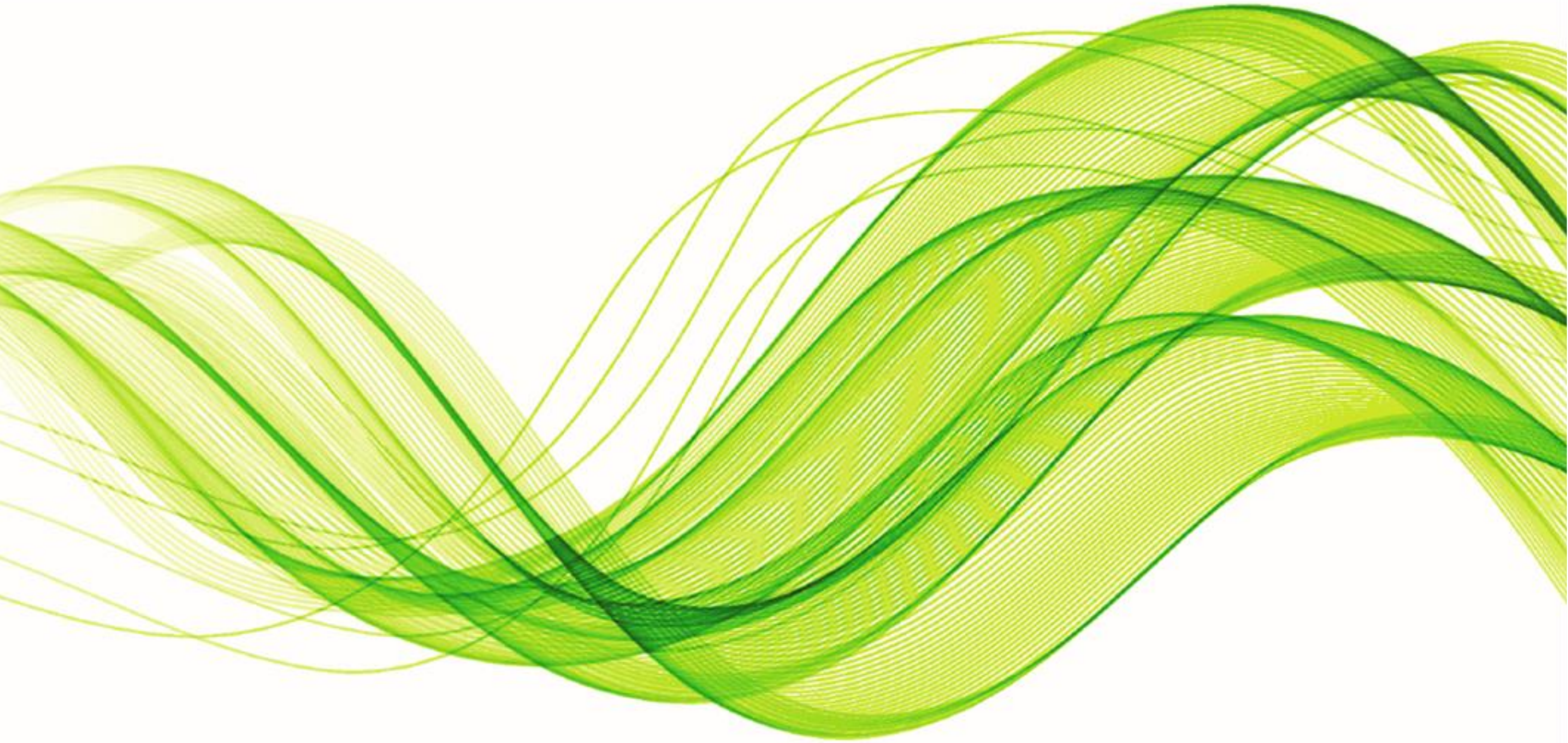
Thermal Energy Harvesting

The Path to Tapping into a Large CO_2-free European Power Source

Version 1.0



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About the Knowledge Center on Organic Rankine Cycle technology - KCORC

KCORC is a not-for-profit global association of professionals from companies, academia, research institutes and government agencies. It was informally established in 2013 and legally incorporated in 2017. It counts approximately 400 registered members at any time.

MISSION STATEMENT

The Knowledge Center on Organic Rankine Cycle technology (KCORC) promotes the interdisciplinary knowledge exchange between dedicated international professionals from academia, industry, governmental agencies and policy makers. The aim is to advance the research, development and implementation of ORC technology by means of providing relevant technical and scientific information, organizing technical conferences and workshops, fostering engineering education, and advising on proper regulation.

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Executive Summary

The solution or mitigation of the climate change problem demands for a complex set of behavioral transformations, concerted actions, global and continental policies, national implementations and new or improved technologies, whose ultimate goal is to avoid disastrous changes of ecosystems resulting in irreparable effects on human civilization. Such technologies have also the important potential of creating widespread societal benefits, like more employment, more fairly distributed wealth, and significant and widespread health improvements.

The amount of thermal energy generated by human activity that is dispersed into the atmosphere in any given instant is so large that it escapes human comprehension. Thermal energy is discarded to the atmosphere by almost all industrial processes and by all mobile or stationary engines. As it is the case for many human activities, this unbearable waste is also a huge resource that most of the public is not aware of, possibly because it is invisible and intangible. Importantly, even in future scenarios in which fossil fuels will be displaced by other non-carbon fuels, huge amounts of thermal energy will always be generated by industrial processes and engines, as prescribed by the laws of thermodynamics.

Among the technologies that may be adopted to make use of this enormous asset, **one is particularly suitable for the conversion of thermal power into electrical or useful mechanical power: Organic Rankine Cycle (ORC) power plants**. **A prudent estimate** leads to the conclusion that **if only a portion of thermal energy wasted** from industrial processes in EU27 countries were recovered with ORC power plants, this would generate as much as **150 $\mathrm{TWh_{el}}$/year of electricity**. According to some **conservative calculations performed by KCORC**, the electricity generated by this CO_2-free waste-heat-to-power technology may amount to about **5% of the total electricity currently produced** in European Union countries.

An ORC power plant works according to the same principle as that of steam power stations, but instead of water, the working fluid in the closed loop is an organic substance, like so-called refrigerants, hydrocarbons, carbon dioxide, etc., and the fluid is selected according to the temperature level at which the thermal energy source is available and its amount. Such power plants can therefore convert thermal energy that would be otherwise wasted into electricity, making possible something an evolved human society must embrace: re-using, recovering, and avoiding waste.

Waste-heat-to-power by means of ORC technology features many advantages. **The electricity that is generated does not cause any additional emission, does not depend on weather and is dispatchable. Furthermore, it can significantly contribute to the reduction of the dependency of the European Union from imported fuels, providing a sustainable supply of electricity that is detached from the volatility of energy markets**. Electricity is more valuable than heat, much easier to distribute and key to the decarbonization of societies. Arguably, no other thermal energy harvesting technology is equally flexible because ORC systems can be used to generate power from sources of many hundreds of megawatts down to sources of just few kilowatts and at temperature levels that span the range from 100 ^{o}C to 1000 ^{o}C. The thermal energy that is released at low temperature (40 – 80 ^{o}C) can be used for heating networks, industrial usage or green houses, bringing the efficiency of the entire energy chain to almost 100%. European countries are especially suitable for the widespread adoption of thermal energy harvesting: Europe is very industrialized and capillarily connected to the grid. The high-density population is one of the causes of the “not-in-my-backyard syndrome” regarding large power stations of any kind, while **ORC power plants can be easily integrated in already existing industrial sites**, distributed, or embedded aboard means of transportation.

Europe is in a leadership position when it comes to ORC technology, as all major manufacturers are European and they installed and are installing their products not only in Europe but worldwide. In addition, **Europe leads also in related R&D activities**. If proper policy and regulation supported the growth of the market that would be created by making energy efficiency and carbon neutrality a requirement, the number of jobs that would be created would be very large, in the tens of thousands over a decade. It is estimated that, if the adoption of waste-heat-to-power technologies were embraced and supported, **the current annual growth rate of the global market of ORC stationary power plants could double from the current 7.5 % to 15 %.** This would correspond to the creation of **45 000 new qualified jobs over a period of 10 years.** The needed workforce is already available due to the restructuring of the conventional power sector, given that the required skills and competences are the same. Notably, this projection of employment growth does not take into account the possible birth of another large market if ORC technology were to be utilized in the next decade to recover waste heat from thermal engines (trucks, off-road vehicles, ships, trains etc.).

