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Preliminary assessment of waste heat potential in major European industries

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Abstract

Industrial processes are currently responsible for almost 26% of European primary energy consumptions (275 Mtoe/yr). Furthermore, most of the energy sources that drive the industrial sector are fossil fuel based. Every industrial process is characterised by a multitude of waste heat streams at different temperature levels whose recovery would undoubtedly contribute to the enhancement of the sustainability of the industrial sites and their products. Waste heat recovery systems can offer significant energy savings and substantial greenhouse gas emission reductions. For the latter to materialise technological improvements and innovations aimed at improving the energy efficiency of heat recovery equipment and reducing installation costs should take place. This paper outlines the opportunities and the potential for industrial heat recovery in the European Union by identifying and quantifying primary energy consumption in the major industrial sectors and their related waste streams and temperature levels. Through a systematic analysis considering waste heat and Carnot's potential estimation, detailed results are given for all industrial sectors, temperature ranges and EU countries. The 'big picture' is rather promising with regards to the estimated total waste heat potential.

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Keywords: energy statistics; waste heat potential; Carnot's potential

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1. Introduction

The European Union (EU), with its 28 member states, covers an area of over 4 million km² and has 508 million inhabitants. EU is currently responsible for 11.6% of the world final energy consumptions (9425 Mtoe in 2014) and for 10.8% of the world final CO_2 emissions (33.3 $GtCO_2$ in 2014) [1, 2]. In EU, industry accounts for the 25.9% of the final energy consumptions and for the 47.7% of the final CO_2 emissions [3]. European Union has always been a forefront body in terms of awareness and involvement for the mitigation of nowadays environmental issues. Indeed, current greenhouse gas emissions have been lowered by 22.9% compared to those in 1990, while one of the key EU targets for 2030 is reduction of at least 40% with respect to the same reference year (1990) [2]. To achieve this challenging goal, energy saving and a more intensive usage of renewable energy sources are unquestionably suitable trajectories to pursue.

In addition to them, recovery actions from existing energetic systems can offer significant primary energy savings and substantial greenhouse gas emission reductions. For instance, current industrial processes are characterised by a multitude of waste heat streams at different temperature levels. In this context, waste heat recovery is the process of capturing heat from these waste streams and using this heat directly, upgrading it to a more useful temperature, and/or converting it to electrical power or cooling. The energy generated from heat recovery, if not required by the process or industrial site can be exported to neighboring facilities or to electrical or heat distribution networks.

There is now increasing global interest in the development and application of heat recovery systems, driven by government regulatory requirements with regard to emissions and emission reduction targets, rising concerns over the cost of energy and energy security and general environmental and sustainability considerations.

The waste heat recovery market is projected to reach $53.12 billion by 2018 [4]. Europe dominates this market and in 2012 the European market accounted for 38% of the global heat recovery equipment market. It is also expected that the Asia-Pacific region will experience the highest growth rate in the next five years of 9.7% per annum with China and India accounting for the highest number of installations of heat recovery units. For these projections to materialise, however, and for the European manufacturing and user industry to benefit from these developments, technological improvements and innovations, aimed at improving the energy efficiency of heat recovery equipment and reducing installed costs, should take place.

The main aim of this work is to present the industrial opportunities for waste heat recovery potential available in the member states of the European Union. Prior to the assessment of the waste heat recovery potential in EU industry with detailed results by country and industrial sector, the calculation methodology is introduced.

2. Energy recovery potential in the European Union

2.1. Definition of waste heat potential

When considering different technologies for using the industrial waste heat potential, it is necessary to first distinguish which potential type is considered [5]: the theoretical/physical potential [6], the technical potential, and the economic/feasible potential [7] (Fig. 1.a).

The theoretical potential only considers physical constraints: the heat must be above ambient temperature, bound in a medium, and so forth. Not considered here is whether it is possible to extract the heat from the carrier fluid or whether it is possible to use it. The above-mentioned constraints set the technical potential. In addition, the technical potential depends on the technologies considered. An example of a technical constraint is the required minimum temperature. The technical potential to use waste heat is defined by two major constraints: in addition to the boundary conditions of the technology itself, a heating or cooling demand is necessary.

