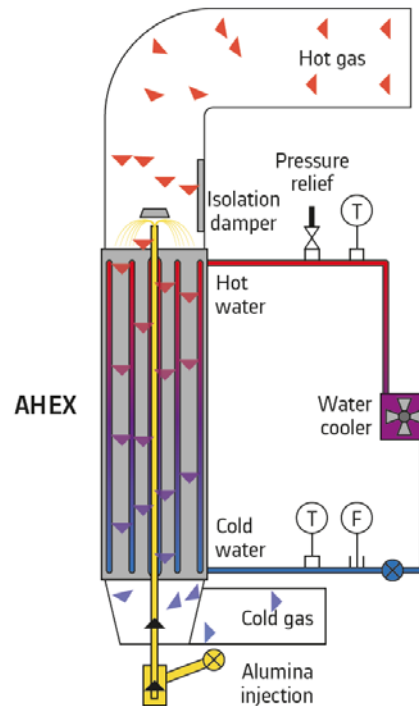
Figure 5: The AHEX, a combined fuel treatment center and heat exchanger. (Source: Alstom/GE).

The heat exchanger concept developed by Hydro and NTNU is described in a patent from 2014 [9] and a conference proceedings article from the 2013 Light Metals conference [10]. A picture of a prototype of the concept is shown in Figure 6. Oval tubes equipped with rectangular fins were chosen in the design, based on a series of small-scale laboratory tests. The pot gas flows perpendicularly on the outside of the tubes.
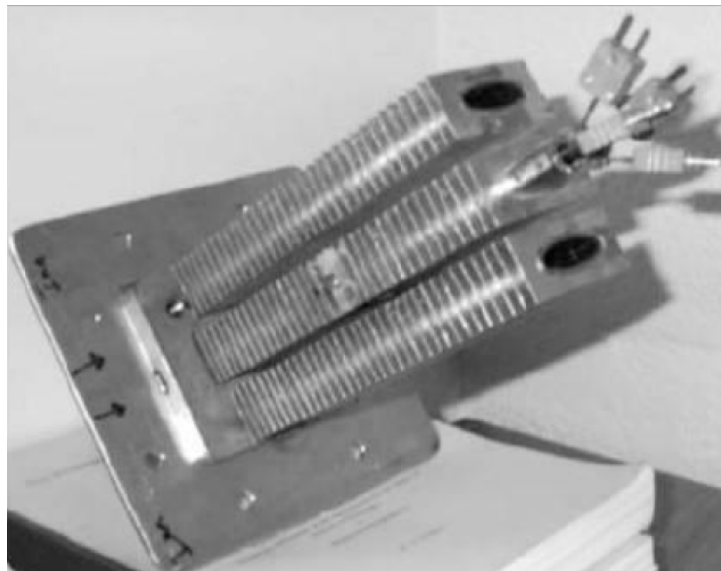

Figure 6: Prototype of the heat exchanger designed by Hydro and NTNU (Source: NTNU).

The Hydro/NTNU concept has also been tested on a larger scale at the Hydro test facility in Øvre Årdal. In collaboration with Fives Solios, units of 129 m^2 and 12 m^2 were built. The largest unit was endurance tested with off-gas from a series of test cells. A decrease in heat transfer coefficient was observed for the first 2000 hours, before the heat transfer coefficient stabilized. This indicates that a stable layer of scale was

formed, and no net particle deposition occurred after 2000 hours. A visual inspection carried out after approximately 9000 hours of testing only showed signs of moderate fouling.

In addition to condensation and scaling, the surrounding process must be considered when designing the heat recovery unit. Firstly, the fans must be able to handle the pressure drop in the heat exchanger, and increased pressure drop will give increased fan work. The gas treatment centre (GTC) will also be strongly affected by the performance of the heat exchanger. Cooling the gas before the GTC reduces the volumetric flow of the gas passing through the filter bags, meaning that a lower filter area is required. This can give significant cost savings. The temperature of the gas entering the GTC must not be too high. Over 120°C, the adsorption of HF on alumina particles is much less efficient, drastically increasing the emissions of HF to the atmosphere. Also, the filter bags have an upper temperature limit, approximately 140°C. In the future, the temperature of the raw gas is expected to increase, meaning that solutions for cooling the raw gas might be necessary to avoid reaching the upper temperature limits. Three possible drivers for raw gas temperature increase are listed below.