The European potential of thermal energy harvesting has been evaluated based on available data per industrial sector (iron and steel, non-metallic minerals, aluminum, cement, glass, nonferrous metals, chemical and petrochemical, oil and gas, stationary power, paper, food and beverages), per temperature level and per geographical location. The result of the analysis is that **ORC technology is applicable in all countries** and that **75% of the thermal energy obtained from burning primary fuels is not exploited** and would be available for recovery. ORC power plants could convert into electricity a large share of this recoverable energy**. Moreover**, many types of **mobile thermal engines** (truck and heavy-duty vehicle engines, ship engines, train engines and aircraft engines) **inherently discard to the atmosphere from one third to half of the energy of the fuel**, **thus also in this case the potential is humongous**. R&D activities and first commercial applications have **already demonstrated the feasibility** of this approach. While cars and other light duty vehicles are bound to become electric, it is easy to argue that complete electrification is impossible in the medium term, and decarbonization will be due mostly to the usage of carbon-free fuels like hydrogen. These fuels will likely be much more expensive, and this will also push the adoption of waste heat recovery for economic reasons, as it increases efficiency. **Also in case of mobile applications of ORC technology, European companies are in the lead and should be supported.**

This report is intended for a wide audience: from the general public to policy makers and politicians, from users of the technology to ORC technology practitioners. KCORC has written this document with the intent of providing useful technical, economical, and policy-related information on which important decisions can be based, and with the conviction that ORC technology will be a relevant part of the solutions advanced by the Green New Deal, if properly supported. **The current policy and regulation scenario on so-called heat-to-power technologies has been summarized, pitfalls and barriers analyzed, and a number of changes and improvements proposed**. In particular, amendments to the European Renewable Energy Directive and to the Energy Efficiency Directive are proposed, such that the role and value of waste-heat-to-power are properly recognized, and hopefully proper regulation is implemented in Member States in a consistent and effective way.

Furthermore, the European scenario of support to technology development has been outlined, highlighting how it is currently rather scattered and inconsistent and, above all, insufficient if the objective is to tap into this immense resource. Research and development are needed to increase the performance and reduce the cost of ORC power systems. As a consequence, in line with the principles established by the *Clean Energy Transition – Technologies and Innovations Report* (CETTIR) of the European Commission (2021), the creation of a proper infrastructure to boost, coordinate and evaluate research and development is proposed. In analogy to what has been done for other renewable energy technologies (for example ETIPWind for wind energy), the creation of the **European Technology & Innovation Platform on organic Rankine cycle – ETIPoRc** is proposed.

In conclusion, this position document about ORC technology is to be intended as the first version of a dynamic repository of convincing information and ideas brought forward by an enthusiastic and dynamic community of volunteers (academics, professionals from companies, researchers in government institutions), supported by small, medium and large ORC companies whose final objective is to substantially contribute to the solution or mitigation of the global climate issue and the betterment of the European Unions and societies at large.

Table of Contents

1 Untapped Thermal Energy

Thermal energy is one of the forms of energy that can be converted into electrical or mechanical energy for further utilization. Thermodynamics dictates that, as a result of this conversion process, still a portion of the thermal energy input must be discharged to the environment at a lower temperature. In some cases, this discharged thermal energy can be used for heating purposes (district and domestic heating) and this is called *cogeneration*.

In general, energy can be available in different forms such as

- chemical energy (in fossil and other fuels, namely carbon-neutral fuels like hydrogen or more sustainable, like biofuels; it can be converted into thermal energy, and subsequently into electricity or mechanical drive);
- solar radiation energy (it can be converted into electricity with photovoltaic panels, or into thermal energy for heating, or further converted into electricity);
- thermal energy as available from geothermal sources (it can be converted into mechanical drive or electricity);
- thermal energy originating from combustion of fossil fuels, or as by-product of other processes (it can be converted into mechanical or electrical energy).
- mechanical energy (it can be used for propulsion, to drive machines, or electric generators and can originate from the conversion of chemical energy or renewables such as wind power);
- electrical energy (it can be used directly for many beneficial tasks, such as lighting, computing, heating, or for propulsion and for machines driving);

All kinds of energy once converted into a useful form result in additional thermal energy at moderate or low temperature which is often thrown away without further use. **Thermal energy discarded to the atmosphere could be a very relevant source to generate clean electricity in Europe and in the world without causing any CO_2 emission. This document is concerned with organic Rankine cycle (ORC) technology for emission-free electricity generation using unutilized thermal energy sources.**

1.1 Manufacturing Processes

Thermal energy is emitted to the environment from various sources, like

- (petro) chemical processes,
- material production (metal, cement, glass etc.),
- production of electricity or of mechanical drive (stationary gas turbines, internal combustion engines),
- combustion of materials in incinerators (waste, fuel residues or biomass), in case it is impossible to burn these substances in internal combustion engines or turbines.

It can be agreed that thermal energy as a by-product of so many processes must be utilized, and not dumped into the environment. There exist various options:

- heating, if demand is available at location,

- so-called *heat upgrading*, that is, increasing the temperature of the thermal energy input by means of a heat pump (also called *heat transformer*), provided that there is demand,
- refrigeration with the help of an adsorption or absorption system, also provided that there is a demand for it,
- conversion into electricity using several technologies, among which, thermo-electric devices, Stirling engines, steam power plants or Organic Rankine Cycle power systems.

Electricity is the prime and often preferred form of energy, because it is transportable and directly useable for a large variety of applications. On the contrary, discharged thermal energy is hardly transportable, thus it can be exploited – if at all – only if directly suitable for local demand in terms of temperature and time profile.

The thermal energy discharged by the industrial sector in EU28 countries has been estimated in a recent study to be around 980 TWh_{th}/yr for 2015 [1]. Other recent literature states that the potential for electricity generation is between 280 TWh_{el}/yr [1] and 300 TWh_{el}/yr [2]. This amounts to almost 10% of the 3050 TWh_{el}/yr of electricity generated in EU28 countries in the same year [3].

Useable thermal energy can be classified depending on the temperature level at which it is available. **KCORC performed some calculations to independently and conservatively estimate the potential for electricity generation from currently discarded thermal energy.**[1] Thermal energy discharged at low-temperature (< 100 ^{o}C) can be used for space heating including greenhouses. Although the amount of thermal energy available at low temperature is enormous, the amount of electricity that can be generated from it is comparatively small, approximately 32.2 TWh_{el}/yr. At moderate temperature (100 – 200 °C) the potential for electricity generation is 9.5 TWh_{el}/yr, at an intermediate temperature (200 – 500 °C) is 61.7 TWh_{el}/yr, and 47.2 TWh_{el}/yr at high temperature (> 500 °C). Therefore, the estimation of the total amount of electricity that can be generated adds up to approximately 150 TWh_{el}/yr. Taking into account the potential for electricity generation reported in recent literature, 280 TWh_{el}/yr in Ref. [1] and 300 TWh_{el}/yr in Ref. [2], it is hence reasonable to **conservatively assume that at least 150 TWh_{el}/yr of electricity** could be generated by harvesting currently untapped thermal energy, therefore this figure is used in the following. This electricity can be generated **without emissions of additional CO_2** or any other harmful substance, consequently it should be treated conceptually as fully renewable electricity.

150 TWh_{el}/yr of electricity is the **yearly electricity consumption of more than 20 million households, or the annual electricity production of 19 nuclear plants of 1 GW capacity each, or the combined annual consumption of electricity of the Netherlands and Denmark.** In terms of CO_2 emissions, this 150 TWh_{el}/yr of electricity corresponds to avoiding 123 Mton/yr of CO_2 emissions if the electricity were generated by burning coal, to 75 Mton/yr of CO_2 if it were generated by burning natural gas, and to around 45 Mton/yr of CO_2 if the emissions were calculated by considering the average emissions in the EU 28 in 2017 (294 g/kWh_{el}) [4], including electricity generated from renewable energy sources. At the same time, a reduction of NO_x can be accounted for at a rate of approximately 107 kton/yr, whereby the emission factor (0.71 g/kWh_{el}) is derived from various international sources.

As this untapped thermal energy is most often continuously available because of the nature of its sources, **the generated green electricity can be made available on demand (dispatchable),** as opposed to other forms of renewable electricity, like that obtained from solar radiation and wind, which are time- and weather-dependent.

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[1] These calculations are derived from 2018 Eurostat statistics, based on Regulation (EC) No. 1099/2008 for EU27 countries. The potential for electricity generation from otherwise wasted thermal energy is determined based on conversion technologies described in Ref. [75] and assuming a cold sink temperature of 17 ^{o}C as well as a lower temperature limit of gaseous streams of 120 °C due to the dew-point constraint for acidic corrosion avoidance.

1.2 Natural Gas Supply Infrastructure

Another promising field of application for organic Rankine cycle technology is thermal energy harvesting from the natural gas supply infrastructure. A very large amount of thermal energy could be recovered from exhaust gases released by gas turbines installed in gas pipeline recompression stations, which mechanically drive natural gas compressors. The total length of gas pipelines worldwide is greater than 2.7 million km and recompression stations are needed every 100 to 180 km to compensate for the pressure drop: the distance between recompression stations depends on gas temperature, pipeline diameter and the variation of natural gas demand along the pipeline. Mostly, these recompression stations are equipped with a set of open-cycle gas turbines (power capacity in the 5 – 35 MW_{el} range) thus a very large amount of thermal energy at relatively high temperature (400 – 600 °C) is available for heat recovery and ORC power plants are the most suitable technology for this purpose [5].