If we go one step further, then the technical potential can be separated into a theoretical technical potential and an applicable technical potential, which are distinguished by the fact that the first one is calculated using a theoretical/generic process-related analysis, while the second one is calculated by using onsite data with all plant specific parameters taken into consideration (Fig. 1.b). Accordingly, the feasibility of the technology considered is further analysed using economic criteria/analysis.

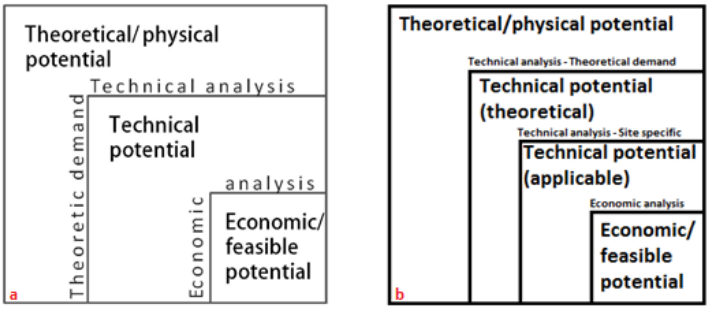

Fig. 1. Types of potential (a: graph based on [5-7], b: proposed modified graph)

2.2. Waste heat potential evaluation

The data used for the estimation of the waste heat potential are those presented in [8]. As aforementioned the waste/rejected heat can be further distinguished by its applicability per the respective temperature range (qualitative analysis).

In terms of Thermodynamic analysis, energy is described as the sum of exergy and anergy, where exergy stands for the energy that can be totally turned into technical work. Thus, the exergy content of waste/rejected heat can be calculated by Carnot's theorem, which states that the maximum efficiency of a heat engine is determined by the two available heat reservoirs. Applying the Carnot factor (η_c) (Eq. 1) to the waste heat amounts and their corresponding waste heat temperatures (T_{high}) gives the respective technical work potential further indicated as Carnot's potential.

$$\eta_{\max} = \eta_C = 1 - \frac{T_{low}}{T_{high}} \tag{1}$$

The waste heat temperature ranges can be distinguished into three categories as follows:

- Low Temperatures (LT): < 100°C
- Medium Temperatures (MT): 100–299°C
- High Temperatures (HT): ≥ 300°C

According to the results of reference [8], the waste heat potential and Carnot's potential are calculated as the percentage of the consumed energy for each temperature range respectively, as can be seen in the Table 1.

Table 1: Waste heat potential and Carnot's potential according to [8]

Potential	**LT**	**MT**	**HT**
Waste Heat	12.60%	6.00%	11.40%
Carnot's	1.73%	2.00%	6.40%

Carnot's potential provides a more precise indication on whether waste heat could still perform technical work or, better, be used for heat transfer. Thus, as one should expect Carnot's potential increases with temperature range.

In Table 2 the main processes used in the different types of industries that were identified through a literature review are presented along with their respective temperature range and its classification.

