Reverse electrodialysis heat-engine: Case studies of improving energy efficiency through recovery of low temperature excess heat

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Abstract

Reverse Electrodialysis (RED) is a technology for generating electricity from the difference in salinity between two solutions. RED is usually applied to natural water streams with different salinities, like seawater vs. freshwater. In the RED Heat-to-Power project we explore the option of using artificial water solutions operating in a closed loop where the difference in salinity is regenerated in a separation step powered by heat at temperature ranges between 60 and 100 °C. We call this system Reverse Electrodialysis Heat Engine (RED HE).

In this paper, first we summarise the possible system configurations and the overall amount of excess heat available in Europe for powering the RED HE process, as described in our previous publications. Then we take a closer look at specific sites, where a RED HE engine could be potentially applied, assessing the amount of waste heat that can be technically and realistically recovered and sizing the RED HE system for those applications.

The case studies include the excess heat recovery from:

1. a typical large-sized pulp and paper industry based in Sweden
2. a typical medium-sized food industry as described within the IEE project GREENFOODS
3. a relatively large biogas plant in Germany
4. the on-board auxiliary engine of a medium-sized bulk carrier
5. a gas compressor station in Poland.

The results show that the RED HE is suitable to be used by all those sectors. For most cases, the typical heat engines would be of relatively small size, because of the Carnot limits for temperatures at 100 °C or lower: Industry 150–600 kW, Biogas plants 5–20 kW, Marine 4–17 kW. On the other hand, the gas compressor stations are suitable for larger applications, in the range of 2–8 MW.

Introduction

The Reverse Electrodialysis Heat Engine (RED HE) is based on the generation of electricity from salinity gradients using a Reverse Electrodialysis (RED) device in a closed-loop system. In this concept, limited amounts of artificial saline solutions are used as working fluids. The solutions exiting from the RED unit are then regenerated, in order to restore the original salinity gradient, by means of a separation step, which uses low-temperature heat as its energy source. Essentially the system converts low-grade heat to electricity, as shown in Figure 1. This technology is particularly interesting, not only because it has the potential to offer higher thermal efficiency compared to Organic Rankine Cycle (ORC) for heat at temperatures between 60 and 120 (A. Tamburini *et al.*, 2017), but also because the salty solutions can be stored in tanks, practically cost-free (Papapetrou and Kumpavat, 2016), giving the technology a unique flexibility, an energy storage function, which is getting more and more important in the current energy system with high shares of variable renewable energy sources.

This paper examines the availability and characteristics of excess heat sources in Europe, as this could be used to power the regeneration part of the RED HE and be converted to electricity. These heat sources are available in various sectors. We examine in particular the excess heat in industry, decentralized power plants, the marine sector and gas compression stations. It is essential to identify the expected scale and capacity of each source, as well as its temperature level, in order to provide input to the cost analysis (initial calculations show that a Levelized Cost of Electricity of about €0.10/kWh is feasible once this technology becomes commercial (Bevacqua *et al.*, 2017)) and the initial business plan that would identify the most promising sectors to employ the RED Heat-to-Power technology. For that reason, we have examined a number of case studies covering all sectors of interest.

Design Options for the RED Heat Engine

The concept of the Reverse Electrodialysis heat engine has been explained in detail in a previous publication (A. Tamburini *et al.*, 2017). In that paper, different possible designs were shown. The main design alternatives have to do with the principle used for regeneration. The objective of the regeneration process is to rebalance the concentrations of the solutions, bringing them back to the original salinity difference. In order to do that, we have two options. We will either extract solvent from the high salinity solution and move it to the low salinity solution (Figure 2), or we will extract salt from the low salinity solution and move it to the high salinity solution (Figure 3).

