Electricity generation from low temperature industrial excess heat – an opportunity for the steel industry

Maria T Johansson[a,b*], Mats Söderström [a]

[a] Department of Management and Engineering, Division of Energy Systems, Linköping University, SE-58183 Linköping, Sweden

[b] Department of Technology and Built Environment, Division of Energy and Mechanical Engineering, University of Gävle, SE-80176 Gävle, Sweden

* Corresponding author: fax: +46 (0)13 281788; E-mail address: maria.johansson@liu.se

Abstract

Awareness of climate change and the threat of rising energy prices have resulted in increased attention being paid to energy issues, and industry seeing a cost benefit in using more energy-efficient production processes. One energy-efficient measure is the recovery of industrial excess heat. However, this option has not been fully investigated and some of the technologies for recovery of excess heat are not yet commercially available.

This paper proposes three technologies for the generation of electricity from low temperature industrial excess heat. The technologies are thermoelectric generation, organic Rankine cycle and phase change material engine system. The technologies are evaluated in relation to each other, with regard to temperature range of the heat source, conversion efficiency, capacity and economy.

Because the technologies use heat of different temperature ranges, there is potential for concurrent implementation of two or more of these technologies. Even if the conversion efficiency of a technology is low, it could be worthwhile to utilise if there is no other use for the excess heat.

The iron and steel industry is energy intensive and its production processes are often conducted at high temperatures. As a consequence large amounts of excess heat are generated. The potential electricity production from low temperature excess heat at a steel plant was calculated together with the corresponding reduction in global CO_2 emissions.

Keywords: Low temperature excess heat, Heat recovery, Electricity generation, Thermoelectric generator (TEG), Organic Rankine cycle (ORC), Phase change material (PCM) engine

1 Introduction

Industry accounts for about 30% of global final energy use and almost 40% of global CO_2 emissions are attributed to industrial activities (IEA 2010). Rising energy prices and requirements to reduce CO_2 emissions are of great concern for energy-intensive industry and energy efficiency measures are therefore an important issue. Energy efficiency measures include, for example 1) production planning; 2) investment in energy-efficient equipment; 3) recycling of energy in the industrial production process; and 4) recovery of excess energy and subsequent utilisation in other processes.

Recovered energy can be used in its original form or converted into other energy forms. However, in order to identify "true" excess heat, it is important that the first three energy efficiency measures listed above are implemented before recovery of excess heat is applied. Recently, technologies for the recovery and utilisation of industrial excess heat have gained increased attention because they offer an opportunity for industry to be more energy efficient and, at the same time, reduce its CO_2 emissions. Excess heat can be distributed to district heating systems or exported to other purchasers with a demand for heat, (e.g., greenhouses and algae cultivation systems). However, if there are no heat sinks in the area the heat can be converted into electricity. Since a high proportion of industrial excess heat has a low temperature, the development of technologies that recover and utilise heat with low temperatures is worthwhile. Moreover, even technologies with low conversion efficiencies can be of interest if there is no other use for the excess heat.

Bianchi & De Pascale (2011) compared and evaluated five technologies for electricity generation from excess heat with temperatures 200–500°C. The technologies were the organic Rankine cycle (ORC), micro Rankine cycle, Stirling engine systems, thermoelectric generation (TEG) and inverted Brayton cycle. The results showed that ORC had the best thermodynamic performance and was the most proven of the technologies. Law et al. (2012) reviewed technologies for low temperature industrial excess heat recovery including the ORC, the Kalina cycle and TEG for electricity generation. They concluded that the ORC was the most mature and tested technology, that the Kalina cycle needed more industrial demonstration and that TEG would only be useful to power low current equipment near the heat source. Chan et el. (2013) reviewed technologies for the utilisation of low-grade excess heat, they grouped into three categories: 1) chemical heat pumps, 2) thermodynamic cycles to produce electricity and 3) energy storage to improve the performance of low-grade heat energy systems. The thermodynamic cycles presented were the ORC, the supercritical Rankine cycle (SRC) and the trilateral cycle (TLC). Chan et el. (2013) concluded that the thermal efficiency of SRC and TLC had the potential to be 10–30% higher and 50–100% higher, respectively, compared to that of ORC. However, according to Chan et al. (2013) TLC is still in the research stage.

The energy-intensive iron and steel industry often conducts production processes at high temperatures. As a consequence, large amounts of excess heat are generated (e.g., heat from hot material, hot flue gases and cooling water of low temperatures). If this excess heat were recovered and utilised, both the steel plant and the society would benefit from reduced energy costs and CO_2 emissions.

The objective of this study is to analyse three technologies for the conversion of low temperature excess heat into electricity. These technologies were evaluated and compared to each other with regard to the temperature range of the heat source, conversion efficiency, capacity and economy. Furthermore, the potential electricity production from low temperature excess heat at a steel plant and corresponding reductions in global CO_2 emissions were calculated and presented in this paper.

2 Methodology

This study is based upon a scanning of technologies for excess heat recovery and energy conversion. The scanning was conducted through a literature survey of books, scientific journals and company websites. Additional information was collected through personal contact with researchers and employees at companies that sell equipment for excess heat recovery and conversion. The technologies chosen for evaluation were 1) TEG; 2) ORC; and 3) phase change material (PCM) engine system. The economic evaluation was performed by calculating and comparing the net present value (NPV) of one example from each technology. The NPV was calculated using Equation 1.