Table 2: Main processes used in different types of industries

Type of Industry	Processes used	Temperature range (°C)	Temperature range
Iron and Steel Production	Sinter Process	1300 – 1480	HT
	Pelletisation Plants - Induration process	straight grate process: 1300 – 1350 grate kiln process: 1250	HT
	Coke oven plants – Jewell - Thompson oven	1150 – 1350	HT
	Blast furnace – Hot Stoves	900 – 1500	HT
	Basic Oxygen Steelmaking	1200	HT
Large Combustion Plants	Combustion/Gasification / Liquifaction process	430 – 630	HT
	Steam process - Boiler	Coal and Lignite fuels: 540-570 Liquid fuels: 120–140	HT
	Co-generation/combined heat and power	100	LT
	Combined cycle plants	430–630	HT
Large Volume Inorganic Chemicals- Ammonia, Acids and Fertilizers	Conventional steam reforming - Desulphurization process	350-400	HT
	Conventional steam reforming - Primary and Secondary reforming	Primary: 400-600 Secondary: 400-600 Exhaust gas: 1000	HT
	Ammonia Partial oxidation - Gasification of heavy hydrocarbons and coal	N/A	N/A
	Ammonia Partial oxidation - Sulphur removal	N/A	N/A
	Sulphuric Acid - Sulphur combustion SO_2 production process	900-1500	HT
	Sulphuric Acid - Regeneration of spent acids SO2 production process	400-1000	HT
	Sulphuric Acid - Spent acid from TiO_2 production and roasting of metal sulphates	850+	HT
Large Volume Inorganic Chemicals - Solids and Others industry	Sulphur burning process	145	MT
	Tank furnace process	430-650	HT
	Sodium silicate plant (revolving hearth furnace) process	600	HT
Food, Drink and Milk Industry	Seed oil extraction process	65	LT
	Solubilisation/alkalizing process	45-130	MT
	Utility processes -CHP	60-115	MT
	Heat recovery from cooling systems	50-60	LT
	Frying	180-200	MT
Production of Glass	Heating the furnaces and primary melting	750 – 1650	HT
Production of OFC	Energy Supply	45 – 130	LT
	Thermal oxidation of VOCs and co-incineration of liquid waste	950 – 1000 (SNCR) or SCR	HT
	Recovery and abatement of acetylene	N/A	N/A
Production of Non-ferrous metals	Primary lead and secondary lead production	200 – 400	MT
	Smelting Process	400 – 1200	HT
	Zinc sulphide (sphalerite)	900 – 1000	HT
Production of Cement, Lime & Magnesium Oxide	Kiln firing	≥2000	HT
	Clinker burning	1400 – 2000	HT
Production of Polymers	Thermal treatment of waste water	N/A	N/A
Ferrous Metals Processing	Hot rolling mill	1050 – 1300	HT
	Re-heating and heat treatment furnaces	N/A	N/A

Pulp, Paper and Board production	Kraft pulping process (chemical pulping)	155 – 175 (Cooking and delignification)	MT
		90 – 100 (Oxygen delignification)	LT
	Sulphate pulping process (chemical pulping)	800 – 1100 (calcination reaction - lime kiln)	HT
	Mechanical pulping and Chemimechanical pulping	95 – 125 (Grinding- Pressure Groundwood pulping) 70 – 170	LT-MT
	Processing of paper for recycling (with and without deinking)	N/A	N/A
	Papermaking and related processes	45 – 90 (Paper machine) >350 (Coated wood-free printing tissue process with conventional Yankee dryer)	LT- HT
Surface Treatment Using Organic Solvents	Printing	700-800	HT
	Drying and curing	400-700	HT
	Waste gas treatment from enamelling	500-750	HT
	Manufacturing of Abrasives	35-110 in the drier	LT
		700 for the exhaust air treatment	HT
	Coil coating	150-220	MT
Tanning and Hides and Skins	Drying	60-90	LT
Textiles industry	Dirt removal	1200	HT
	Optimisation of cotton warp-yarn	60-110	LT-MT
	Dyeing	80-100	LT
	Oxidation	750	HT
	Drying	130	MT
Waste Incineration	Drying and degassing	100-300	MT
	Pyrolysis	250-700	MT-HT
	Gasification	500-1600	HT
	Oxidation, Combustion	800-1450	HT
Waste Treatment	Thermal Treatment	Vitrification 1300-1500 Sintering 900-1200	HT
	Drying	100	LT
	Regeneration of carbon	650-1000	HT
	Incineration	850-1200	HT
	Catalytic combustion	200-600	MT-HT
	Dying of wood particles	200-370 for single and triple pass	MT
		500 at rotary dryers	HT
Wood based panels production	Drying of wood fibres	60-220	MT
	Pressing	100-260	MT
	Lamination	130-200	MT

Consequently, by using the data presented in Table 2 concerning the processes used in each industrial sector and their respective waste heat stream temperature range, the waste heat potential and Carnot's potential for each industry are calculated and the results are presented in the following Table.