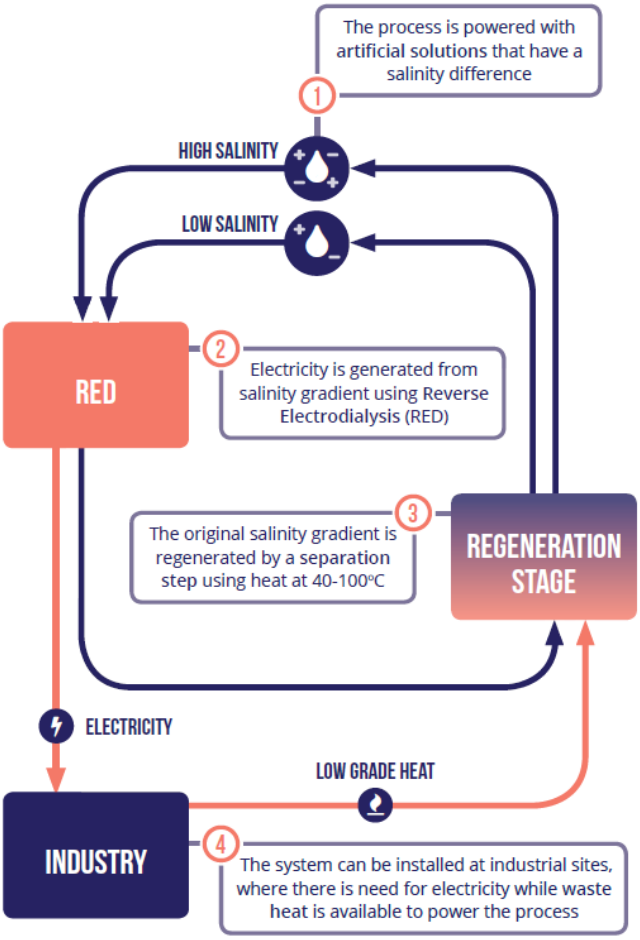

Figure 1. The RED Heat Engine concept.

When using the solvent extraction approach, there are a number of technological options that could be employed according to (A. Tamburini *et al.*, 2017): Evaporative separation processes, Liquid-Liquid extraction process (organic solvent), Azeotropic mixture separation, Absorption/desorption and adsorption/desorption cycles and Extraction by Forward Osmosis using T-sensitive drawing agents. Regarding the solute extraction process the main alternatives include the use of thermolytic salts and the use of the salt precipitation processes.

Out of all these options, the most mature one is the evaporative solvent extraction process, as it builds on the many years of development of the desalination industry. More specifically, either the well-established Multi Effect Distillation (MED) process can be used, or the more recently developed Membrane Distillation (MD). When using the MED for regeneration, the paper of Tamburini (A. Tamburini *et al.*, 2017) has shown that when using a heat source at 90 °C, the efficiency of converting the heat to electricity can range from 5 to 15 %, depending on the performance of the RED Heat Engine components.

Sectors

In this section, we introduce the sectors that we have identified as the ones that are most promising for applications of the RED HE., as they reject large amounts of heat that. These sectors are suitable for the heat to power technology under development, as they reject large amounts of heat at low temperatures.

INDUSTRY

Industrial waste heat corresponds to heat rejected from industrial processes, in which energy (mostly heat or electricity) is used to produce high-added value products. The amount of waste heat as a fraction of energy consumption varies between the industrial sectors, with a mean value of about 10 % (Panayiotou *et al.*, 2017). However, over time this figure is being reduced, as more efficient processes are adopted. The temperature at which the heat is rejected varies within a very large range, from about 50 °C up to even 1,000 °C, depending on the industrial sector (e.g. steel, paper, food, chemical) and the process that is employed. Even though the rejected heat characteristics are not uniform among the industrial sector, it is clear that with overall energy consumption of 3,200 TWh (Eurostat, 2016), there are opportunities for using the RED HE to recover part of the heat and convert it to electricity.

POWER GENERATION

In the power generation sector, power plants reject large amounts of heat, about 50–70 % of the input heat, depending on their type (steam Rankine, combined cycle, nuclear, diesel engine, and gas turbines), technology (subcritical or supercritical steam Rankine, power-only or combined heat and power – CHP) and fuel type (coal, natural gas, oil, biogas). Large power plants usually have thermal efficiency of about 35–55 % (the highest efficiency is reached with Combined Cycle Gas Turbine (CCGT) plants and the lowest with coal-fired and nuclear plants).

