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Theoretical Potential to Convert Excess Heat into Mechanical Work in the Finnish Industry

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The improvement of energy efficiency is seen as one of the most promising measures for reducing global emissions and dependence on fossil fuels. One opportunity for boosting the energy efficiency is to enhance the utilization of excess heat. The excess heat means waste energy which is not exploited in any manner. Most of the excess heat is generated in the industry. One possibility is to convert excess heat into mechanical work (electricity) using different conversion technologies. These technologies are for example Kalina cycle and organic Rankine cycle. The goal of this paper is to evaluate theoretical potential to convert excess heat into electricity in Finnish forest industry, chemical industry and refining of metals using the exergy analysis. According to the results, the total theoretical exergy potential is 6.9 TWh/y, which is 10 % of the electricity produced in Finland in 2011.

1. Introduction

The use and cost of energy have constantly increased due to economic growth and well-being of humans. Most of the energy use is covered by combusting fossil fuels which increases CO_2 emissions. The European Union (EU) aims to reach 20 % savings in primary energy use, increase use of the renewable energy resources by 20 % and decrease CO_2 emissions by 20 % from the 1990 levels by the year of 2020. The improvement of energy efficiency is seen as one of the most promising and cost-effective measures for reducing global emissions, consumption and dependence on fossil fuels. The enhancement in energy use is fulfilled when energy is consumed less to deliver a service or, when more services are delivered than before by the same energy input. In Finland, the industry is the most significant end user of energy, which makes it the most potential sector in society to improve the energy efficiency.
The energy used by the industry can be divided into primary energy and secondary energy. Primary energy refers to fuel or electricity which is obtained outside the mill or produced and used by the mill itself. The majority of the primary energy converts into heat in the process in which primary energy is used. The generated heat from the process is called the secondary energy when it is utilized somehow in next processes. The energy which is not used anymore or put into practical use is called the excess or waste heat. In the industry the excess heat is usually accumulated into exhaust steam, flue gases, waste water, coolant water, exhaust gases from a drier, process gases, or it is released heat from condensation of mechanical refrigeration or exhausts of production area. (YIT, 2010) Utilization of excess heat can be described as a green, carbon neutral, energy source as it is making use of what is essentially a waste product (Law et al., 2012).
Primarily, excess heat should be used internally in plants' own processes. The most economical practice is to use heat where it is formed because utilization and formation are simultaneous and near each other (YIT, 2010). The most general and conventional method to utilize excess heat is heating of a stream by excess heat. The excess heat is used for example in district heating (YIT, 2010). The excess heat can also be upgraded for example by a heat pump (Ingman et al. 2007) or used as a heat source in biomass drying (Li et al., 2012). It is also possible to convert excess heat into mechanical work (electricity) using different conversion technologies such as organic Rankine cycle (ORC) (Goldschmidt, 2009; Varga et al., 2012) and Kalina cycle (Ogriseck 2009). Johansson and Söderström (2011) have been studied several options to use excess heat: for example thermal energy storage, ORC and Kalina cycle, for the Swedish steel

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industry. Law et al., (2012) have been examined the low-grade waste heat sources common to the food and drinks processing industry and the various opportunities for the use of the heat (for example ORC, Kalina cycle and heat pumps). Wang et al., (2009) have also studied conversion of excess heat into mechanical work by ORC or Kalina in a cement plant.

The Efficient Energy Use (EFEU) research program has begun in Finland in 2012. The program focuses on building knowledge and competence to enable future economic growth in new energy efficiency product and service innovations. Part of the EFEU program aims to minimize excess heat in the industry. The aim of this study is to evaluate theoretical potential to convert excess heat into electricity in Finnish forest industry, chemical industry and refining of metals using the exergy analysis. Available excess heat potential used in the analysis is based on the YIT report called Exploitation of excess heat from the industry in district heating (in Finnish) made on assignment from the Finnish Energy Industries and the Ministry of Employment and Economy in Finland.