Table 3: Waste heat and Carnot's potential

Type of Industry	Waste heat potential	Carnot's potential

Iron & Steel	11.40%	6.40%
Chemical and Petrochemical	11.00%	5.13%
Non-ferrous metal industry	9.59%	4.93%
Non-metallic minerals (glass, pottery & building materials industry)	11.40%	6.40%
Food and Tobacco	8.64%	1.89%
Paper, Pulp and Print	10.56%	4.59%
Wood and Wood Products	6.00%	2.00%
Textile and Leather	11.04%	2.72%
Other industry	10.38%	4.84%

Accordingly, the energy consumption of the industries of each EU-28 country (Table A1, see Appendix A) are used together with the calculated waste heat and Carnot's potential to calculate the waste heat potential and Carnot's potential of the investigated industries for each country and are presented in detail in Tables A2–A3 (see Appendix A). Additionally, the results concerning the waste heat potential and the Carnot's potential per industry are shown in Figures 2 and 3 respectively.

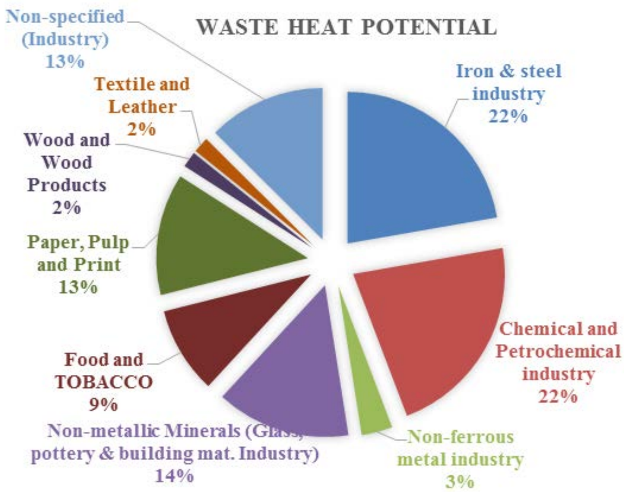

Fig. 2. Waste heat potential per industrial sector in the EU

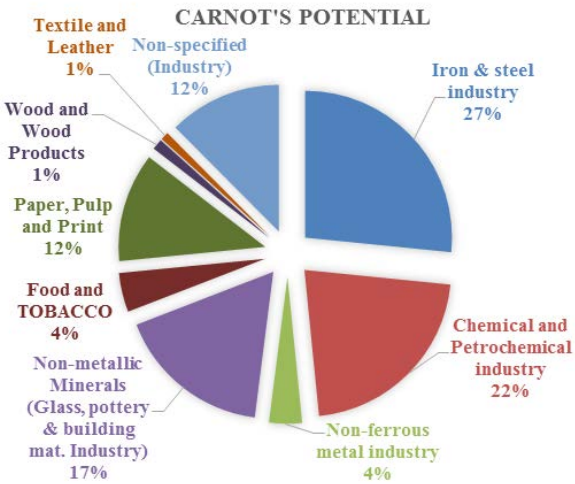

Fig. 3. Carnot's potential per industrial sector in the EU

It can clearly be seen that the waste heat and the Carnot's potential can differ even for the same type of industry. For example, in the Iron & Steel industry the waste heat potential is 22% while the Carnot's potential is 27%. This is due to the different temperature range of the processes used in each industry. If an industry mainly uses HT processes then the Carnot's potential will be higher than the waste heat potential, while when the processes are mainly LT then the opposite occurs.

Finally, in Fig. 4 the waste heat potential and the Carnot's potential per EU country are depicted. As shown, Germany ranks first place (due to the country's strong industry), followed by Netherlands, France, Italy, UK and Spain respectively.