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+i)^t} \qquad \text{Equation 1}$$

where *i* is the discount rate and R_t is the net cash flow during period *t*. A positive value for the NPV infers that the investment is profitable for the company, and the higher the value, the more profitable the investment. The costs of auxiliary equipment, such as pipes for transportation of excess heat and cooling water, were not included in the calculations since they may vary from case to case.

Additionally, annual profit was calculated using Equation 2. This calculation was performed to estimate investment opportunity, (e.g., for buying auxiliary equipment).

$$Annual\ profit = R_{el} - C_c - C_{O\&M} \qquad \text{Equation 2}$$

where R_{el} is revenue for electricity production, C_C is annual capital cost and $C_{O\&M}$ is operation and maintenance (O&M) costs.

Maximum electricity production in a general ORC was calculated using Equation 3 (Asp et al. 2008).

$$Q_{el} = Q_{th} \times \eta \times \left(\frac{T-(30+T_{diff})}{T-30}\right) \qquad \text{Equation 3}$$

where Q_{el} (Wh) is maximum electrical energy that can be produced, Q_{th} (Wh) is the energy content of the excess heat source, η is the electricity efficiency of the ORC, T (°C) is the temperature of the excess heat source and T_{diff} (°C) is the temperature difference between outgoing excess heat flow from the boiler in the ORC and incoming flow of working medium in the ORC. T_{diff} was set at 20°C for liquid excess heat flows and 50°C for gaseous excess heat flows. In this case, evaporation temperature was 30°C for the working medium in the ORC.

Maximum electricity production in a PCM engine system was calculated using Equation 4 (Bengt Östlund, Exencotech AB, personal communication, 30 November 2011).

$$Q_{el} = Q_{th,net} \times 0.024 \times \frac{T_{diff}}{25} \times \frac{1}{k^2} \times \sum_{i=0}^{k-1}(k-i) \qquad \text{Equation 4}$$

where Q_{el} (Wh) is maximum electrical energy that can be produced, $Q_{th,net}$ (Wh) is the energy content of the excess heat source that is used by the PCM engine, T_{diff} (°C) is the temperature difference between ingoing excess heat flow and incoming cooling water. The number of cascades, k, depend on minimum available temperature difference between heat source and heat sink, $T_{diffmin}$ (°C), during operation time with respect to seasonal variations, according to:

k=1, if 20°C ≤ $T_{diffmin}$ < 40°C
k=2, if 40°C ≤ $T_{diffmin}$ < 60°C
k=3, if 60°C ≤ $T_{diffmin}$ < 80°C

and $Q_{th,net}$ depends on the number of cascades, as the temperature difference between ingoing and outgoing excess heat flow is (k x 10)°C.

Potential electricity production at a steel plant was estimated and the resulting reductions in global CO_2 emissions were calculated using a marginal electricity production approach. This implies that the marginal electricity producer reduces its electricity production by an amount equal to what is produced at the steel plant. Potential marginal electricity producers are coal condensing power plants and natural gas combined cycles (NGCC) (Axelsson and Harvey 2010; Lund et al. 2010). If the marginal electricity producer is a coal power plant, global CO_2 emissions would decrease by 809[1] kg/MWh electricity produced from industrial excess heat, and if the marginal electricity producer is a NGCC, the reduction would be 374[2] kg/MWh electricity.

3 Theory

Low temperature heat is defined in this paper as heat with a temperature below 230°C (DOE 2008). Three technologies which use low temperature heat to produce electricity are TEG, ORC and PCM engine system. They are briefly described in the next section.

3.1 Thermoelectric generator (TEG)

In thermoelectric energy conversion, electricity is generated through the Seebeck effect in which a voltage difference is generated in a conductor or semiconductor, due to a temperature difference in the material. For example, when a rod of metal is heated at one end and cooled at the other, the electrons in the hot end become more energetic and start to move towards the cooler end. This results in a positively charged hot end and a negatively charged cold end, which builds up an electric potential difference in the material. The thermoelectric voltage developed per unit of temperature difference is called the Seebeck coefficient. (Kasap 2001)

A thermoelectric generator (TEG) is a device that uses the Seebeck effect to produce electricity. A TEG is comprised of one or more thermoelectric modules followed by a cooling system. A module is a large number of thermocouples connected electrically in series and thermally in parallel (Rowe 2005). A thermocouple consists of two semiconductors with different Seebeck coefficients. The voltage output from a thermocouple is hundreds of microvolts per temperature degree difference. The voltage output is directly proportional to the number of thermocouples, the Seebeck coefficients of n- and p-type semiconductors and the temperature difference between the hot and cold side. A schematic basic thermocouple can be seen in Fig. 1.

[1] LCA CO_2 emissions for a coal power plant with electricity efficiency 0.45.
[2] LCA CO_2 emissions for a NGCC plant with electricity efficiency 0.60.