2. Excess heat potential of the Finnish industry

In Finland the total electricity consumption of the whole industry was 41.4 TWh in 2011. The greatest user of electricity was forest industry (over 51 %) and next biggest users were chemical industry (17 %) and refining of metals (13 %) (OSF, 2012). Manufacturing of timber, wood, cork, paper and board products are included in the forest industry. Manufacturing of coke, oil refining and chemical products are incorporated into the chemical industry. The field of refining of metals consists only of the sector Refining of metals. The excess heat potential has been evaluated in the YIT report by collecting data from specific mills of each sector and their calculated excess heat potential is then proportioned to the whole industrial sector. Table 1 presents the excess heat potential and temperature ranges of various excess heat streams for the Manufacturing of timber, wood and cork products and Table 2 shows the same data for the paper and board industry. Nine Finnish mills of the paper and board industry are selected in the report and these mills are divided into three types (A,B,C) according to their energy consumption. The data of Table 2 does not include the excess heat of which temperature is under 35 °C (YIT, 2010). In this study, relative share amounts (Table 2) are calculated from the excess heat potential values of examined mills and these relative share amounts are used to calculate the excess heat potential of each stream in the whole sector. The total excess heat potential of the paper and board industry is 18,740 GWh/y according to the report.

Table 1: The excess heat potential for Manufacturing of timber, wood and cork products (YIT, 2010)

Stream	Temperature [°C]	Excess heat potential of the sector [GWh/y]
Exhaust gas	120-155 / 135	1,938
Exhaust gas	65-25 / 55	2,626

Table 2: The excess heat potential for Manufacturing of paper, board and paper products (YIT, 2010)

Mill type	Stream	Temperature [°C]	Excess heat potential of the examined mill [GWh/y]	Relative share, the examined mill [%]	Excess heat potential of the whole sector [GWh/y]
Mill A1	flue gas	126	81.8	2.294	429.8
	air	50-70	49.2	1.380	258.5
	water	41.5	3.2	0.090	16.8
Mill A2	air	40-50	16.2	0.454	85.1
	water	43-45.2	24.6	0.690	129.3
Mill A3	air	-	25.9	0.726	136.1
	water	39-41	10.6	0.297	55.7
Mill B4	flue gas	-	108.8	3.051	571.7
	air	50-70	185.8	5.210	976.3
	water	70-75	147.2	4.127	773.4
	water	70	56	1.570	294.2
Mill B5	air	50-70	222.3	6.233	1,168.0
	water	42-52	79.4	2.226	417.2
	steam	100-120	168	4.711	882.7
Mill B6	air	50-70	135.7	3.805	713.0
	water	40-45	131.5	3.687	690.9
	steam/ water	100 / 75	118.4	3.320	622.1

Table 2: The excess heat potential for Manufacturing of paper, board and paper products (YIT, 2010)

Mill C7	air	50-65	203.8	5.714	1,070.8
	water	80	39.3	1.102	206.5
	water	65-70	44.7	1.253	234.9
	water	70	96.8	2.714	508.6
	flue gas	160	24	0.673	126.1
	flue gas	160	347.5	9.743	1,825.9
Mill C8	air	60-70	203.8	5.714	1,070.8
	water	80	249.5	6.996	1,311.0
	water	46	23.1	0.648	121.4
	water	65-70	85.6	2.400	449.8
	flue gas	180	62.4	1.750	327.9
	flue gas	180	451.8	12.668	2,373.9
Mill C9	air	60-70	78.4	2.198	411.9
	water	70-80	20.8	0.583	109.3
	air/ steam	60 / 140	15.2	0.426	79.9
	flue gas	120	55.2	1.548	290.0
		TOTAL:	3,566.5	100	18,739.7

The excess heat potential of Manufacturing of coke and oil refining products, and Manufacturing of chemicals and chemical products are shown in Tables 3 and 4 respectively. It should be noticed that the excess heat potential of Manufacturing of chemicals and chemical products sector is evaluated only for one Finnish mill (Borealis Polymers Oy) in the report of YIT. The excess heat potential of Refining of metals is shown in Table 5.

Table 3: The excess heat potential for Manufacturing of coke and oil refining products (YIT, 2010)

Stream	Temperature [°C]	Excess heat potential of the sector [GWh/y]
Water	20-40	7,525
Flue gas	170-600	2,167
Air	40-190	2,296

Table 4: The excess heat potential for Manufacturing of chemicals and chemical products (YIT, 2010)

Stream	Temperature [°C]	Excess heat potential of the sector [GWh/y]
Water	>70	360
Water	80-90	240
Water	65-70	240
Water	-	2,160

Table 5: The excess heat potential for Refining of metals (YIT, 2010)

Stream	Temperature [°C]	Excess heat potential of the sector [GWh/y]
Water	over 50	1,830
Flue gas/ process gas	250-700	4,800
-	below 55	8,270