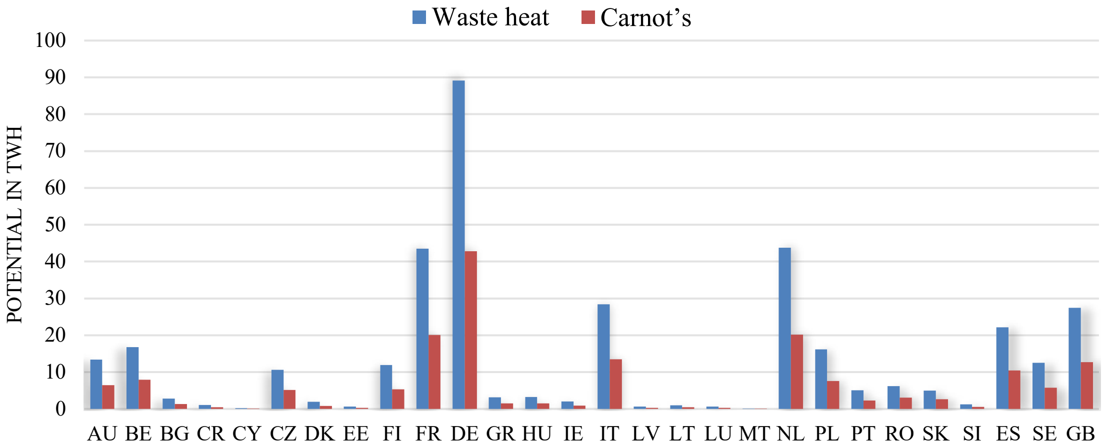

Fig. 4. Total Waste heat and Carnot’s potential per EU country per year

3. Conclusions

In this study the waste heat potential and the Carnot’s potential were calculated using statistical data concerning the energy consumption of the industrial sectors of each EU country together with the factors calculated by [8]. In addition, to use these factors the individual processes of each industrial sector were identified and classified according to their temperature range as LT, MT and HT.

The main outcomes of this study, although the results are preliminary, are the following: (a) insight information into the different processes used in all industrial sectors in EU together with their temperature ranges has been identified; (b) the waste heat and Carnot’s potential of the industrial sectors of all EU countries have been estimated and tabulated comprehensively and (c) most importantly the ‘big picture’ has shown that there is a rather significant potential accounting 370.41 TWh (Waste heat) or 173.99 TWH (Carnot’s) per year in the European industry. The next step is to perform a more detailed and more elegant analysis that will extent the results presented in this work.

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Appendix A.

Table A1. Primary energy consumptions in European Union [TWh]