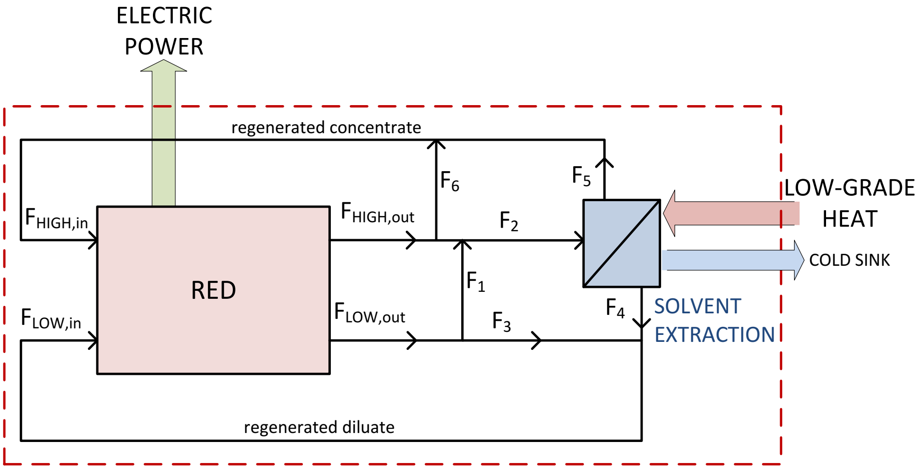

Figure 2. The RED Heat Engine with the solvent extraction process.

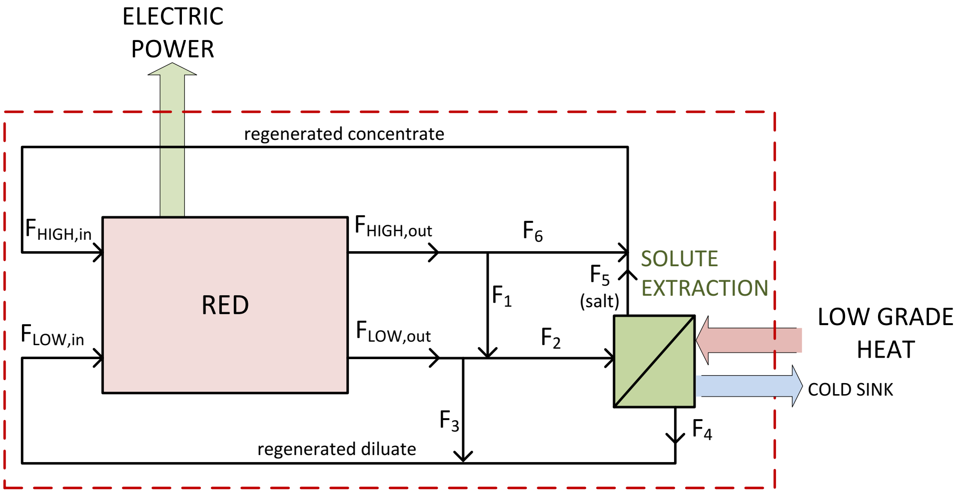

Figure 3. The RED Heat Engine with the solute extraction process.

The electricity generation in the EU from centralised large thermal power plants is about 3,000 TWh/year (Eurostat, 2017). With a mean conversion efficiency of 40 % (taking into account all different power plants: old/new, nuclear plants, steam power plants, etc.) the resulting waste heat from all power plants in EU is about 4,500 TWh/year. In all these plants, the main sources of waste heat are in the condenser (cooling towers) and in the exhaust gases. However, the heat rejected through the cooling system is at temperatures of about 30–40 °C, which is too low to be recovered for our purposes. The exhaust gases usually are rejected when their temperature reaches the limit (about 160–180 °C) beyond which it is not allowed to be cooled further (its temperature should be kept above the dew point, in order to avoid condensation of water vapour and the production of H_2SO_4 from the SO_x emissions of the exhaust gas). Gas turbines are mostly used for backup purposes or for covering the peaks of the load, with low capacity factors (around 10 %), making the exploitation of their waste heat less attractive.

Although the overall amount of rejected heat from large thermal power plants is high, its exploitation is not possible due to technical restrictions or the very low temperature at which it is available. Therefore, the above sources from centralized power plants are not suitable to be exploited by the RED HE and will not be further examined in this paper.

On the contrary, decentralized power plants (capacities ranging between a few hundred kWs and some MWs) based on internal combustion engines, have a cooling circuit where the waste heat is rejected at temperatures of about 80–90 °C, making them ideal to supply the RED HE. Especially the biogas engines, whose electricity is subsidized, seem an attractive option with their market share and applications steadily increasing. The waste heat of the exhaust gases is not easily harnessed, since all these engines are supercharged and the hot gases leaving the engine cylinders are directed to turbocompound devices, where their temperature decreases from about 400–500 °C (depending on fuel type) to about 200 °C, before leaving the engine. The remaining thermal content of this gas is already exploited in CHP biogas plants for other purposes.