For example, in North America, starting from 1999, Ormat installed seventeen ORC power plants recovering waste heat from gas turbines powering compression stations, with a total electric capacity greater than 85 MW_{el} [6]. Recently, Baker Hughes commissioned an ORegen^{TM} waste heat recovery system (15 MW_{el}) featuring a two-stage integrally geared turbine [7].

Another interesting example is the largest high-temperature waste heat recovery ORC system that is being supplied by Turboden in Egypt, starting from the spring of 2021 [8] [9]. This ORC power plant will be coupled with 20 MW_{el} electric motor driven (EMD) compressors supplied by Siemens Energy, and will boost the efficiency of the GASCO Dahshour gas compressor station (GCS). The GASCO Dahshour project is a first of its kind. It will exploit the thermal energy discharged by four existing gas turbine trains and by a new high-efficiency gas turbine supplied by Siemens Energy. This integrated solution will allow to generate 192 GWh_{el}/yr of fuel-free electricity powering two 10 MW_{el} compressors, and will save 65 million m^3 of natural gas per year, thus avoiding the annual emission of 120 kton of CO_2.

The potential for waste heat recovery in Europe amounts to an installed capacity of 1.3 GW_{el} (EU-27: 664 MW_{el}), with an annual electricity production of 10.5 TWh_{el}/yr and CO_2 emission savings equal to 3.7 Mton/yr [10].

Within the natural gas supply infrastructure, LNG (liquified natural gas) plants are another relevant source of thermal energy currently unutilized. At the production site, natural gas is compressed and then cooled down and liquefied at cryogenic conditions: power for natural gas compressors is provided on site by aeroderivative gas turbines that lead to a plant-specific thermal energy recovery potential in the range of 45 – 70 MW_{th} at temperatures of 400 – 600 °C [11]. After transportation in cryogenic conditions (ambient pressure and -160 °C) LNG is vaporized at the regasification terminals by means of different technologies which involve the use of electrical energy and/or fossil fuels, thus offering additional possibilities for ORC power plant installations.

One of the most promising options to increase the energy efficiency of regasification plants, thus reducing related CO_2 emissions, is the integration of a power plant operating with seawater as thermal energy source and the vaporizing LNG as the thermal energy sink. Studies on this particular form of thermal energy harvesting have been carried out since 1980 and several pilot plants based on ORC technology have been commissioned in Japan [12] [13]. More recently, researchers have investigated various configurations to further increase the efficiency of the process [14] [15] . Recently Ormat applied for a related patent [16] and installed the first ORC power plant based on such configuration at the Huelva regasification site [17]. The potential for thermal energy harvesting from regasification stations can be estimated considering that the world market of LNG is around 355 Mton in 2019 [18] and that a reference ORC power plant for heat recovery from an LNG terminal plan could generate approximately 22 kWh_{el} per ton of vaporized natural gas [19]. Considering that the worldwide annual trade of LNG was equal to approximately 350 Mt [18] this would result in the production of approximately 8 TWh_{el}/yr, corresponding to CO_2 emission savings of around 2 Mton/yr.

Finally, gas-to-liquid plants also offer a huge potential for waste-heat-to-power installations. In gas-to-liquid plants, large amounts of mid temperature heat are rejected to the environment. A clear example of this potential is represented by Shell plants in Qatar and Malasia with an average availability of 5 – 600 MW_{th} at 130 – 185 °C [11].

1.3 Propulsive Engines

Another very large source of untapped thermal energy comes from propulsion engines of all sorts and for all diverse uses. Internal combustion engines, independently from the fuel, release about two thirds of the chemical energy of the fuel to the environment. For example, the exhaust gas of truck engines amounts to approximately one third of the energy input and is at approximately 330 °C, while water and oil cooling discharge to the environment another third of the input energy at approximately 100 °C. Gas turbines, depending on their size and application, release 70 % to 55 % of the chemical energy of the fuel to the environment with the exhaust gas at temperatures between 400 °C and 600 °C.

Figure 1. The prototype of a waste heat recovery system on board of a long-haul truck. Courtesy of AVL GmbH.

The recovery of thermal power for the generation of additional mechanical or electrical power has been already demonstrated on board of long-haul trucks [20], [21], [22], [23], see, e.g., Figure 1, ships [24], and trains [25], and is being studied in case of aircraft engines [26], [27], [28], [29], [30]. Trucks are powered by diesel engines, and it is possible that soon natural gas and even hydrogen become widespread fuels for trucks [31]. Ships can be powered by diesel engines or gas turbines and also trains, in case the line is not electrified.

The potential for reduction of CO_2 and other emissions, and in any case for efficiency increase by means of conversion into additional power of part of the thermal energy otherwise wasted by all types of thermodynamic engines is enormous. As an example, in 2019, more than 270,000 heavy commercial vehicles over 16 ton have been registered in Europe (EU 25, excluding Cyprus and Malta) while the same figure rises up to over 370,000 when considering also commercial vehicles, coaches and heavy buses above 3.5 ton [32]. In 2018 there were around 6 million trucks on the roads of the European Union (excluding UK); with more than 1.1 million trucks, Poland has the largest truck fleet, followed by Germany (946,541) and Italy (904,308) [33]. Almost the totality of EU heavy duty vehicles (98.3%, Ref. [33]) are powered by diesel engines and have been responsible in 2016 for 27 % of the CO_2 road transport emissions and for almost 5 % of the EU greenhouse gas emissions [34] and approximately equal to 200 million ton/yr of CO_2 emissions [35].

The recent 2019/1242 regulation of the European parliament and Council (20 June, 2019) sets CO_2 emission performance standards for new heavy-duty vehicles in such a way that thermal energy recovery is arguably key to achieving the set targets. Similar regulation is under discussion regarding ships [36]. In general, it can be argued that thermal energy recovery becomes technologically easier to realize with the increase of the capacity of the engines, therefore from train and ship engines.

1.4 Hydrogen Combustion and Electrochemical Reactions

In order for the current Green Deal policy of the European Union [37] to succeed, a large variety of combustion processes which are essential for very many industrial sectors (steel and metal making, cement and glass production, chemical processes, refining, food processing, pulp and paper, construction and many others) must switch from the use of natural gas and other fuels to hydrogen [38], [39], [40], [41]. A very large amount of thermal energy will therefore still be available from these processes even when combustion of hydrogen will have substituted fossil fuels.

Moreover, a large share of the electricity production by means of fossil-fueled thermal power stations is projected to be substituted by wind and solar energy conversion, which should reach 66% of the total by year 2050 according to Refs. [42], [43], [44]. As well known, these sources are unpredictable and fluctuating, therefore it is envisaged that wind and solar farms will be complemented by thermal power stations fueled by hydrogen and powered by gas turbines or fuel cells.[2]

Hydrogen is likely to be a relatively costly fuel, given the costs involved in the processes to produce it [45]. The cost of producing hydrogen is projected to be in the range of 1 to 2 USD/kg by 2050 [42], if a number of technological challenges are overcome. This compares for instance with the current natural gas price of 0.3 US$/kg (average value between Oct. 2020 – May 2021) [46]. Therefore, even for just economic reasons, it seems logical that the inevitable thermal energy content of the exhaust of any reaction involving hydrogen (combustion, or other thermochemical reaction) should be recovered in order to increase the efficiency of these processes, thus reducing their overall cost. Prompt Incentives and regulation aimed at thermal energy harvesting technology are bound to bear fruits even during the transition to carbon-free fuels and beyond.

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[2] Fuel cells for stationary electricity generation operate at mild to high temperature, therefore discharge electrochemical reaction product gases at temperature of approximately 200 °C (PEM), 600 °C (MCFC) and 900 °C (SOFC).

2 Organic Rankine Cycle Technology and its Advantages

Untapped thermal energy can be converted into electricity or mechanical energy using a well-known principle which is already the foundation of large-scale electricity production, the so-called Rankine cycle of steam power plants. The same principle, but with fluids different from water (organic fluids), can be used to generate electricity or mechanical energy from thermal energy at a variety of temperature levels and from sources with a large range of capacities (from kW to hundreds of MW). Organic Rankine cycle (ORC) technology is arguably the most flexible and efficient technology for the conversion of medium and low temperature energy sources, for any capacity.

The working fluid of ORC power plants is formed by organic molecules[3] like those of hydrocarbons, refrigerants, siloxanes, and carbon dioxide. These substances can be used as working fluids pure or in blends. With reference to Figure 2, the pressure of a liquid fluid is increased in a pump, evaporated using the energy of an external thermal energy source, the vapor is expanded in a turbine possibly connected to an electrical generator, and liquified again in a condenser using atmospheric air or sea, lake, or river water. The choice of the optimal working fluid is related to the capacity of the power plant and the temperature level of the thermal energy source. While water is possibly the perfect working fluid for large power capacity and high temperature levels, other fluids make it possible to realize power plants with capacity from few kW to tens of MW and to efficiently convert energy from sources at temperatures as low as 100 °C [47].