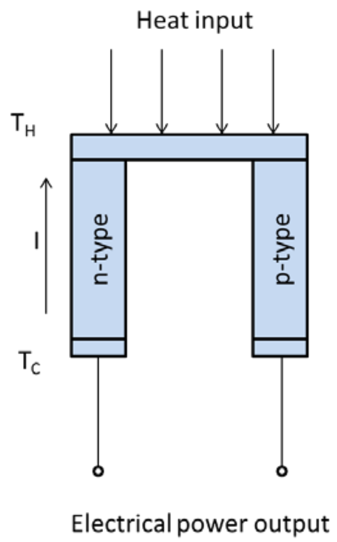

Fig. 1 Schematic basic thermocouple. The thermocouple is two semiconductors, one n-type and one p-type, which are connected in a circuit. When the junctions are set at different temperatures, T_H (hot side) and T_C (cold side), the Seebeck effect generates thermoelectric power. (Modified from Rowe (2005))

A thermoelectric material has a specific temperature at which the conversion efficiency is at its maximum. Thus, when working in a temperature range, the material often operates below its potential maximum performance. To increase its performance, a TEG can be segmented with materials optimised for different temperature ranges. (Rowe, 2005)

Commercially used thermoelectric materials can be divided into three groups (Qiu and Hayden 2012):

- low temperature materials, up to about 250°C, (e.g., materials based on bismuth telluride)
- intermediate temperature materials, up to about 600°C, (e.g., materials based on lead telluride)
- high temperature materials, up to about 1000°C, (e.g., silicon germanium alloys)

Recently, scientists have made progress in synthesising new materials (Bubnova et al. 2011) and in constructing materials with low-dimensional structures (Liu et al. 2012) with enhanced thermoelectric performance.

Heat-to-power conversion efficiency depends upon temperature difference between hot and cold side, the material properties of the semiconductors and external load resistance (Rowe 2005). Chen et al. (2012) did experimental studies on the thermodynamic performance of TE modules and found that power generation strongly depended on the temperature of the heat source. This finding was confirmed by Gou et al. (2013), who showed that TEG power output mainly depended on temperature difference between hot and cold side. However, enhancing cooling at the cold side improved the power output more than increasing temperature on the hot side did. Karabetoglu et al. (2012) analysed maximum power output from a commercially available TEG based on Bi_2Te_3 and found that a mean operating temperature of 250K was a critical point for maximal power output.

Riffat and Xiaoli (2003) suggested the recovery of excess heat from automobiles, from flue gases at incinerations plants and from hot gases and liquids in industry as potential applications for TEG. According to Riffat and Xiaoli (2003), another possible application could be power generation in spacecraft and TEG power plants on Mars. Recovery of excess heat from automobiles to save fuel has been studied (e.g., Korzhuev and Katin 2010; Kumar et al. 2013; Tatarinov et al. 2012; and Wang et al. 2013c). O'Shaughnessy et al. (2013) presented results from small-scale electricity generation with a TEG integrated with a cooking stove. The installation was tested in Malawi to charge mobile phones, lights and radios. Chen et al. (2010) modelled integration of TEG in combined heat and power (CHP) production and showed reduced fuel demand and reduced CO_2 emissions compared to a CHP production without TEG. Ogbonnaya et al. (2013) integrated a small-scale solar thermal collector with a TEG and the results of the study showed a larger power output if the thermal solar collector was coated with a selective absorber.

3.2 Organic Rankine Cycle (ORC)

The Rankine cycle is a process which converts thermal energy into work. During the process, a working medium, usually water, circulates in a closed loop and changes between liquid and gaseous phases during a power cycle. The liquid working medium is pressurized and pumped into a boiler where it is heated and vaporized into a gas. The gaseous working medium expands in a turbine and the mechanical energy generates electricity in a generator. The working medium is then cooled into liquid form in a condenser and pumped back to the boiler. (Opcon 2012)

The ORC is a Rankine cycle which uses an organic working fluid with a lower boiling point than water. Hence, heat sources with lower temperatures can be used than in a traditional Rankine cycle. There are organic fluids with a wide range of boiling points, and a suitable organic fluid is chosen to match the temperature of the heat source. Fig. 2 shows an example of an ORC process.