MARINE SECTOR

In the marine sector, there are numerous ships equipped with diesel engines for their main propulsion and for auxiliary purposes. In most of the ships there is steam produced from the heat recovered from the main engines (from both the exhaust gases and the cooling circuit) and from the exhaust of the auxiliary engines (with the highest potential). However, the waste heat of the cooling water of the auxiliary engines with typical temperature of 80–90 °C remains unexploited and its heat is rejected to the sea (cooling is accomplished with seawater). This heat can be exploited by the RED Heat Engine. It is important though to keep in mind that there are severe space restrictions on-board ships.

GAS COMPRESSION STATIONS

Gas compression stations (GCS) are used to maintain the gas at high pressure (due to the pressure losses in the pipes). Gas turbines are coupled with centrifugal compressors with typical capacity of 40 MW each, burning gas from the pipeline. The exhaust gases of these turbines with temperature at about 250–300 °C are readily available for heat recovery and further exploitation, since potential heat users are not usually available (e.g. GCS are located in isolated areas far away from district heating networks most of the times).

Excess Heat per Sector

INDUSTRIAL SECTOR

The waste heat in the industrial sector has been calculated by the authors in a previous study (Papapetrou *et al.*, 2017). In this paper, we used an older study that reports detailed data from the UK industry over the period 2000–2003. Based on that data, we calculated the waste heat fractions (WHFs) per industrial sector and per temperature level of the rejected heat. Then, we adjusted the calculated set of WHF to the realities of each of the other Members States of the European Union, by multiplying with a factor that indicates the relative energy intensity of each country compared to the UK for the same period (2000–2003). At that stage, we had a set of WHFs, per country, per industrial sector and per temperature range of the rejected heat. The next step was to update the fractions accounting for the energy efficiency improvements from 2000 up to 2015. The resulting set of WHFs was multiplied with the 2015 Eurostat heat consumption data per industrial sector, giving us an estimation of the waste heat potential from the European industry.

We have found that the highest potential, over 100 TWh/year, is available at the temperature level of 100–200 °C, representing about one third of the total industrial waste heat potential in Europe. This is available in various industrial sectors, such as chemical, non-metallic minerals, food, and paper industries. The waste heat available at temperatures between 200 and 500 °C is about 78 TWh/year, while at temperatures over 500 °C the potential is over 120 TWh/year, but is mainly available at sectors that use high temperature process heat, like the steel industry. The total industrial waste heat potential in the EU is 304.13 TWh/year, which is 16.7 % of the industrial consumption for process heat, and represents about 9.5 % of the total industrial energy consumption.

DECENTRALISED POWER STATIONS

Most decentralized power plants operate based on reciprocating internal combustion engines. There are various types of such engines, using different fuels, such as diesel oil, heavy fuel oil, natural gas, biogas, syngas, mining gas, etc. Their capacity starts from some kW up to some tens of MW with the advantage that they have the flexibility of adjusting their operating load within a wide range. The number of decentralized power plants being installed annually is increasing in the last years. The majority of these engines are diesel engines. Engines using gaseous fuels (natural gas, biogas) represent a small fraction of this capacity (about 10 %). However, most of the diesel engines are used for backup or peaking purposes, while gaseous engines are mostly used in CHP mode for continuous operation with a high capacity factor.

The installed capacity in Europe is estimated to 36.5 GW (TU Delft and Enipedia, 2017), and generate annually about 138.3 TWh of electricity, which means that the average capacity factor is 43 %. With a mean thermal efficiency of 40 % (considering gaseous engines with efficiency of 35–40 % and modern diesel engines with 40–45 % and part load operation with reduced efficiency), the total fuel heat consumption is equal to 345.75 TWh/year.

The main sources of waste heat are from the exhaust gases and the cooling circuit. The rejected heat of the cooling water represents about 30 % of the combustion heat (includes jacket water and charge air cooler, both cooled by the same cooling circuit), and the exhaust gases about 25 % (includes both tailpipe exhaust gases and exhaust gas recirculation-EGR cooling). In case of even larger engines with heavy fuel oil (HFO), a large fraction of the exhaust gas heat is used for preheating the fuel, in order to increase its viscosity, and the heating of lubricant oil. The result is a reduced exhaust gas temperature of about 150–200 °C, further limiting the potential of this heat source. On the other hand, the temperature of the cooling water is constant at about 80–90 °C.