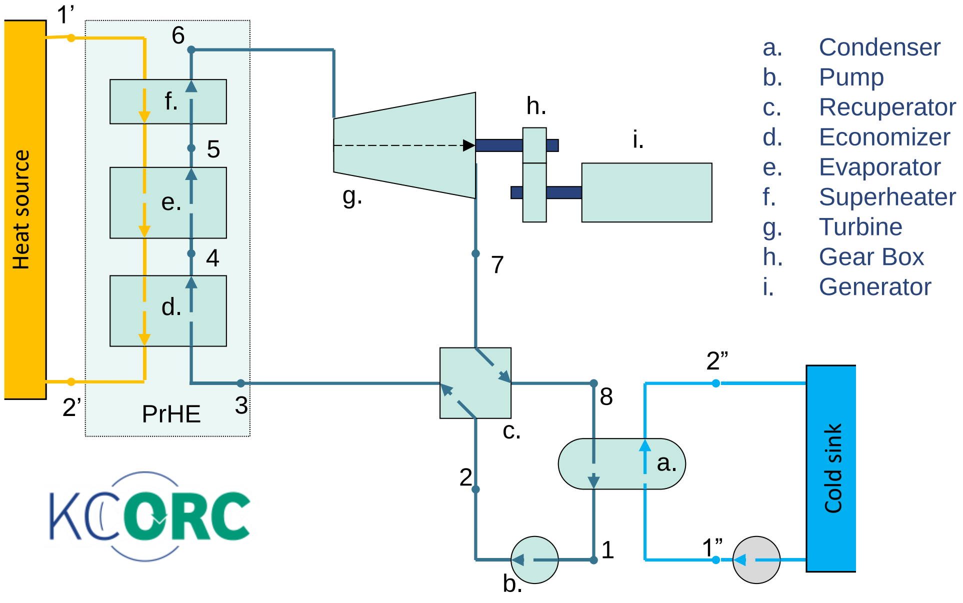

Figure 2. Simplified process flow diagram of an ORC power plant. Taken from [47].

An ORC power unit is arguably the most economically viable and efficient technology for the conversion of thermal energy into electrical or mechanical energy whenever [47]

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[3] An organic molecule is a molecule containing at least one carbon atom.

- the thermal energy source is in the temperature range 100 – 600 °C, it is a gas, a vapor, or a pressurized liquid;
- the available thermal energy is in the range from several kW up to approximately 50 MW_{th};

The use of carbon dioxide as working fluid makes ORC technology possibly competitive with conventional steam power plants for much higher temperatures and capacities, though it is at a lower level of technological readiness [48], [49].

Moreover, it is well possible to operate ORC plants if:

- cooling water is scarce, or its use is forbidden,
- qualified operators on site are unavailable or costly (full automation),
- the thermal energy source is rather variable in time because of the high turn-down ratio.

ORC power plants, see, e.g., Figure 3, are efficient at both nominal and off-design conditions, can be modular, require a small footprint, boast a very high level of availability, a wide operational range, can be fully automated and require very low maintenance. Very importantly, the cooling of the power plant does not necessarily require water, and air cooling is possible and widespread.

In case of stationary applications, each ORC power plant can be tailor-made without excessive additional cost. Another considerable advantage of the envisaged deployment of ORC power plants is that they would always be situated close to the untapped thermal energy source, therefore in an industrial environment, where electrical grid connections are already available, and public resistance would be minimal because of the already present industrial activity.

a) b)

Figure 3. a) aerial view of a 6 MW_e ORC power plant (Courtesy of Turboden); b) the power block of a 150 kW_e ORC unit (Courtesy of Triogen).

2.1 Other Technologies for Thermal Energy Harvesting

The harvesting of thermal energy is possible also with technologies other than ORC or steam power plants, and with purposes different from converting thermal energy into mechanical power or electricity.

Thermal energy can be converted directly into electricity by means of the Seebeck effect, i.e., the creation of an electric voltage due to a temperature gradient. Such voltage is proportional to the temperature difference. **Thermo-electric devices** are commercially available, their advantages are mainly the absence of moving parts and compactness. However, they work only with high temperature difference, they are suitable only for small-capacity power conversion, they are rather inefficient if compared to thermodynamic engines, and they are rather expensive [50], [51].

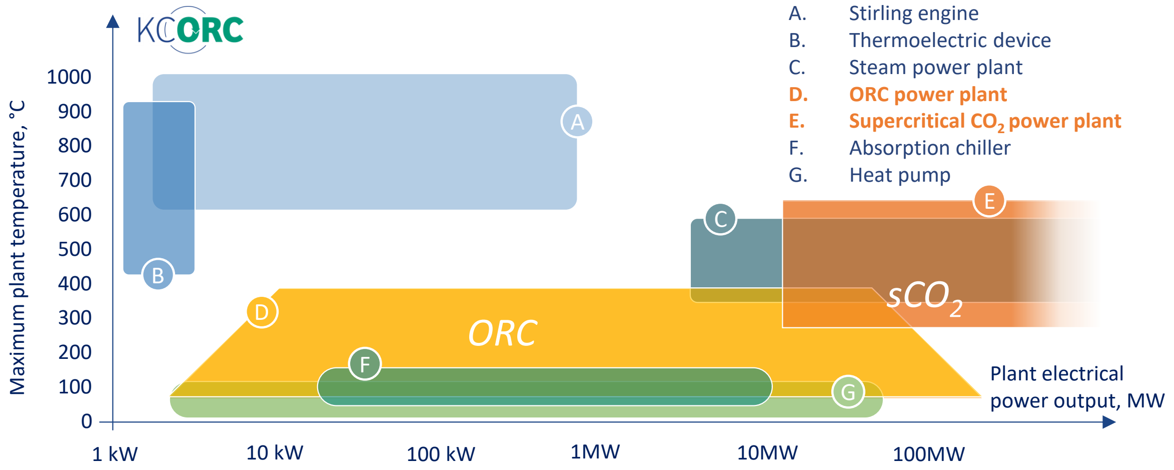

Figure 4. Range of applicability of various technologies for thermal energy harvesting.

The so-called inverse Rankine cycle is at the basis of **heat pumps**: machines that, similarly to domestic refrigerators, can transfer thermal energy from a source at a certain temperature (the inside the refrigerator for example) to another environment at a higher temperature (the air surrounding the refrigerator), thanks to the electric energy input needed by the compressor. Heat pumps therefore can be used to "upgrade" thermal energy that would be otherwise discarded to the environment. A typical application scenario occurs, for example, if, in a dairy factory low-grade thermal energy resulting from the process is recovered by a heat pump system to generate steam at higher temperature, which in turn is also used in the process. Efficient heat pumps "upgrade" 3 to 5 units of thermal energy for each unit of electricity fed to the compressor. A necessary condition for the utilization of heat pumps is that there must be a demand for thermal energy at higher temperature [52], [53], [54].

Thermal energy can also be used in another process at the basis of **absorption chillers**: in this case, low-grade thermal energy can be the energy source for a thermodynamic machine generating a cooling effect. The operating principle is based on the mixing and de-mixing of a mixture working fluid and the advantage is that almost no moving parts are involved. The efficiency of these machines depends on the temperature difference between the thermal energy source and the temperature at which the cooling effect is needed and cannot be very high: for each thermal energy unit, one or two cooling energy units can be obtained. The dairy process example can also be used for an absorption chiller, as discarded thermal energy can be used to provide refrigeration to the process [55], [56].

Finally, an engine that, like the ORC system, can generate electrical or mechanical power from thermal power is the **Stirling engine**: like the ORC power plant, it takes the name from its inventor. Its working principle is based on another thermodynamic cycle, the Stirling cycle. In this case, however, the operation is not continuous like that of the ORC power plant and its rotating turbine, but it is based on an alternating motion of one or more pistons, like internal combustion engines. Stirling engines can be rather efficient, are suitable only for power capacities up to hundreds of kW and temperature sources between approximately 400 and 1000 °C. Even if their features are attractive in many applications, reliability is often an issue, given the relatively large number of moving parts, the complex kinematics, and the working fluid leakage issues [57], [58]. For these reasons Stirling engines have not reached commercial maturity yet.

The range of applicability of the various technologies in terms of temperature level of the thermal energy source and capacity of the power plant is depicted in Figure 4. The graph outlines the large range of applicability of ORC technology, which arguably includes $scCO_2$ power plant technology, which is based on the same working principle and utilizes carbon dioxide as working fluid, thus also an organic compound.