3. Theory

In thermodynamics exergy is defined as the maximum amount of useful work that a system can perform when it is brought into thermodynamic equilibrium with its surrounding by reversible processes. The theoretical maximum power production available can be calculated by using the classic exergy equation (W_{theor}, physical exergy):

$$W_{theor} = \dot{m}(e - e_0) = \dot{m}[h - h_0 - T_0(s - s_0)] \quad (1)$$

Where $\dot{m}$ is the mass flow, e the initial exergy of a stream of substance, e_0 the exergy of a stream of substance in the state of the surroundings, h the initial enthalpy, s the initial entropy, T_0 is temperature [K] of the surroundings. The enthalpy and entropy values for steam and water are taken from Schmidt's steam tables. The air and flue gas are assumed to follow the equation of state for a perfect gas. Thus for air and flue gas physical exergy is calculated using Eq(2).

$$W_{theor} = \dot{m}[c_p(T - T_0) - T_0\left(c_p ln\frac{T}{T_0} - \frac{R}{M} ln\frac{p}{p_0}\right)] \quad (2)$$

Where T is the temperature [K] of the excess heat, c_p the average specific heat capacity between the temperatures T and T_0, R the molar gas constant, M the molar mass of the gas, p the pressure of the stream and p_0 the pressure of the surroundings. The mass flow for each excess heat stream is evaluated using Eq(3).

$$Q = \dot{m}c_p(T - T_0) \quad (3)$$

Where Q is the excess heat potential, T the initial temperature of the excess heat and T_0 the temperature of the surroundings (assumed to be 15 °C). The initial temperature is either precise or average value. The reference environment state (T_0, p_0) is assumed to be 15 °C and 1.01325 bar in the exergy calculations. When calculating the theoretical work gained from the excess air or flue gas, the initial pressure (p) is assumed to be 1.01325 bar and for the flue gas the average specific heat capacity is assumed to be 1.1 kJ/(kgK). The available excess steam is assumed to be saturated.

4. Results and discussion

Tables 6 and 7 show the temperatures of the excess heat streams used in the exergy calculations and theoretical exergy potential for the forest industry.

Table 6: The theoretical exergy potential for Manufacturing of timber, wood and cork products

Stream	Temperature T used in the calculations [°C]	Excess heat potential of the sector [GWh/y]	Theoretical exergy potential W_{theor} [GWh/y]
Air (assumption)	135	1,938	317.8
Air (assumption	55	2,626	167.0
Total:)		4,564	484.8

Table 7: The theoretical exergy potential for Manufacturing of paper, board and paper products

Mill type	Stream	Temperature T used in the calculations [°C]	Excess heat potential of the whole sector [GWh/y]	Theoretical exergy potential W_{theor} [GWh/y]
Mill A1	flue gas	126	429.8	66.2
	air	60	258.5	18.3
	water	41.5	16.8	0.7
Mill A2	air	45	85.1	4.1
	water	44.1	129.3	6.1
Mill A3	air	45 (assumption)	136.1	6.6
	water	40	55.7	2.3
Mill B4	flue gas	120 (assumption)	571.7	84.2
	air	60	976.3	69.1
	water	72.5	773.4	68.3
	water	70	294.2	25.0
Mill B5	air	60	1,168.0	82.7
	water	47	417.2	21.6
	steam	110	882.7	240.1
Mill B6	air	60	713.0	50.5
	water	42.5	690.9	31.1
	steam	100 (assumption)	622.1	153.9
Mill C7	air	57.5	1,070.8	72.0
	water	80	206.5	20.3
	water	67.5	234.9	19.1
	water	70	508.6	43.2
	flue gas	160	126.1	24.0
	flue gas	160	1,825.9	346.9
Mill C8	air	65	1,070.8	83.4
	water	80	1,311.0	129.0
	water	46	121.4	6.1

Table 7: The theoretical exergy potential for Manufacturing of paper, board and paper products

	water	67.5	449.8	36.6
	flue gas	180	327.9	68.6
	flue gas	180	2,373.9	497.0
Mill C9	air	65	411.9	32.1
	water	75	109.3	10.0
	steam	140 (assumption)	79.9	27.5
	flue gas	120	290.0	42.7
		TOTAL:	18,739.7	2,389.4

Tables 8 and 9 present the temperatures of the excess heat streams used in the exergy calculations and the theoretical exergy potential for the chemical industry. Table 10 shows the same data for the refining of metals.