The waste heat potential is thus divided according to the main fuel types: heavy fuel oil (usually over 1 MW), diesel (below 1 MW), natural gas, biogas and other low gaseous calorific fuels. The estimated waste heat sources and typical performance data for the engines with different fuel types are given in Table 1, using data from (Senary *et al.*, 2016), (Opcon Energy Systems, 2017) and (GE Power, 2017).

Moreover, most of the engines supplied with gaseous fuels (natural gas, biogas, and other low calorific gaseous fuels such as landfill gas) operate at CHP mode, already exploiting the waste heat of the exhaust gas and cooling water. In the cases of biogas plants, a fraction of this heat (mean annual is about 20 %) is used to produce the gaseous fuel itself, leaving a small part of heat that is currently rejected, which is estimated to about 20 %, varying within a large range, depending on the heat consumer. With the above limitations, the resulting waste heat potential for each engine type is shown in Table 2.

The total waste heat source in this sector is 195.79 TWh/year, covering a large range of engines and fuel types. The technical potential of waste heat is reduced to 56.2 TWh/year, consider-

Table 1. Efficiency and waste heat sources for engines with different fuel types.

Fuel type	Efficiency (%)	Waste heat sources (%)		
		Exhaust gas	Cooling water	Other (radiation, lubricating oil, etc.)
Heavy fuel oil	50	27	20	3
Diesel	42	26	30	2
Natural gas	40	28	31	1
Biogas	38	30	30	2
Other low calorific gaseous fuels	35	34	29	2

Table 2. Waste heat potential for engines with different fuel types.

Fuel type	Available (TWh/year)		Technical potential (TWh/year)	
	Exhaust gas	Cooling water	Exhaust gas	Cooling water
Heavy fuel oil	14.41	10.68	2.32	10.68
Diesel	5.68	6.55	1.58	6.55
Natural gas	32.02	35.45	8.00	8.86
Biogas	39.38	39.38	7.88	7.88
Other low calorific gaseous fuels	6.10	5.64	1.32	1.13
Total	**98.09**	**97.70**	**21.10**	**35.10**

ing all limitations. The biogas shows the highest potential with an additional important advantage: its electricity is subsidized in most of the EU countries, making it very attractive to produce additional "green" electricity from the heat recovery of biogas engines.

MARINE SECTOR

According to a Royal Academy of Engineering report (Engineering, 2013) the total (global) fuel oil consumption of the marine sector is more than 350 million tonnes per year. The global fleet is about 90,000 ships (from small up to very large ones), increasing with a growth rate of about 3.5 %/year (United Nations, 2016). The energy consumption that corresponds to this fuel oil consumption is about 4,150 TWh per year (with heating value equal to 42.65 MJ/kg (Entec, 2002)). Although the number of ships and their tonnage is increasing, fuel consumption decreases due to the modern engines and higher efficiency of new ships. This leads to a decrease of fuel/energy consumption and less potential for further waste heat recovery measures, since modern engines already exploit most of the rejected heat from the exhaust gas and cooling water circuit.

Marine engines for propulsion (usually two-stroke, low speed) have large size with efficiency approaching 48–50 % or even higher in new ships. Auxiliary engines for electricity generation are usually four stroke medium speed ones with capacity about 0.5–1 MW and lower efficiency, about 45 %. Most of the fuel consumption in ships is for the main propulsion engines, while auxiliary engines (and boilers) represent about 12 % of this consumption resulting to 498 TWh/year.

In all ships the waste heat sources from the main engines are already recovered and exploited, for fuel/lubricant preheating, fresh water production through thermal desalination, and other heating purposes. The exhaust gas from the auxiliary engines is also utilized in most of the cases, leaving the waste heat of their cooling water to be exploited (representing about 30 % of their fuel consumption). The resulting waste heat potential of the auxiliary engines is 149.4 TWh/year.

Finally, the main drawbacks of waste heat recovery in ships are: (1) the uncertainty of the capacity factor, since every ship operates differently, and (2) the space restrictions in the engine room. These issues require a case-by-case study for each ship and operational time, in order to identify the actual potential over a year.