3 European Leadership

Since the end of the 18th century, Europe has been the epicenter of the development of thermodynamic sciences and of the thermal machines powering the world. ORC technology belongs to this scientific tradition, which greatly benefited from the diversity characterizing the European continent. European manufacturers occupy strong positions in the market. It seems therefore essential that technological and commercial leadership is further developed in Europe.

3.1 Stationary Power Plants

Europe is by far the continent hosting the largest number of ORC power plant suppliers and industrial innovators in this field. Againity (Sweden), Atlas Copco (Sweden), Baker Hughes Nuovo Pignone (Italy), Climeon (Sweden), Dürr Cyplan (Germany), Enertime (France), Enogia (France), Exergy (Italy), GMK (Germany), Turboden-Mitsubishi Heavy Industries (Italy), Orcan (Germany), Ormat (USA/manufacturing in Europe), Rank (Spain), Siemens Energy (Germany), Star Energy (Italy), Triogen (Netherlands) and Zuccato (Italy) represent almost the totality of the established worldwide suppliers, and their ORC power plant products are already installed all over the world.

Universities and Research Centers in Belgium, Finland, France, Germany, Greece, Italy, Netherlands, Norway, Poland, Spain and Sweden collaborate among each other and with industrial partners to develop innovative ORC solutions and move the technological frontier forward for the benefit of the transition to a CO_2-free society.

European companies offer ORC units with a rated power output as small as 20 kW and as large as 20 MW for the conversion into electricity of renewable or renewable-equivalent energy sources as diverse as geothermal reservoirs, biomass combustion, and already industrial waste heat recovery, including waste heat recovery from gas turbines and internal combustion engines. Successful installations of ORC power plants manufactured by European companies are spread all over the world, see, e.g., the ORC World Map on the KCORC website (www.kcorc.org). The comparably large success of ORC technology in general can be appreciated from the charts of Figure 5, which also shows that the potential of the technology related to the conversion of otherwise wasted thermal energy is not exploited yet, given that the trend is clearly positive and with a steep increase of number of power plants.

The growth of the global market of ORC power plants for thermal energy harvesting points to the possibility of a much larger increase, if appropriate economic and regulatory conditions are put in place [59]. The global waste heat recovery market is expected to surpass an annual net sales volume of $65 billion by the end of 2021 with a compound annual growth rate of 6.9% [60]. The exploitation of the European waste heat recovery market with ORC technology would amount to a net invested value of €75 billion. This would allow for potential annual net sales value of electricity in the range of €18 billion. Currently, Europe leads the waste heat recovery equipment market (in 2012, Europe gained a 38% share of the global market [1]). Moreover, the future increased growth rate of the waste heat recovery market worldwide [61] is estimated to be larger than the European growth, allowing to foster the industrial leadership of European ORC companies and to consolidate their access and dominance at a global level. Notably, EU ORC companies are also in an advantageous position thanks to their specialization and long research and development history: ORC power plants with a size between few MW and tenths of MW are not standardized and need to be efficiently designed and promptly realized according to the requirements arising from the specific location and application.

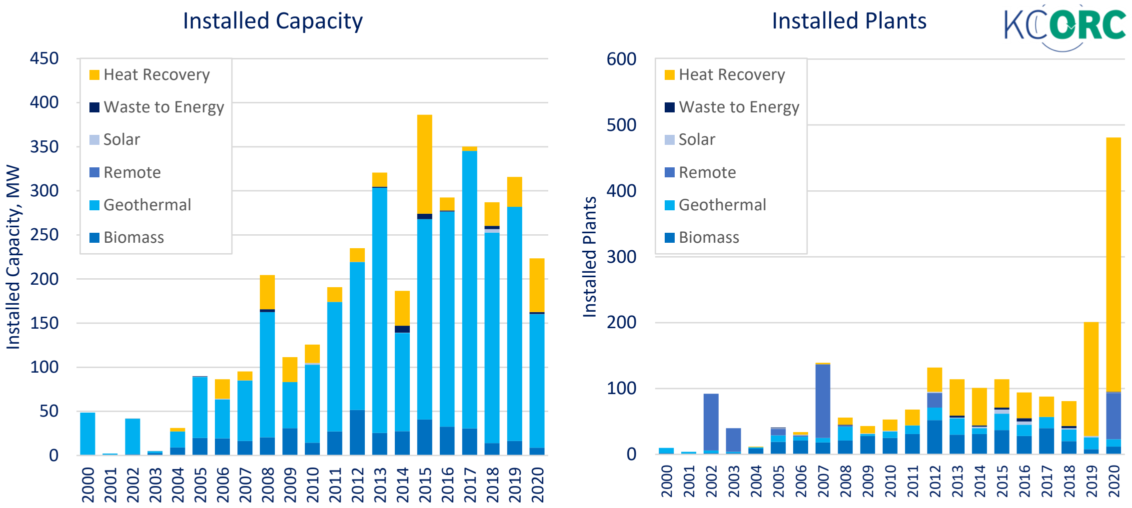

Figure 5. (left) Installed ORC power plants capacity and (right) number of installed ORC power plants over the years, indicating also the thermal energy source (biomass combustion, geothermal reservoirs, waste thermal energy, solar radiation) [62]

This demands for a highly specialized and nimble team of engineers and professionals and proprietary technology, something in which European companies clearly excel, thus creating an advantage with respect to, for example, Asian competitors.

3.1.1 Jobs Creation Perspective

ORC power plant installations in the EU and export of the technology outside of Europe are continuously creating many hundreds of job opportunities for highly skilled industrial workers and engineers and could easily generate many thousands of new jobs, if a proper policy (see Chapter 5) is put in place to support the European market and European ORC companies so that they can improve their technology (see Chapter 6) and their capacity to distribute it worldwide. Moreover, the COVID-19 crisis is severely impacting and will continue to affect large parts of the European industrial manufacturing industry and particularly the precision machining industry working for the aeronautic, power and transportation industry. Support to ORC technology therefore not only would be beneficial with respect to Green Deal goals related to the global environmental problem but could contribute to alleviating the difficulties of these industrial sectors by considerably expanding its employment possibilities.

A recent report on the assessment of the value and trends of the Waste Heat Recovery market [61] states that the value of global sales of waste heat recovery equipment is $65B/year. European countries are responsible for a 38% share of this market. The global annual growth rate is 6.9%, however the current growth rate in Europe is lower than that in North America. This is arguably a long-term strategic threat for the European waste heat recovery industry.

Unfortunately, from this information it is not possible to deduce an estimate of the value of the global sales related to ORC power plants. The information reported in Table 3 is unrelated to Ref. [61], however it can be used to obtain a first rough prediction of the opportunity for creating jobs in relation to an expansion of the ORC power plants market, through simple calculations. In Europe, if the full potential for thermal energy harvesting were to be exploited by realizing ORC power plants, the total installed power would amount to 18.8 GW_{el} and this would fulfill the urgent need for emission-free electric generation. Therefore, these power plants should and could be realized in about 10 years, an ambitious target that calls for some fundamental improvements in structure and regulations in Europe, see Chapter 5. The annual rate of ORC power plant installations would therefore correspond to a power generation capacity of 1.9GW$_{el}$/year, which would require the creation of 45 000 new jobs in a decade.[4] This is a total number of jobs that matches fairly well, in terms of volume and competence, the large amount of skilled workforce that was laid-off during the current restructuring of the fossil-based power sector [63].

3.2 Waste Heat Recovery Systems for Long Haul Truck Engines

While Rankine-cycle-based heat recovery systems are an established technology in the power generation and industrial sector, the application of the ORC concept to mobile engines only just achieved the demonstration stage, also because it is technologically more challenging. Currently, leadership in mobile ORC systems is not European, and efforts in the United States seem to be leading the development of ultra-efficient truck engines incorporating an ORC waste heat recovery system. At the end of the 70's, as a consequence of the energy crisis, truck engine manufacturers started looking into the potential of recovering exhaust thermal energy using mini-ORC systems in order to reduce fuel consumption. The most notable development at that time was the Mack Trucks and Thermo Electron Corp (TECO) project [64]. The objective of this project was to equip a truck with a 676 Mack diesel engine enhanced with a small ORC system (10 kW). The concept consisted into recovering exhaust gases by means of a high-temperature regenerative Rankine cycle system, using a high-speed turbine as expander. This program was in 3 phases: first design studies were carried out, then the system was operated on an engine test bench, and finally the mini-ORC waste heat recovery system was demonstrated under real life operating conditions on a vehicle on the road. While the fuel consumption benefit was proven (up to 12.5% reduction of fuel consumption), the project never made its way to serial production due to the drop in oil prices at the beginning of the eighties. Several attempts to revive the technology were made during the following decades: notable projects are partly documented in Refs. [65] or [66] but those demonstration projects remained rather confidential.