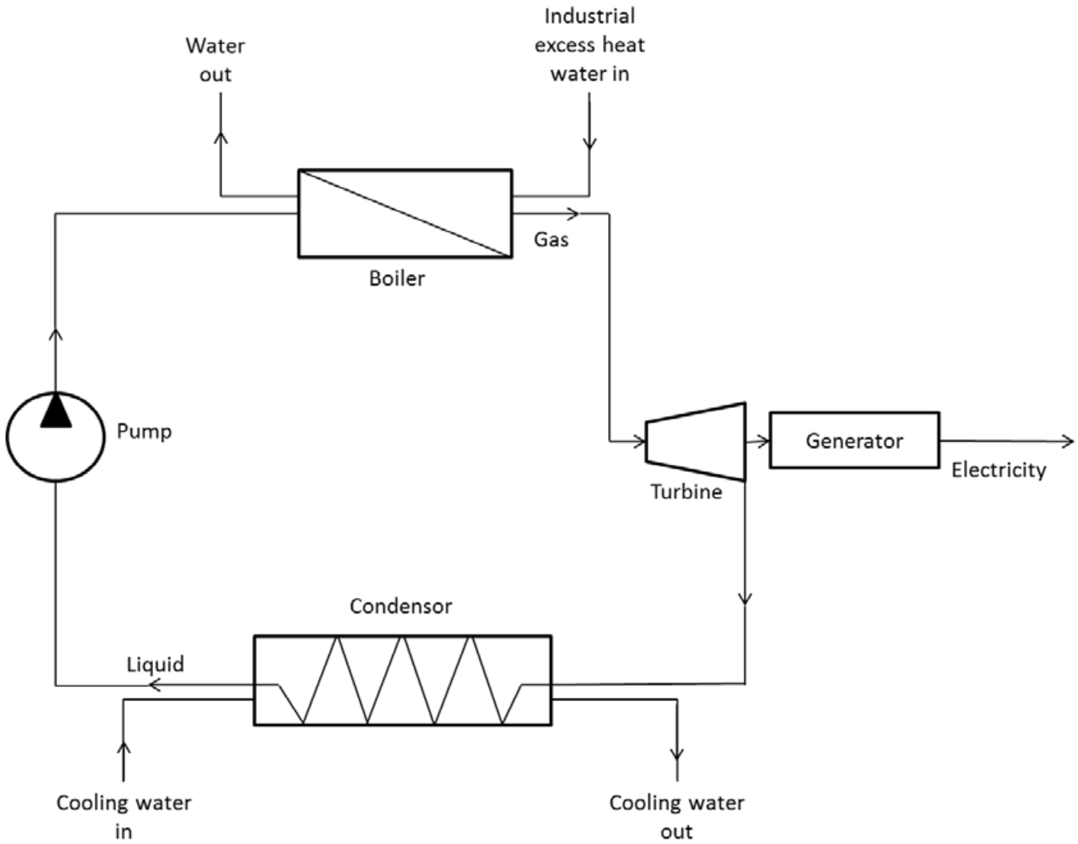

Fig. 2 In an ORC process, the organic working medium circulates in a closed loop. In a power cycle, the fluid is pumped to a boiler where it is heated to above boiling point under pressure. The gaseous working medium is then expanded in a turbine and the mechanical energy is converted into electricity in a generator. The working medium is cooled in a condenser and the fluid is again pumped into the boiler (Modified from Opcon (2012)).

The conversion efficiency depends upon the temperature difference between the heat source and the heat sink, the heat of vaporisation of the working medium and the phase of the heat source. The working medium is a key factor in the thermodynamic performance of the ORC process. Several studies have investigated the performance and characteristics of different organic fluids for ORC, (e.g., Aghahosseini and Dincer (2013), Han and Yu (2012), Lliu et al. (2013), Vélez et al. (2012) and Wang et al. (2013a)). Furthermore, temperature and flow of both heat source and cooling water are important factors in the conversion efficiency.

In studies on the use of ORC for heat recovery,Vélez et al. (2012) and Quoilin et al. (2013) presented an overview of different ORC applications, (e.g., solar thermal power, biomass CHP, geothermal and industrial excess heat). They performed a market review, did an economic analysis and discussed the choice of working fluid. In a study of ORC applications, (e.g., solar thermal electricity, ocean thermal energy conversion, biomass powered CHP and industrial excess heat), Tchanche et al. (2011) included a review of current state of the technology and possible heat sources.

Walsh and Thornley (2012a; 2012b) analysed the economic and environmental impact of low-grade heat recovery with ORC applied in industrial case studies. They found that when heat in flue gases from coke production at a steel plant was recovered and used to produce electricity, the process could be profitable, but this depended on the targets set by industry. Furthermore, heat recovery with ORC would reduce lifecycle greenhouse gas emissions of coke production. Öhman (2012) presented and analysed field data from an ORC installed to produce electricity from excess heat at a pulp mill. The results showed a thermal efficiency of 8–9% at capacities 50–100%. Wang et al. (2013b) did a parametric optimisation of an ORC and analysed the maximum ratio of net power output and total heat transfer area from an economic point of view. They concluded that a number of factors significantly affected net power output and heat transfer area: the turbine inlet pressure; the turbine inlet temperature; the temperature difference between the heat source leaving the evaporator and the boiling point corresponding to the evaporation pressure; and the temperature difference between the boiling point corresponding to the evaporation pressure and the exit temperature of working fluid from sub-cooled region.

3.3 Phase Change Material (PCM) engine system

The Phase Change Material (PCM) engine system uses volume expansion of a PCM, when it changes from solid to liquid phase, to produce electricity. The PCM used by the PCM engine system is a paraffin mixture and its composition can be adjusted to suit specific applications. The system's key component is an energy cell in which heat is converted into mechanical energy. A heat source heats the paraffin in the energy cell and the paraffin melts and expands under high pressure (300–400 bar). The liquid is then cooled and changes back to solid state and the volume is reduced. The work of expansion and contraction is captured in a hydraulic system and converted into electricity by a generator. In a heat power cycle, the PCM changes from solid to liquid phase and then back to solid phase. (Bengt Östlund, Exencotech AB, personal communication, 30 November 2011) Fig. 3 shows a schematic picture of an electricity generating system using PCM technology.