GAS COMPRESSION STATIONS

The installed capacity of gas compression stations in Europe is 9 GW with 613 stations (and further increasing) and another 50 GW between Russia (44 GW) and Ukraine (6 GW) (Campana *et al.*, 2013). Most of these gas turbines operate with capacity factor over 90 %, while some others only cover seasonal peaks or are used as backup. Their thermal efficiency is within the range of 32–35 %, with a single typical gas turbine of 40 MW rejecting about 80 MW of heat. Considering a mean capacity factor of 40 % (taking into account also the backup units and the ones operating at specific seasons), the annual combustion heat in Europe is 94 TWh/year. By also adding the compressor stations in Russia and Ukraine, the total heat consumption increases to 616 TWh/year. The resulting waste heat from the exhaust gas is 63 TWh/year for the compressor stations in Europe. By adding the ones in Russia and Ukraine as well, the total waste heat equals to 412.72 TWh/year. This waste heat is available at temperature of about 250–300 °C, making it appropriate for RED Heat-to-Power technology. Moreover, these stations are located in isolated areas away from heat consumers, limiting the possible alternative uses for that heat. However, the actual potential of this waste heat is reduced, due to technical limitations (not possible to cool the exhaust gas down to ambient temperature). The lower limit is about 150 °C or

Table 3. Technical potential of waste heat in all sectors of interest.

Sector	Technical potential of waste heat (TWh/year)	Temperature range	Average waste heat per site (GWh/year)	Average capacity of RED HE per site (kWe)
Industry	100	Up to 200 °C	100	150–600
Biogas plants	29.00	80–150 °C	1.70	5–20
Marine	149.4	80–90 °C	1.65	4–17
Gas compressor stations	202.31	Up to 250 °C	660.00	2,000–8,000

even less (Chaczykowski, 2016), since the produced sulfur oxides are very low (depending on the natural gas composition). Therefore, the technical potential equals about 50 %, reducing to 202.31 TWh/year, with about 30 TWh/year available in EU countries and the rest, 170 TWh/year, in Russia and Ukraine.

All results of this section are summarised in Table 3, where average recoverable excess heat per site is also calculated, together with the size of a RED HE that could be installed in such a site for converting that recoverable heat to electricity.

Case Studies

INDUSTRIAL SECTOR

Case study of a pulp and paper industry

A typical large-sized pulp and paper industry based in Sweden includes a mill that produces bleached Kraft pulp with a production capacity of 250,000 t/year (ICF, 2015). This industrial site has an average energy intensity of about 17,000 MJ/t (4,722 kWh/t), which is close to the EU average value. About 84 % of this energy demand concerns process heat. The annual heat demand is 1,180 GWh/year. The waste heat recovery fraction for this industry type is 7.39 %, resulting to a waste heat potential of 87.2 GWh/year at temperature in the range of 100–200 °C (although closer to the lower range limit). This corresponds to a thermal capacity of about 12 MWth and with a RED HE efficiency of 7.5 %, its electric capacity would be 0.9 to MWe in case all sources of waste heat are utilized. Finally, the electricity production would be equal to 7.5 GWh/year, assuming a reasonable capacity factor.

Case study of a food industry

A typical medium-sized food industry has been described within the IEE project GREENFOODS (AEE, 2013), in which energy audits have been performed in food industrial sites of different type and size. The typical medium sized industrial site requires about 6,300 MWh/year of heat from natural gas for high-pressure steam production and auxiliary heating, and another 800 MWh/year from heating oil for low-temperature steam. The waste heat losses are high especially from the gas boiler due to the high-temperature operation (from flue gases). They have been estimated at almost 2,800 MWh/year at approximate temperature of about 200–250 °C, with a waste heat potential of 1,500 MWh/year. The waste heat potential from the oil boiler is much lower and estimated to about 150 MWh/year at 180 °C.

The total waste heat potential is thus 1,950 MWh/year and considering a RED HE unit with efficiency of 7.5 %, the heat capacity is 300 kWth and production of 23 kWe. The annual electricity production is 150 MWh/year.