With the increase in oil prices of the end of the 2000's, vehicle manufacturers and especially truck OEM's have started again to consider mini-ORC systems for the recovery of the exhaust thermal energy as a viable solution to radically improve fuel efficiency and emissions. During the 2010's, all major truck makers have reported working on mini-ORC technology. In 2010, the US Department of Energy (DoE) established the SuperTruck I multimillion grant, prolonged with the SuperTruck II program, which aimed to develop and demonstrate a 50% improvement in freight efficiency. Funds were provided to four OEM's: Cummins, Daimler Trucks of North America, Navistar and Volvo Trucks. All four reported developments in the field of waste heat recovery systems in order to reach the efficiency goal set by the DOE ([67], [68], [69]). At the same time, major activities were reported in Europe, either thanks to public funding or internal R&D budgets. Most relevant examples of commercially funded R&D projects are those related to Renault Trucks [70], Mercedes Trucks [71], CNH Industrial [72]. The European funded project *NoWaste* within the FP7 program is an example of public support [73]. It shall be stated that the development activities conducted by the different truck manufacturers have been heavily supported also by the supply base in terms of component development.

Figure 6 indicates most of the automotive companies which were actively involved in the development of mini-ORC systems for waste heat recovery from truck engines, together with their main locations along with their homeroom. It can be noticed that European companies have been much more engaged in terms of development. No specific regulatory framework currently exists for the support of waste heat recovery technology, and these efforts were mainly driven by fuel economy. At the moment, the future of this technology is uncertain because other technological options exist, namely battery electric vehicle (BEV) and fuel cell electric vehicle (FCEV), and the general development is unclear. However,

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[4] Assumptions: 1) sales price: 4 000€ / kWel; 2) job cost: €0.1M/year; and 3) 60% of the sales value is allocated to pay for the wages of the new personnel.

waste heat recovery would be beneficial both in case of the adoption of high-efficiency / high-temperature fuel cells or other hydrogen-fueled internal combustion engines, and also in case of a transition to less carbon-heavy fuels, like liquefied natural gas (LNG) or liquefied petroleum gas (LPG). For this reason, R&D efforts aimed at waste heat recovery from truck engines are a long-term investment and should be encouraged and sustained.

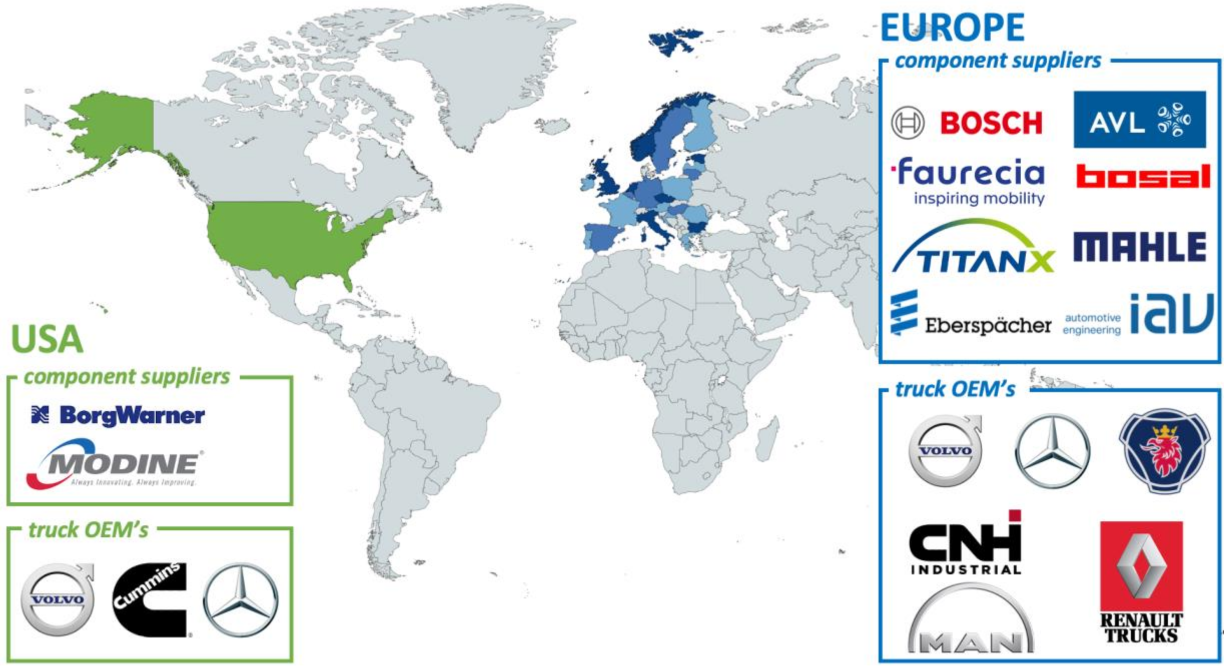

Figure 6. (Incomplete) list of the companies that have been developing mini-ORC technology for waste heat recovery from long-haul truck engines and their location in the world.

3.3 Indexing European Scientific and Industrial Leadership

Scientific and industrial leadership is often evaluated by means of indexing of scientific publications and patents, respectively. Figure 7 shows the number of publications indexed by Scopus with the keywords 'Organic+Rankine+Cycle+Power' since 2000. Europe leads the ranking ahead of China, with almost 50% more scientific documents on the topic. The United States lags behind, with one fourth of the scientific literature production.

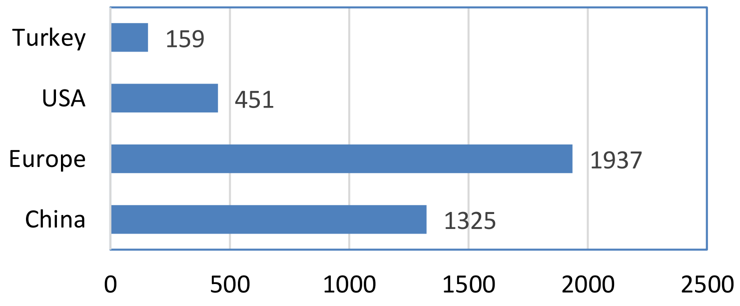

Figure 7. Number of scientific publications on 'Organic+Rankine+Cycle+Power' in the period 2000-2022 (Source: Scopus www.scopus.com) .

Scientific leadership is nevertheless only part of the equation. From a technology standpoint, it is of interest to track how much of this knowledge is transferred to society through industrial products. This can be ascertained to a large extent from the charts of Figure 8, presenting the number of patents granted in different areas of the world [74]. Figure 8.left shows the total number of patents in the area of industrial heat recovery whilst Figure 8.right shows the same information, but only for those patents whose degree of protection extends to more than one country. Even if China holds ten times more patents overall than any other region/country in the world, the European Union is a clear leader as far as so-called *valuable*[5] patents are concerned. This confirms that the supporting programs in place in the European Union are being effective in contributing to the leadership of the European industry.

It can therefore be inferred that Europe is already leading the development of Organic Rankine Cycle technology worldwide, both scientifically and industrially. This is a priceless asset from multiple standpoints. First, it puts Europe forward as the hub where knowledge that can pave the way to carbon neutrality by 2050 is generated. Second, it provides the European industry with the necessary knowledge, skills and infrastructure needed to meet the ambitious goals of the European Green Deal cost-effectively. Third, it opens up vast opportunities for high-end, high added-value jobs in STEM areas. Finally, it supports the numerous efforts to ensure the sustainability, reliability and security of the European energy market.

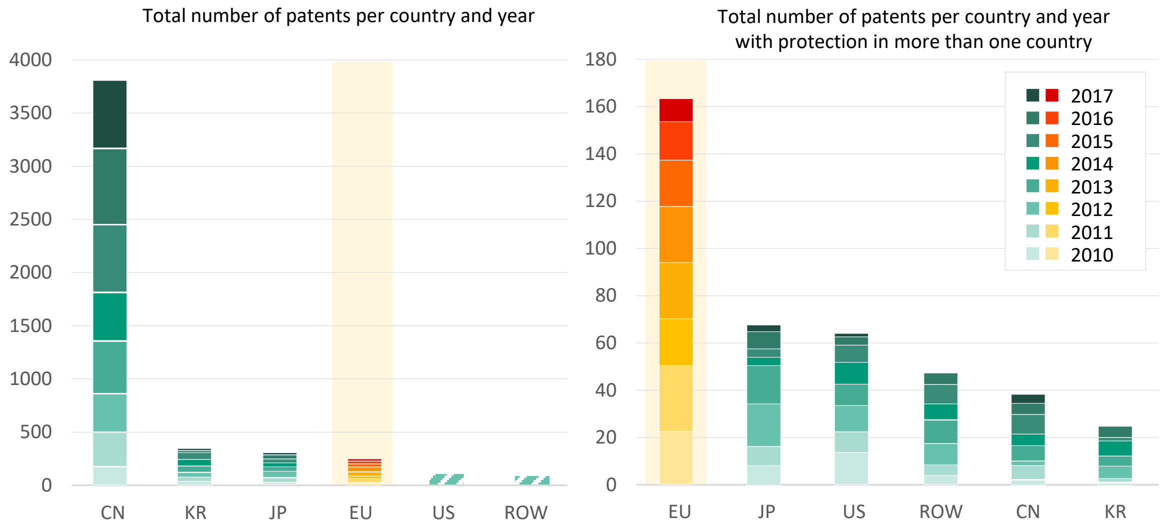

Figure 8. (left) Total number of patents per country and year related to industrial waste heat recovery technologies. (right) Total number of patents per country and year, with protection in more than one country, related to industrial waste heat recovery technologies [74].