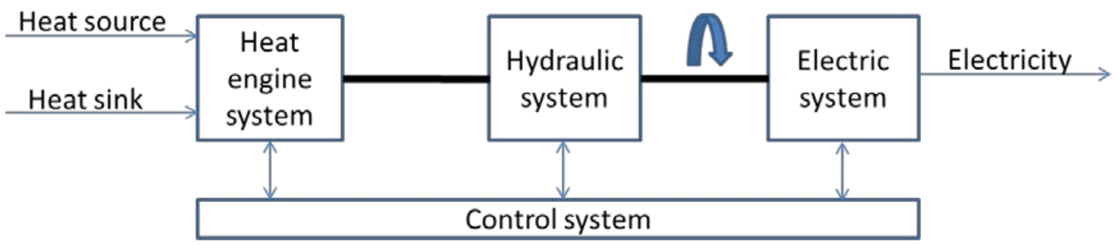

Fig. 3 Schematic picture of the PCM engine system. The heat is converted into electricity. In an energy cell in the heat engine system, heat is absorbed by a paraffin mixture which changes from solid to liquid phase. This results in a volume expansion. The liquid paraffin is then cooled and changes back to solid state and the volume is reduced. The work of expansion/contraction is captured in a hydraulic system and the mechanical energy is then converted into electricity by a generator. (Exencotech 2012)

The heat source must be in a liquid form and water must be available for cooling. The heat source and cooling water have equal flow rates and the power output is linearly proportional to the flow of the heat source and heat sink. (Bengt Östlund, Exencotech AB, personal communication, 30 November 2011)

To the authors' knowledge, there are no other publications about electricity generation technologies based on solid PCM. Research on PCM has mainly focused on thermal energy storage. That application is known as latent heat storage and, in comparison to sensible heat storage, latent heat storage provides higher energy storage density (Farid et al. 2004; Zalba et al. 2003).

4 Results

In this section, the technical performance and economy of TEG, ORC and PCM engine system are evaluated in relation to each other. This study used configurations of these technologies designed for low temperature heat recovery. For TEG, modules based on bismuth telluride were evaluated because this is a low temperature material. Finally, the potential electricity production from low-temperature excess heat at a steel plant is presented. Opcon 2012; Turboden 2012; Electratherm 2012; Pratt & Whitney 2012; Ormat 2012)

4.1 Technical performance

TEG, ORC and PCM engine system have different applications because they operate in different temperature ranges. TEG based on bismuth telluride can utilise a heat source with temperatures from 150 to 300 °C (Hi-Z Technology 2012; TEG Power 2012; Tellurex 2012; Termo-Gen AB 2012). ORC designed for low-temperature heat sources can utilise heat sources with temperatures between 55 and 300 °C (Electratherm 2012; Pratt and Whitney 2012; Opcon 2012; Ormat 2012; Turboden 2012), while the PCM engine system can produce electricity from a heat source with temperatures between 25 and 95 °C (Exencotech 2012). Table 1 gives the specification data of the technologies.

Table 1 Specifications of three technologies for converting low temperature excess heat into electricity. Information was taken from Hi-Z Technology (2012), TEG Power (2012), Tellurex (2012), Termo-Gen AB (2012), Electratherm (2012), Opcon (2012), Ormat (2012), Pratt & Whitney (2012), Turboden (2012) and Exencotech (2012).

	TEG (bismuth telluride)	**ORC**	**PCM engine**
Converter mechanism	Solid state converter: semiconductors	Phase change cycle: liquid–gas	Phase change cycle: solid–liquid
Working medium	Charge carriers (electrons and holes)	Organic fluid	Paraffin
Heat source temperature	150–300°C	55–300°C	25–95°C
Heat sink	Water cooled	Water cooled	Water cooled
	Air cooled (free convection or forced convection)	Air cooled (forced convection)	
Conversion efficiency	1–5%	7.5–16%	2.5% at ΔT=24°C between heat source and heat sink (increases by 2.5 percentage points for every increase in ΔT by 24°C)
Size	0–500 W_{el}	30 kW_{el}–20 MW_{el}	10 kW_{el}– 1 MW_{el}
Technical lifetime	11–30 years	20–30 years	20 years
Stage of development	Commercially available on a small scale	Commercially available	First customer installation planned in 2013

The conversion efficiency is subject to the temperature difference between the heat source and heat sink for all three technologies and the power output depends on the heat flow rate. Moreover, the systems can be optimised for a specific heat source temperature by choosing the appropriate TE material or working medium.

ORC systems and PCM engine systems can be purchased in sizes of kW_{el} up to MW_{el} (Opcon 2012; Turboden 2012; Electratherm 2012; Pratt & Whitney 2012; Ormat 2012; Bengt Östlund, Exencotech AB, personal communication, 30 November 2011). In contrast, TEG systems are only available up to 500 W_{el} (Tellurex 2012; TEG Power 2012; Termo-Gen AB 2012; Hi-Z Technology 2012). Upscaling of TEG modules is limited by thermal expansion and contraction of the thermoelectric materials (Tellurex 2012). One side of the TE material expands as it heats while the other side contracts as it cools and so the thermoelectric elements and their solder junctions are stressed. Over time, this will result in an increased electrical resistance. Since the thermal expansion is based on length, the larger the TEG, the greater the stress. However, it would be possible to connect more than one TEG to the same heat source in order to recover more energy from a large heat source. However, cost may be a barrier for using larger TEG systems based on telluride, because tellurium is a rare metal. With regard to ORC and PCM engine systems, there are essentially no barriers for upscaling other than the weight and volume of the equipment and the amount of cooling water available.