	TYPE OF INDUSTRY												
	I&S	**C&P**	**NFM**	**NMM**	**TE**	**MAC**	**M&Q**	**F&T**	**PPP**	**WWP**	**CON**	**T&L**	**Total**
AU	40.6	16.6	3.2	14.3	2.1	10.4	2.5	9.2	27.7	11.1	8	1.4	147.1
BE	38.7	45.2	4.9	21.2	6.1	2.1	0.6	21.7	12	4	3.2	3.2	163
BG	1.2	9.1	1.7	5.8	0.2	1.4	1.1	2.8	2.9	0.7	0.8	0.8	28.3
CR	0.3	1.6	0.2	3.9	0.2	0.7	0.3	2.5	0.7	0.4	1.3	0.3	12.3
CY	0	0	0	1.6	0	0	0.1	0.3	0	0	0	0	2.1
CZ	34	16.5	1.0	15.7	7.4	11.9	1.3	9	9.5	3.6	3.2	2.2	115.3
DK	0.5	2.8	0	4.4	0.4	3.2	0.7	7.3	2	1	1.8	0.3	24
EE	0	0.9	0	2	0.1	0.5	0.2	0.8	0.7	1.4	0.6	0.2	7.2
FI	13.1	12.2	3.5	3.1	0.7	3.3	1.8	4	68.5	7.2	4.6	0.4	122.4
FR	90.3	84.4	18.6	67.9	18.1	32.1	4.4	80.4	44.7	9.6	18.2	5	473.8
DE	218.7	231.7	31.9	105.3	50.7	95.8	6.1	80.5	94.9	24	0	8.1	948
GR	1.6	1.3	10.3	8.5	0.1	0.3	0.9	5.5	1.1	0.3	1	0.5	31
HU	4.5	8.7	1.8	4.4	2.4	4.4	0.3	5.9	2.1	0.7	2.3	0.4	38
IE	0	2.7	5.6	3.5	0.3	2.8	1.3	5	0.3	1.6	0.1	0.2	23.4
IT	60.6	47.9	7.4	58.1	4.2	39	1.3	30.9	23.5	4.7	4.2	13.6	295
LV	0.3	0.3	0	1.7	0.1	0.2	0.2	1.1	0.1	4.2	0.5	0.1	8.8
LT	0	3.5	0	2.2	0.0	0.3	0.1	2.2	0.4	1.1	0.5	0.4	10.7
LU	2.8	0.6	0	1.2	0.1	0.3	0	0.3	0.1	0.2	0.3	0.2	6.1
MT	0	0	0	0	0	0.1	0	0.1	0	0	0	0	0.3
NL	38.1	98.1	5	8.9	1.5	8.4	1.8	31	11.2	0.9	7.8	1.7	214.6
PL	28.1	34.6	4.7	29.6	4.7	8.5	4.4	21.4	18.3	10	2.1	1.3	167.8
PT	2.1	5.8	0.3	12.6	0.6	1.9	1.3	4.9	16.3	1.2	1.6	3.4	51.9
RO	19.5	19.1	0	9.2	2.4	4.2	0.5	6.2	0.9	3	4.6	0	69.5
SK	25.6	3.4	2.8	4.5	1.9	2.2	0.1	1.6	5	0.5	0.3	0.3	48.3
SI	1.7	1.7	1.8	2.1	0.4	1.6	0.2	0.7	1.9	0.5	0.3	0.3	13.1
ES	37.2	46.7	12.8	39.3	4.5	10	4.9	25.3	23.9	5.9	14.6	4	229
SE	18.3	6.5	3.8	3.7	2.3	4	5.2	4.4	68	6.3	1.1	0.2	124
GB	45	37.8	6.3	30.5	11.3	20.9	0.2	31.1	19	0	7.2	8.4	217.7
EU	722.9	739.9	127.6	465.2	123	270.3	41.6	396.2	455.8	103.9	90.3	57	3592.7

Legend:
I&S: Iron & Steel industry, C&P: Chemical and Petrochemical industry, NFM: Non-ferrous metal industry, NMM: Non-metallic Minerals, TE: Transport Equipment, MAC: Machinery, M&Q: Mining and Quarrying, F&T: Food and Tobacco, PPP: Paper, Pulp and Print, WWP: Wood and Wood Products, CON: Construction, T&L: Textile and Leather

Table A2. Waste heat potential in EU countries [TWh]

	TYPE OF INDUSTRY								
	I&S	**C&P**	**NFM**	**NMM**	**F&T**	**PPP**	**WWP**	**T&L**	**Total**
AU	4.6	4.5	3.9	4.6	3.5	4.3	2.4	4.5	36.6