DECENTRALISED POWER PLANTS

Case study of biogas plant

In 2006, a biogas plant was developed in a German farm (University of Glamorgan, 2009). This plant includes two gas engines of capacity 370 kWe (gross) each for CHP operation. The electricity production is 5,800 MWh/year with parasitic losses – own consumption – about 10 % of that (580 MWh/year). Heat production is 5,000 MWh/year with about 25 % of this required by the anaerobic digester for its operation. The rest is partially used for drying purposes and the remaining is dissipated to the ambient.

It is estimated that the rejected amount of heat to the ambient is about 1,900 MWh/year, and considering that the capacity factor is 89.5 %, heat capacity is 242 kW at temperature in the range 90–150 °C. In case RED HE with an efficiency of 7.5 % the expected capacity would be of 18 kWe and the produced electricity per year between 150 MWh/year, covering about one third of the plant's own consumption. Once the own consumption of the plant is decreased, additional "green" electricity can be provided to the grid with the secured feed-in-tariff of 16.9 cents/kWh for the specific plant. This results to an additional income up to €32,000/year.

MARINE SECTOR

Case study of an on-board auxiliary engine:

A medium-sized bulk carrier of 35,000 deadweight tonnage (DWT) serves as a typical example for investigating the waste heat potential in ships (Schnack, 2009). This ship is equipped with three auxiliary engines for electricity production, each with a net capacity of 500 kWe, which is the typical size of gensets in ships (two for standard operation and one for backup). According to the usual time distribution at sea, loading/unloading, and manoeuvring, as well as the operating load and number of engines operating (most of the times only one), the electricity production is 3.95 GWh/year. The available waste heat from the cooling circuit (at temperature of 85–90 °C) of both auxiliary engines is 2.8 GWh/year, and if only the main auxiliary engine is considered then this potential decreases to 2.4 GWh/year. If the RED HE sizing is based on the maximum capacity, then the heat input is 625 kWth (at 85–90 °C), and with a mean efficiency of 4 to 8 % (because of the lower temperature) the electric capacity is 25–50 kWe with annual electricity production from 112 to 224 MWh/year, provided to the ship for covering a part of its electric demand. This is equivalent to fuel savings of up to 43.8 ton per year. With a fuel price of €300/ton, up to €13,140/year are saved, reducing the vessel's fuel costs.

GAS COMPRESSION STATIONS

Case study of a gas compressor station:

A gas compressor station in Poland serves as the case study to examine here. It is a €51.3 MW in total station located in Halberstadt (Kostowski *et al.*, 2015). It has two separate units; the first is equipped with 8 electric-driven compressors (€2.5 MWe each), and the second with two gas turbines of €31.3 MW capacity. The waste heat is about 112 GWh/year at temperature about 250–300 °C. However, the technical potential of this waste heat is reduced by almost 10 %, leading to 100 GWh/year that can be recovered. The capacity factor of this station relevant to the gas turbines is very low, about 12 %, since they operate at very low load, supported by the electric-driven compressors.

This available waste heat corresponds to a thermal capacity of about 11 MWth and with a RED HE unit with efficiency of 10 %, the electrical capacity is 1.1 MWe and the produced electricity is 8 GWh/year with a reasonable capacity factor of 80 % for the RED HE. This electricity can reduce the station's self-consumption (about 16.7 GWh/year), resulting to energy savings of about €0.95 million/year.

Conclusions

The RED HE is an interesting option for recovering waste heat and converting it to electricity. When heat is available at 100 °C, it can be converted to electricity with an efficiency that starts at about 5 % and could be increased to 10 % as the performance characteristics of the innovative RED HE components improve and for higher heat source temperatures. This means that the RED HE could tap on a large potential of recoverable waste heat available from industrial units (100 TWh/year), biogas plants (29 TWh/year), vessels (149.4 TWh/year) and gas compression stations (202.31 TWh/year).

An average gas compressor station could host a large RED HE of 2–8 MW, while average industrial sites could host medium sized RED HE of 150–600 kW. On the other hand, the waste heat available on vessels and in biogas plants is more suitable for small RED HE applications ranging from 4–20 kW. These figures were confirmed also with the case studies presented in the current work.

The next step is to conduct detailed economic analysis of the RED HE technology and conclude to the most appropriate applications in terms of techno-economic criteria. One major parameter in this analysis is the future performance and specific cost of this new technology that brings in a large margin of uncertainty. However, initial economic calculations have revealed the potential of the RED HE technology in all the presented sectors with short payback periods, directly competitive to standard ORC solutions.

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