The reported lifetime for TEG modules is 11–30 years (Termo-Gen AB 2012; Riffat and Xiaoli 2003), but the lifetime can be reduced if the modules are exposed to repeated hot side temperature changes. Repeated heating-cooling cycles may cause material deterioration of a TEG (Hatzikraniotis et al. 2010), so it is preferable to use TEGs in continuous heat flows. Both the ORC and PCM engine systems can manage an intermittent heat flow but the electricity efficiency is reduced and, consequently, the profitability. For example, in a 750 kW_{el} Opcon Powerbox (an ORC), the equipment is automatically turned off if the power output is below 40–45 kW_{el} because the operation costs exceed the income for produced electricity (Henrik Öhman, Opcon AB, personal communication, 25 November 2011). The lifetime for an ORC is 20–30 years (Opcon 2012; Turboden 2012) and the expected lifetime for a PCM engine system is 20 years (Exencotech 2012).

The three technologies are at different stages of development. Small-scale TEG modules based on bismuth telluride are commercially available from a range of suppliers, but TEG systems larger than 500 W_{el} are not available. On the other hand, different sizes of ORC systems, ranging from kW_{el} to MW_{el}, are commercially available from a number of companies. With regard to the PCM engine system, the technology is fully developed and the first customer installation is planned for 2013.

4.2 Economy

The TEG and ORC systems can be purchased from a number of companies, but the PCM engine system can only be bought from one company. To perform an economic evaluation of the technologies, one example of each technology was evaluated.

As noted, TEG modules made of bismuth telluride were used; they are typically in the range of 0 to 500 W_{el}. Tellurium is a rare metal and large TEG modules based on telluride are expensive. Consequently, moderate module sizes are used. In this study, a F2F200W fluid-to-fluid TEG from TEG Power (TEG Power 2012) was used as an example in the economic evaluation. This device can generate 200 W if the heat source has a temperature over 270°C and the cooling water flow is 0.09 m^3/h at 30°C. Multiple units can be used to generate higher outputs. If the hot water were below

100°C, this TEG would yield approximately 20–25% of its maximum rating. The retail price is EUR 1,600[3]. Because TEG modules have no moving parts, there are basically no O&M costs.

The ORC system chosen for the economic evaluation was a 750 kW_{el} Opcon Powerbox from Opcon AB (Opcon 2012). The Opcon Powerbox operates with R717 (ammonia), R410a, R134a, R236fa or R245fa as working fluid, and the system can operate with a heat source temperature between 55°C and 150°C. The electrical efficiency of the system is approximately 8.4% at match load conditions. Investment cost including installation was MEUR 1.2–1.3 and O&M costs were 11,300 EUR/year (Henrik Öhman, Opcon AB, personal communication, 25 November 2011, and Henrik Österman, Opcon AB, personal communication, 7 December 2011).

The PCM engine system chosen for the economic evaluation was one from Exencotech AB (Exencotech 2012). The investment cost including installation for a 100–200 kW_{el} PCM engine system was 2,140 EUR/kW_{el} and for a 1 MW_{el} system the investment cost was 1,910 EUR/kW_{el}. The O&M costs were 4.5 EUR/MWh_{el}. For example, the investment cost for a 750 kW_{el} system with an operation time of 8,000 h/year was MEUR 1.5 and corresponding O&M costs were 27,000 EUR/year. (Bengt Östlund, Exencotech AB, personal communication, 30 November 2011)

To compare investment opportunities, NPV and annual profit for the above-mentioned systems were calculated. Electricity prices were the average seasonal Elspot prices at Nord Pool 2010. The results of the calculations can be seen in Table 2.

Table 2 Economic evaluation of a TEG, an ORC and a PCM engine system. The operation time is 8,000 h/year and the electricity price was set at 61 EUR/MWh during winter (4,000 h/year) and 45 EUR/MWh during summer (4,000 h/year). For calculations of the NPV a discount rate of 10% was used. For calculations of annual profit, a capital recovery factor of 13% (10% annual interest, 15-year discount period) was used. EUR/SEK=8.88

Technology	**TEG (TEG Power)**	**ORC (Opcon Powerbox)**				**PCM engine system (Exencotech AB)**			
Heat source:									
Temperature (°C)	270	90	85	75	60	90	85	75	60
Flow (m^3/h)		350	350	350	350	350	350	350	350
Heat sink:									
Temperature (°C)									
Winter	30	5	5	5	5	5	5	5	5
Summer	30	20	20	20	20	20	20	20	20
Flow (m^3/h)	0.09	700	700	700	700	350	350	350	350
Net produced electricity[a] (kW)									
Winter	0.2	770	680	530	325	695	647	405	324
Summer	0.2	530	450	300	95	573	525	324	227
Size of the equipment (kW_{el})	0.2	750	750	750	750	700	650	410	350