Table 8: The theoretical exergy potential for Manufacturing of coke and oil refining products

Stream	Temperature T used in the calculations [°C]	Excess heat potential of the sector [GWh/y]	Theoretical exergy potential W_{theor} [GWh/y]
Water	30	7,525	189.5
Flue gas	385	2,167	773.1
Air	115	2,296	325.0
Total:		11,988	1,287.6

Table 9: The theoretical exergy potential for Manufacturing of chemicals and chemical products

Stream	Temperature T used in the calculations [°C]	Excess heat potential of the sector [GWh/y]	Theoretical exergy potential W_{theor} [GWh/y]
Water	80 (assumption)	360	35.4
Water	85	240	25.2
Water	67.5	240	19.5
Water	45 (assumption)	2,160	105.3
TOTAL:		3,000	185.5

Table 10: The theoretical exergy potential for Refining of metals

Stream	Temperature T used in the calculations [°C]	Excess heat potential of the sector [GWh/y]	Theoretical exergy potential W_{theor} [GWh/y]
Water	55 (assumption)	1,830 +8,270 = 10,100	643.0
Flue gas	475	4,800	1,931.2
Total:		14,900	2,574.2

Although this study contains only rough evaluation about the potential to produce electricity from excess heat, the results offer a good overview if it is reasonable to focus on utilizing this potential. The total potential to convert excess heat into mechanical work in three Finnish industrial fields is 6.922 TWh/y, which is c. 10 % of the electricity produced in Finland in 2011 and 14 times higher than the power produced by wind power (0.5 TWh). This supports the conclusion that it is meaningful to try to utilize the excess heat in the industry. The greatest theoretical exergy potential is in the forest industry (2,874 GWh/y) and the next greatest potentials are in the refining of metals (2,574 GWh/y) and the chemical industry (1,473 GWh/y). It should be noticed that manufacturing of chemicals and chemical products sector includes just one mill's theoretical exergy potential. For example fertilizer factories, manufacturing of nitric, sulphuric acid and titanium dioxide, which also have reasonable amounts of excess heat, are not included in the YIT report. The total theoretical exergy potential would be higher if all industrial sectors and all their excess heat streams were included in the assessment.

All upgrading and conversion technologies are not suitable for all excess heat streams; usually the temperature mostly limits if the excess heat can be converted into work using a certain technology. Additionally, some technologies are still at the level of development. The excess heat can be used in electricity production for example by ORC and Kalina cycle. In ORC processes, the typical temperature of the heat source is between 80 and 350 °C and the net electric efficiency is c. 7 - 20 %. Only few Kalina cycle plants are built; these plants use geothermal or waste heat as heat source at the temperature range of 100 - 500 °C. Reported electrical net efficiencies for Kalina cycle are c. 12 - 17 %. Table 11 shows how much excess heat is available (relative share of the whole exergy potential of the field) at different temperature levels for all industrial fields included in the study. The highest temperatures are in the refining of metals and chemical industry: 75 % and 52 % of the field's theoretical exergy potential are at temperature over 200 °C. In the forest industry most of the theoretical exergy potential is at the temperature range of 100 - 200 °C. The higher the temperature of the excess heat, the higher is the electricity production gained from it. Basically, ORC and Kalina are suitable for all industrial fields, but as Table 11 shows the refining of metals and chemical industry offer high temperatures and thus best opportunities to convert part of the excess heat into work, although the theoretical potential is higher in the forest industry. It should be noticed that excess heat stream may include components which cause for example blockage and thus the stream can be unsuitable for the use. The actual exploitation potential is a fraction of the calculated theoretical exergy potential. Nevertheless, the huge potential for enhancement in energy efficiency exists and the excess heat recovery represents a great opportunity to mitigate climate change.

Table 11: The relative share of the available exergy potential at different temperature levels for each field

Industrial field	T ≤ 55 °C [%]	55 °C < T ≤ 100 °C [%]	100 °C < T ≤ 200 °C [%]	T > 200 °C [%]
Forest industry	9	32	60	0
Chemical industry	20	5	22	52
Refining of metals	25	0	0	75

5. Conclusions

In this study, by using the exergy analysis, the theoretical potential to convert excess heat into mechanical work has been evaluated in three greatest energy consumer industries of Finland: forest industry, chemical industry and refining of metals. The results indicate that the total theoretical exergy potential is 6.9 TWh/y. The greatest temperature of the excess heat and high theoretical exergy potential is in the refining of metals. However, in every industrial field is found suitable excess heat streams for the utilization. Already commercial ORC and Kalina technologies are suitable for the excess heat use.

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