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[5] Valuable patents refer to the number of patents whose protection is extended to more than one country.

4 The Potential: A Techno-Economic Analysis of the European Scenario

4.1 Waste Heat Recovery in Industry

The more viable industrial sectors for thermal energy harvesting are listed in Table 1, which shows the temperature level at which the energy is currently released to the atmosphere and the fraction of the total wasted thermal energy pertaining to each industrial sector, which is also listed.

Table 1: Temperature distribution of waste heat sources per industrial sector as percentage of the total wasted thermal energy (also reported). The shade of blue cells indicates the fraction of the total wasted thermal energy available at the given temperature range (light blue <20%, mid blue <50%, dark blue >50%). Data are taken from Refs. [2] and [59]. The light grey cells indicate additional potential resulting from technologies involved in the conversion process as described in Ref. [75]. Values for sectors marked with an asterisk are taken from Ref. [59]

	Temperature range of waste thermal energy / °C								
	<100	100 – 200	200 – 300	300 – 400	400 – 500	500 – 600	600 – 1000	>1000	TWh/a
Iron and Steel	░		▒	▓	░	▓	░	▓	73.0
Non-metallic minerals	░	▒		▓		█	░		91.2
Clinker*	░		░	█			░		
Glass*	░		░	█			▓		
Non ferrous metals (Primary aluminum*)	░	█	░	░		█	░		32.3
Chemical and Petrochemical	░	▓	░	▓	▓				141.7
Pulp, Paper and Printing*	█	▒	░	░					125.5
Others	░	█	░						263.0
Refinery*	█	▓	░						
Food and Beverages	▓	█	░						115.2
Gas and Diesel Engines	▓			▒	▒				2013.5

In general terms, the higher the temperature of the energy source and the larger the amount of energy, the more economically attractive the conversion of otherwise wasted thermal energy into electricity by means of ORC technology is. It can therefore be argued that the industrial sectors offering immediately an economically viable opportunity for the installation of ORC power plants are:

- iron and steel,
- non-metallic minerals (e.g., clinker and glass),
- non-ferrous metals,
- chemicals and petrochemicals.

Figure 9 shows the distribution of industrial sites over EU-27 countries plus the UK with significant potential for thermal energy harvesting. It is therefore self-evident that there exists a huge potential at continental level and that such potential is also rather well distributed geographically over each and every country. While industry related to non-metallic minerals is found in all EU countries, there are regional characteristics that policy makers might want to take into account with more targeted actions. For example, there is a high concentration of pulp and paper industry in the Scandinavian countries, while waste-to-energy plants are located mainly in Western Europe.

According to an analysis by Persson *et al.* [76], in these European energy-intensive industries thermal energy is utilized only for as much as 25% of the total energy input, thus 75% of the thermal energy obtained from primary fuels is currently wasted and would be available for recovery with appropriate technologies (re-use, upgrade, heating network, or conversion into electricity). The article reports that a total of 1175 sites feature a waste heat potential of more than 50 MW$_{th}$, and these are responsible for about 713 Mt of CO_2 emissions per year.

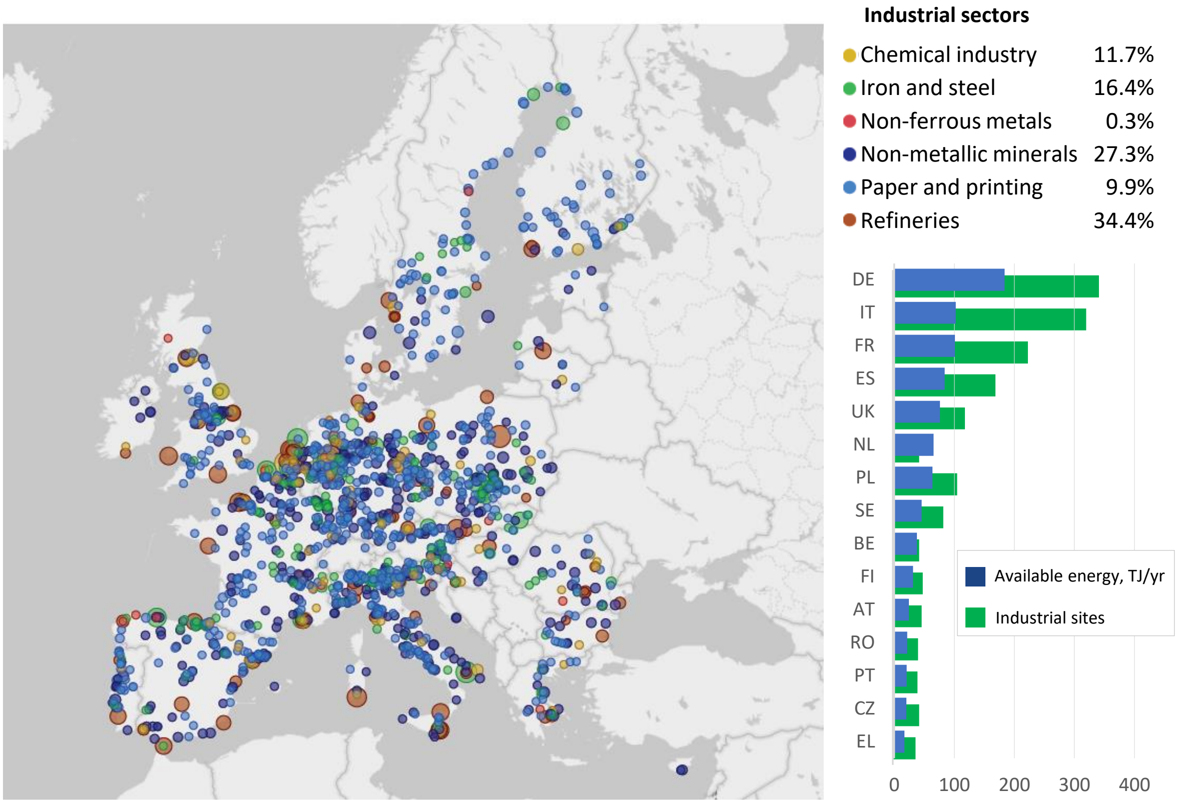

Figure 9: Map of industrial sites with significant waste heat recovery potential in Europe. Data taken from Ref. [76]

Unfortunately, an established approach for the accurate assessment of the European potential for thermal energy harvesting is not available yet and such an evaluation is affected by large uncertainty. Site-specific data about the amount and temperature level of the thermal energy that is discarded to the atmosphere are not consistently available: much information is not collected or is not available to the public. The reported data shall therefore be considered as a partial assessment of the overall potential at EU level, while the actual amount of recoverable thermal energy is expected to be remarkably higher. **An official survey of these data is therefore strongly suggested, also because it would support the appropriate policy and regulatory actions.**

Arguably, the most reliable source of information about the potential for thermal energy harvesting by means of ORC power plants is provided by Ref. [59]. In that report, the number of ORC power plants that could be installed in selected European countries has been estimated in a rather conservative way. The starting points are data of the International Energy Agency and an in-house database. The specific constraints that would make the installation of an ORC power plant feasible according to present-day conditions are taken into account and the conversion efficiency achievable with contemporary technology is considered. In order to obtain a realistic estimate, and using an excessively conservative approach, economic viability has also been assessed by taking into account specific electricity prices, regulation and current ORC power plant installation costs. For these reasons, only thermal energy sources at temperature greater than 250 °C have been reckoned. Finally, the study was limited to several relevant European countries for which somewhat reliable data were available.

Table 2 shows the results of the investigation, namely the potential for installation of ORC power plants in terms of power output, per country and per industrial sector providing the thermal energy otherwise discarded to the environment. It is remarkable that just for these seven EU countries and with this conservative approach, a total of 6.6 GW of electric power could be obtained (equivalent to approximately three large nuclear power stations). A similar analysis was performed for extra-European countries and the results reported in Ref. [59] demonstrate that the potential for waste-heat-to-power worldwide is humongous; something to be considered regarding the opportunities for the current leadership of European ORC technology.