[3] EUR/USD=1.24

Investment cost (MEUR)	0.0016	1.2	1.2	1.2	1.2	1.4	1.3	0.8	0.7
O&M costs (EUR/year)	-	11,300	11,300	11,300	11,300	22,800	21,100	13,100	9,900
Net present value (MEUR):									
Economic lifetime 30 years	-0.0007	1.24	0.93	0.38	-0.36				
Economic lifetime 20 years	-0.0008	1.01	0.73	0.24	-0.43	0.64	0.59	0.36	0.21
Annual capital cost (EUR/year)	210	158,000	158,000	158,000	158,000	187,000	173,000	109,000	93,000
Annual profit (EUR/year)	-130	114,000	78,000	14,000	-73,000	63,000	58,000	35,000	17,000

The calculations indicated a negative NPV for the TEG system. On the other hand, the results showed a positive NPV for the Opcon Powerbox, if the heat source had a temperature of 75°C or higher. With regard to the PCM engine system, the NPV was positive for all heat source temperatures analysed. A positive NPV implies an investment opportunity for auxiliary equipment and can result in a cost-effective total investment. When analysing investment opportunity, it is important to include the costs for pipes and pumps for excess heat flows and cooling water; they must be evaluated case by case and may form a significant portion of total costs. However, additional advantages (e.g., reduced operation costs in external coolers) could influence the profitability in a positive direction.

A comparison of the profitability of the ORC and PCM engine systems indicates that it would be best to invest in an ORC system if the heat source has a temperature above 80°C and in a PCM engine system if the heat source has a temperature below 80°C (see Fig. 4).

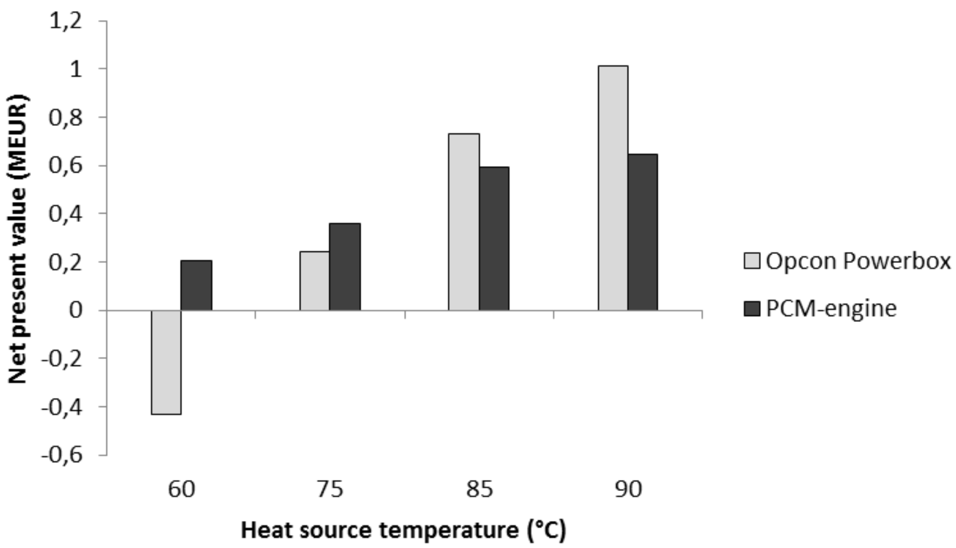

Fig. 4 The net present value of the Opcon Powerbox (an ORC system) and the PCM engine system, operating 8,000 h/year with a heat source flow rate of 350m3/h. For 4,000 h/year, the cooling water has a temperature of 5°C and 4,000 h/year the cooling water temperature is 20°C. The discount rate is 10 % and economic lifetime is 20 years

4.3 Applications in the steel industry

The iron and steel industry is an energy-intensive industry and its production processes are often performed at high temperatures. As a result, large amounts of excess heat are generated. In this study, potential electricity generation from excess heat was calculated for a steel plant if ORC and PCM engine systems were installed. Because TEG based on bismuth telluride has limitations in upscaling capacity and low conversion efficiency, it is not suitable for large-scale heat recovery in the industry. Therefore, this technology was not included in the analysis of potential electricity generation.

The steel plant is a scrap-based plant that produces stainless steel and further refines it into bars and sheets (Asp et al. 2008). It produces about 450 kt steel per year and its electric arc furnace (EAF) has a charge-weight of 100 tonnes. The steel plant's annual energy use is around 420 GWh of electricity, 130 GWh of oil, 340 GWh of LPG and 40 GWh of district heating. Examples of excess heat flows are heat from hot steel products and slag with temperatures of 600–900°C, hot flue gases with temperatures of 230–320°C and cooling water with temperatures of 60–100°C (Asp et al. 2008). Table 3 shows a compilation of the excess heat flows of interest for this study (i.e. heat with temperatures up to 230°C). Heat with temperatures below 50°C has not been quantified.

Table 3 Excess heat produced at a scrap-based steel plant with production of 450 kt steel per year. Only heat sources with temperatures between 50°C and 230°C are presented. The reference temperature of the heat is 30°C. The information is taken from Asp et al. (2008).