1. To be able to produce more aluminium, there is an interest in increasing the cell amperage. Increased cell amperage causes proportionally increased raw gas temperatures.

2. It is possible to operate the electrolysis cells with reduced ventilation in order to improve the energy efficiency of the process. Hydro has operated some cells with DPS (distributed pot suction) for some time, where the ventilation is demand controlled. Generally, DPS leads to higher raw gas temperatures.

3. In the future, the capture of CO_2 from the raw gas might become a requirement. In order to make this possible, the CO_2 concentration in the raw gas will have to be increased, which can be achieved through the reduction of the amount of draft air. A side effect of reducing the amount of draft air is increased raw gas temperatures.

2.3 "Surface" - Aluminium electrolysis cell sidewall

The bath of an aluminium electrolysis cell consists of cryolite (Na_3AlF_6) with around 12 wt% aluminium fluoride (AlF_3) and 5 wt% calcium fluoride (CaF_2). In principle, pure, molten aluminium oxide (Al_2O_3) could function as electrolyte. However, the melting point of pure Al_2O_3 is quite high (around 2050°C), and it is therefore necessary to find a solvent that can dissolve sufficient amounts of aluminium oxide at reasonable temperatures. In practice, fluoride melts are the only compounds that fit this description, which is why cryolite is used in the electrolysis bath. Since cryolite is a highly corrosive substance, it has implications on the design of the electrolysis cell. More specifically, the materials that are used on the inside of the cells must be able to handle the following [11]:

- Temperatures around 960°C, periodically over 1000°C
- Extremely oxidizing conditions around the anodes
- Extremely reducing conditions in the bottom of the cell
- Fluoride melts can dissolve all oxidic materials

Finding a material that can meet all four requirements is challenging. In fact, frozen cryolite is the only known material that is suitable. It is therefore crucial for the operation of the cell that a frozen layer of cryolite is maintained to protect the cell wall. The cell is designed to give a large heat flux through the sidewalls. If this heat flux is reduced, the thickness of the frozen cryolite layer will decrease. Similarly, an increase in the heat flux through the walls will increase the thickness of the frozen layer.

Heat recovery from the sidewalls of the electrolysis cells could be a way of increasing the energy efficiency of aluminium plants. However, such heat recovery systems must not interfere with the cell operation. If the layer of frozen electrolyte disappears, serious consequences may follow. Since a heat exchanger mounted

on the sidewall of an electrolysis cells is located inside the electrolysis hall, additional considerations must be taken. For instance, water should not be used as the cooling medium, as leakage into the cells could lead to rapid evaporation, which is a potential safety hazard. It is essential for the plant operation that tapping vehicles and plant personnel can move close to the cells. Therefore, the heat recovery system should be compact, not extending too far from the cell walls.

Two heat exchanger systems for recovering heat from the cell sidewalls have been developed, the EnPot system developed by Energia Potior Limited [12] from New Zealand and a system from the Norwegian company Goodtech ASA [13]. The EnPot heat exchanger uses air as the heat recovery medium, and has been tested on full scale at the TRIMET aluminium plant in Germany. It is stated that the cells operated with EnPot achieved a reduction in energy consumption of 1 kWh/kg aluminium, which is a significant saving. During testing, TRIMET experienced a power outage, and the EnPot cells were claimed to perform better and were easier to restart than the conventional cells. In Figure 7, a sketch of how the EnPot system is integrated on the side of the cell is shown:

Figure 7: The air flow in the EnPot heat recovery system [12].