BE	4.4	5	0.5	2.4	1.9	1.3	0.2	0.4	16.8
BG	0.1	1	0.2	0.7	0.2	0.3	0	0.1	2.8
CR	0	0.2	0	0.4	0.2	0.1	0	0	1
CY	0	0	0	0.2	0	0	0	0	0.2
CZ	3.9	1.8	0.1	1.8	0.8	1	0.2	0.2	10.6
DK	0.1	0.3	0	0.5	0.6	0.2	0.1	0	2
EE	0	0.1	0	0.2	0.1	0.1	0.1	0	0.6
FI	1.5	1.3	0.3	0.4	0.3	7.2	0.4	0	11.9
FR	10.3	9.3	1.8	7.7	6.9	4.7	0.6	0.6	43.5
DE	24.9	25.5	3.1	12	7	10	1.4	0.9	89.2
GR	0.2	0.1	1.0	1	0.5	0.1	0	0.1	3.1
HU	0.5	1	0.2	0.5	0.5	0.2	0	0	3.3
IE	0	0.3	0.5	0.4	0.4	0	0.1	0	2
IT	6.9	5.3	0.7	6.6	2.7	2.5	0.3	1.5	28.4
LV	0	0	0	0.2	0.1	0	0.3	0	0.6
LT	0	0.4	0	0.3	0.2	0	0.1	0	1
LU	0.3	0.1	0	0.1	0	0	0	0	0.6
MT	0	0	0	0	0	0	0	0	0
NL	4.3	10.8	0.5	1	2.7	1.2	0.1	0.2	43.7
PL	3.2	3.8	0.5	3.4	1.8	1.9	0.6	0.1	16.2
PT	0.2	0.6	0	1.4	0.4	1.7	0.1	0.4	5.1
RO	2.2	2.1	0	1	0.5	0.1	0.2	0	6.2
SK	2.9	0.4	0.3	0.5	0.1	0.5	0	0	5
SI	0.2	0.2	0.2	0.2	0.1	0.2	0	0	1.2
ES	4.2	5.1	1.2	4.5	2.2	2.5	0.4	0.4	22.1
SE	2.1	0.7	0.4	0.4	0.4	7.2	0.4	0	12.5
GB	5.1	4.2	0.6	3.5	2.7	2	0	0.9	27.4

Table A3. Carnot's potential in EU countries [TWh]

	TYPE OF INDUSTRY								
	I&S	**C&P**	**NFM**	**NMM**	**F&T**	**PPP**	**WWP**	**T&L**	**Total**
AU	2.6	0.9	0.2	0.9	0.2	1.3	0.2	0	6.4
BE	2.5	2.3	0.2	1.4	0.4	0.6	0.1	0.1	7.9
BG	0.1	0.5	0.1	0.4	0.1	0.1	0	0	1.3
CR	0	0.1	0	0.2	0	0	0	0	0.5
CY	0	0	0	0.1	0	0	0	0	0.1
CZ	2.2	0.8	0	1	0.2	0.4	0.1	0.1	5.2
DK	0	0.1	0	0.3	0.1	0.1	0	0	0.8
EE	0	0	0	0.1	0	0	0	0	0.3
FI	0.8	0.6	0.2	0.2	0.1	3.1	0.1	0	5.3
FR	5.8	4.3	0.9	4.3	1.5	2.1	0.2	0.1	20
DE	14.	11.9	1.6	6.7	1.5	4.4	0.5	0.2	42.8
GR	0.1	0.1	0.5	0.5	0.1	0.1	0	0	1.5
HU	0.3	0.4	0.1	0.3	0.1	0.1	0	0	1.5
IE	0	0.1	0.3	0.2	0.1	0	0	0	0.9
IT	3.9	2.5	0.4	3.7	0.6	1.1	0.1	0.4	13.4
LV	0	0	0	0.1	0	0	0.1	0	0.3
LT	0	0.2	0	0.1	0	0	0	0	0.4
LU	0.2	0	0	0.1	0	0	0	0	0.3
MT	0	0	0	0	0	0	0	0	0
NL	2.4	5	0.2	0.6	0.6	0.5	0	0	20.2
PL	1.8	1.8	0.2	1.9	0.4	0.8	0.2	0	7.6
PT	0.1	0.3	0	0.8	0.1	0.7	0	0.1	2.3
RO	1.2	1	0	0.6	0.1	0	0.1	0	3
SK	1.6	0.2	0.1	0.3	0	0.2	0	0	2.6
SI	0.1	0.1	0.1	0.1	0	0.1	0	0	0.6
ES	2.4	2.4	0.6	2.5	0.5	1.1	0.1	0.1	10.4
SE	1.2	0.3	0.2	0.2	0.1	3.1	0.1	0	5.7
GB	2.9	1.9	0.3	1.9	0.6	0.9	0	0.2	12.7