Heat source	Energy (GWh/year)	Temperature (°C)	Power (kW)
Cooling water from ingot casting	8	60	900
Cooling water from electric arc furnace	20	95	2,500
Cooling water from heating furnaces	36	100	4,400

As presented in section 4.2, ORC would be more profitable if the heat source temperature was higher than 80°C and the PCM engine system would be more cost-effective if the heat source temperature was below 80°C. Hence, in the estimations of potential electricity production from excess heat at the steel plant, ORC with a conversion efficiency of 8.4% was used as the technology for the energy recovery of cooling water from EAF and heating furnaces while the PCM engine system was used for the energy recovery of cooling water from ingot casting. In the calculations, maximum electricity production was calculated with equations 3 and 4. At the steel plant, the potential electricity production from excess heat with temperatures below 230°C is 3.5[4] GWh/year. If the marginal electricity producer were a coal condensing power plant, electricity production from low temperature excess heat at the steel plant would result in reduced global CO_2 emissions by 2.8 kt per year. However, if the marginal electricity producer were a NGCC plant, reductions in global CO_2 emissions would be 1.3 kt per year.

[4] Of the total 8 GWh thermal energy from ingot casting, the PCM-engine uses 5.3 GWh, because at k=2 the temperature difference between ingoing and outgoing excess heat flow is 20°C.

The PCM engine system has no competing electricity generating technology in the temperature range 25–55°C. In the iron and steel industry, large amounts of cooling water with a temperature of 20–40°C are generated in the production processes, hence the PCM engine could be a technology with great potential.

5 Concluding discussion

The TEG, ORC and PCM engine systems are three technologies for low temperature heat recovery. Their required temperature of heat source overlap somewhat, but the PCM engine system is the only technology which can utilise heat sources with temperatures below 55°C. One drawback for TEG based on bismuth telluride is the limitation in upscaling capacity and its low conversion efficiency. As a result, at this time, this technology is not applicable for large-scale heat recovery. However, TEG modules that use other materials (on research stage) could be a competitive technology for recovery of low temperature industrial excess heat.

The NPV was calculated for investments in ORC and PCM engine systems for recovery of excess heat with a flow rate of 350 m^3/h. The temperature of the heat source in the calculations ranged from 60°C to 90°C. Calculations of the NPV showed that investment in a 750 kW_{el} ORC from Opcon AB could be profitable at today's electricity price if the heat source had a temperature of 75°C or higher. Investment in a PCM engine system from Exencotech AB could be profitable at all the temperature ranges investigated. However, for a heat source with temperatures higher than 80°C, it would be more cost-efficient to invest in an Opcon Powerbox than a PCM engine system. It is noteworthy that in the comparison between Opcon Powerbox and PCM engine system, the size of the ORC equipment was fixed at 750 kW_{el}, but the size of the PCM engine equipment was adjusted to the energy content of the heat source. The NPV was negative for the TEG system. The costs for piping and pumping excess heat water and cooling water were not included in the calculations because these are site-specific. These costs may be a significant part of the total costs and the annual profits presented in this study can serve as a guideline for investment opportunity for such equipment. It is important to mention that while the economic evaluation was conducted on one system for each technology, a number of ORC and TEG systems are for sale. However, it was not workable to perform an economic comparison of all of them.

In the calculations of potential electricity production, the cooling water temperature was set at 20°C for 4,000 h/year. This assumption could result in an underestimated potential electricity generation, (e.g., in Northern Europe many rivers, lakes and oceans have a temperature of less than 20°C for more than 4,000 h/year).

It is difficult to draw general conclusions about investment opportunities for electricity production from excess heat e.g., because of industry variations in pricing. The profitability of electricity production from low temperature excess heat depends on electricity price. Green certificates or renewable energy certificates promote electricity production from renewable sources such as wind, solar, hydro, geothermal and biomass. If electricity production from industrial excess heat were to receive a similar certificate, the incentives to invest in TEG, ORC and PCM engine systems would increase. The end-user prices of electricity differ between end-user categories, (e.g., energy-intensive industries have lower electricity prices than small enterprises). Moreover, electricity costs for an industry may not be reflected in the price on the electricity market due to different power purchasing strategies. Some industries have long-term contracts while others have purchasing strategies based on forward electricity prices (Reinaud (2007). In addition, the electricity pricing mechanism differs between countries and regions. Furthermore, in the economic evaluation in this study, the electricity prices were set at the Nordic price level of 2010. Because the European Commission promotes a European electricity market, Nordic prices will all rise to the higher price level in the rest of Europe. Therefore, the calculations of investment opportunity may be a bit pessimistic.

An obstacle for generating electricity from industrial excess heat is that this may not be a core capability of industry. This problem was discussed by Ammar et al. (2012). However, some suppliers of electricity generation equipment lease out the equipment and administer all operations and maintenance.

Because the excess heat flows at a steel mill are of varying temperatures, it would be possible to concurrently implement two or more of the technologies. The technology best suited for a specific heat source should be chosen. Potential electricity production from low temperature excess heat at a steel plant with production of 450 kt steel per year was estimated at 3.5 GWh/year. If the marginal technology for electricity production were a coal power plant, the corresponding reduction in global CO_2 emissions would be 2.8 kt per year and if the marginal electricity producer were a NGCC plant, the reduction would be 1.3 kt per year.

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