The solution developed by Goodtech is mounted on the electrolysis cell in a similar way as the EnPot system. A sketch is shown in Figure 8. Goodtech uses heat pipe technology, and claims that more than 50% of the thermal energy that is normally lost in an aluminium plant can be recovered by installing their heat recovery system [14]. The working fluid is a thermal oil, and heat is recovered both from the sidewalls and raw gas in an integrated concept, as indicated in the figure.
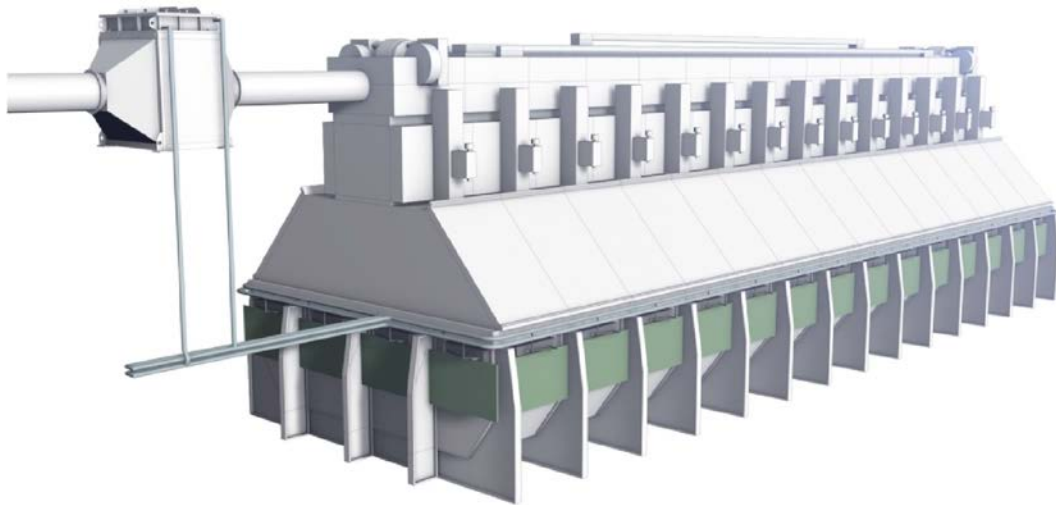
Figure 8: Illustration of Goodtech's patented technology for recovering heat from the sidewalls of an aluminium electrolysis cell.

2.4 "Solidifying" - Metal casting and slags

The production of many types of metals and alloys, e.g. aluminium, ferrosilicon, steel and manganese, is quite energy intensive. The metals are produced in high-temperature furnaces or electrolytic cells, and large amounts of reduction material (usually carbon) is required. The metal product is tapped from the furnaces in liquid form, and may undergo a series of refining steps before it is cast into solid blocks. A picture of the casting process in a silicon plant is shown in Figure 9.

Figure 9: Casting of silicon, from [15].

During melting and refining operations, high-viscosity, non-metallic slags are formed. These waste streams typically contain lime, silica and ash, but the composition will vary from plant to plant. Slags have low thermal conductivities, and the core of a slag pot cooled in air can remain molten for days. Large amounts of heat at high temperatures are available in both the casting and slags, but it is not common to recover heat from these sources in the industry today.

The metal product from the casting process must meet requirements for purity and quality, and installing a heat recovery system must not lower the quality of the product. In some cases, a high cooling rate might be required in order to meet quality requirements. This might be challenging to achieve in a heat exchanger without leading to large exergy losses. Also, practical issues like space limitations and safety hazards (e.g. connected to the use of water as cooling medium) must be considered.

The state-of-the-art for heat recovery from high temperature slags was the topic of a review article from 2011 [16]. Molten slags are claimed to be one of the largest untapped energy sources in metal manufacturing operations, and a worldwide waste heat amount of 220 TWh/year at 1200-1600 °C is estimated. Although the energy from slags is usually not recovered, technologies are under development:

1. The slag is broken up into small droplets with a large surface area available for heat transfer, before the heat is recovered. Several methods for fragmenting the slag have been studied.
2. The thermal energy from the slag is used to produce fuel in a chemical reaction. Endothermic reactions with low exergy losses are suitable for this application, e.g. the steam methane reforming and coal gasification reactions.

Of these three technologies, slag granulation is the most developed. In [16], TEGs are identified as the next emerging technology for heat recovery from high temperature slags. The advantage of TEG systems are their scalability and simplicity. The core "heat engine" has no moving parts, although the heat recovery interface to the heat source would have to be just as extensive as for other such technologies. TEGs typically have efficiencies below 5% of the Carnot efficiency [17], which is much lower than competing heat-to-power technologies. In [17], TEG systems for waste heat recovery from the casting of silicon is explored.

3 Conclusion

In this memo, design criteria are discussed for a selection of heat sources relevant for the HighEFF consortium. The state-of-the-art of heat recovery technologies for each heat source is also included. The discussion shows that coming up with a set of design criteria for a heat source can be challenging, because the properties of the heat source, the surrounding process and the intended application of the recovered heat must be taken into account. Ultimately, design criteria are required to ensure that the heat recovery system does not destroy itself or interfere with the process it is integrated in.

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