Table 2: Estimated potential for installation of ORC power plants in MW_{el} *per selected country and per industrial sector, adapted from Ref. [59]*

Country	Clinker	Container Glass	Flat Glass	Paper	Primary steel	Second. steel	Chemicals	Food and Beverages	Refinery	Total
Belgium	33.4	0	12.1	8.1	14.9	0.3	391.2	130.5	11.2	602
Denmark	9.5	0	0	1.9	0	0	26.1	54.5	2.6	95
France	85.5	36.9	12.1	32.5	32	0.7	453	427.3	20	1100
Germany	164.2	47.3	19.2	89.4	89.8	1.6	1367	486.4	32.6	2298
Italy	98.6	41.3	12.1	34.3	19.7	2.2	357.4	266	23.3	855
Netherlands	13	0	0	11	20.6	0	666.8	193.5	19.8	925
U.K.	43.1	26.7	9.1	17.4	30.6	0.2	300.2	254.7	19.8	702
Total	**447.3**	**152.2**	**64.6**	**194.6**	**207.6**	**5**	**3562**	**1813**	**129.3**	**6577**

By year 2016, fifteen ORC power plants were installed in Europe, recovering thermal energy from clinker, glass, and iron or steel manufacturing processes [77]. This represents less than 3% with respect to the potential for installations of this kind [78] and the potential deriving from the pulp and paper, non-ferrous metal, oil and gas, as well as food and beverages processes is completely untapped.

The harvesting of thermal energy otherwise discarded to the environment by energy intensive industries poses several technical and economic challenges, however solutions are well within reach, if proper decisions are taken and development favored.

It is important to highlight that the extensive application of waste heat recovery technology would lead to a significantly higher efficiency of energy-intensive industrial sectors, which would lead to a considerable competitiveness in the foreseeable *CO_2-emission-restricted* global scenario. Table 3 shows the temperature-dependent potential of waste heat recovery: it is differentiated between total wasted thermal energy (theoretical potential), wasted thermal energy that is convertible into electricity (technical potential) and the total power capacity that could be installed (Installable capacity).

ORC power plant installations would greatly improve the overall energy efficiency of industry, even if hydrogen or other environmentally friendly fuels (carbon-based synthetic fuels or ammonia) will be adopted. Moreover, it should be noted that ORC power plants could also be powered with heat discarded from electric furnaces.

In addition to the energy intensive industries, there is also significant potential resulting from the natural gas supply infrastructure, which is summarized in Table 4 and amounts to a technical potential of 18.4 TWh_{el} of electricity. The data are based on recent publications of the world-wide production capacity [18] and plant-specific potential studies [79].

Table 3: Temperature-specific potential for waste heat recovery from industry by means of ORC power plants in Europe. Theoretical potential= total wasted thermal energy, technical potential = electricity which could be obtained from theoretical potential,[6] and Installable capacity = total power capacity that could be installed. The Installable Capacity is calculated assuming 8000 hours of operation per year.

Temperature level	Theoretical Potential	Technical Potential	Installable Capacity
Below 100 °C	390.4 TWh_{th}	32.2 TWh_{el}	4.0 GW_{el}
100 to 200 °C	60.5 TWh_{th}	2.8 TWh_{el}	0.3 GW_{el}
200 to 500 °C	334.7 TWh_{th}	68.5 TWh_{el}	8.6 GW_{el}
Above 500 °C	97.2 TWh_{th}	47.2 TWh_{el}	5.9 GW_{el}
Total	882 TWh_{th}	150 TWh_{el}	18.8 GW_{el}

Table 4: Additional potential for waste heat recovery by means of ORC power plants from the natural gas supply infrastructure network in Europe Theoretical potential= total wasted thermal energy, technical potential = wasted thermal energy that is convertible into electricity, and Installable capacity = total power capacity that could be installed. The Installable Capacity is calculated assuming 8000 hours of operation per year.

LNG and GTL liquefaction plants	Technical Potential	Installed Capacity
LNG and GTL liquefaction plants	10.6 TWh_{el}	1.5 GW_{el}
Regasification units/LNG Terminals	7.8 TWh_{el}	2.1 GW_{el}
Total	18.4 TWh_{el}	3.6 GW_{el}

Another source of industrial waste heat that could be used to power ORC systems is found in air compression stations. An annual installation of around 31 million air compressors within the EU (2014) [80], means that compressor inter-/after-cooling is a substantial thermal energy source in the European industry. Yet, one single university project aiming at demonstrating ORC-technology for waste heat recovery from air compressors has been identified [81].

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[6] The technical potential is estimated based on an educated simplified approach, assuming an effluent heat source, an idealized conversion process (triangular), as well as exhaust constraints and cooling limitations.

4.2 Waste Heat Recovery from Propulsive Engines

4.2.1 Long-Haul Truck Engines

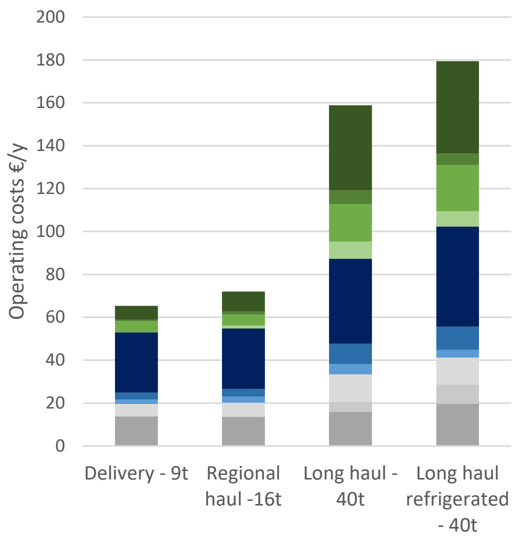
From a purely economic perspective, it is interesting to analyze the operational costs for different trucking industry segments [82]. According to this study, the average yearly expenses of a truck operator are:

- delivery truck with a gross vehicle weight rating of 9 tons: k€ 65.4;
- regional truck with a gross vehicle weight rating of 16 tons: k€ 72.0;
- long haul truck with a gross vehicle weight rating of 40 tons: k€ 158.9;
- long haul refrigerated truck with a gross vehicle weight rating of 40 tons: k€ 179.4.

Figure 10 shows the yearly cost repartition of operating a truck per vehicle segment. As it can be seen, annual fuel costs range from 10% to 25%, depending on the vehicle tonnage (the lower the payload the lower the percentage). It is therefore clear that in case of long-haul trucks, a mini-ORC waste heat recovery system enabling fuel savings between 2.5 and 5% (conservative estimate for technology introduction) can significantly contribute to the reduction of operating costs and can substantially improve the total cost of ownership (TCO). Table 5 shows a summary of the potential yearly benefits of recovering exhaust heat with a mini-ORC system on commercial vehicles. The economic and environmental benefit could substantially grow with the improvement of the technology, which is still in its infancy, and with mass adoption.

Table 5. Yearly fuel cost and potential saving associated with equipping truck engines with an ORC waste heat recovery system.

Application	Delivery	Regional	Long haul	Long haul ref.
Yearly fuel cost (€)	6540	9362	39 704	43 053
Yearly savings (€)	164-327	234-468	993-1985	1076-2153



	Delivery 9t	Regional haul 6t	Long haul 40t	Long haul refrigerated 40t
■ Fuel	10%	13%	25%	24%
■ Tyres	1%	2%	4%	3%
■ Maintenance	8%	7%	11%	12%
■ Tolls	0%	2%	5%	4%
■ Driver wages	43%	39%	25%	26%
■ Driver benefits	5%	5%	6%	6%
■ Insurance	3%	4%	3%	2%
■ Depreciation truck	9%	9%	8%	7%
■ Depreciation trailer	0%	0%	3%	5%
■ Fixed costs	21%	19%	10%	11%

Figure 10: Yearly operating costs of trucks, per segment

Using previously published data [83] [84], Table 6 provides a comparison between several technologies for waste heat recovery systems developed so far and allows to gain a preliminary insight regarding what is possible today in terms of fuel efficiency and payback (without incentives).

Table 6: technical and economic aspects of exemplary ORC waste heat recovery systems for truck engines (example 1 = S1, Example 2 = S2, Example 3 = S3).

System	S1	S2	S3
Source	Exhaust	Exhaust	Exhaust + EGR
Fluid	Ethanol	R245fa	Ethanol
Coupling	Mechanical	Electrical	Mechanical
Expander	Piston	Turbine	Turbine
Fuel consumption reduction (%)	3%	2%	3.5%
System initial cost (€)	2666 $^{+/-266}$	2650 $^{+/-350}$	3450 $^{+/-550}$

Figure 11 shows, based on the data of Table 6, the dependency of the return on investment (in years) from the ORC waste heat recovery system production volume (in units). The results have been obtained using an established cost model [85]. The payback period offered by an ORC waste heat recovery system to a long-haul truck operator was calculated for different production volume scenarios. In this example, in order to reach a viable payback time for the operator (assumed as 2 to 3 years), System 1 would be preferable with a volume of at least 20 000 units per year, which would represent 5.1% of the European yearly truck production (assuming a 2020 production of 389 000 long-haul trucks). Even an introduction of the technology limited to this small share of the market would allow to save 21.6 million liters of fuel every year corresponding to around 56 million kt of CO_2 [86].

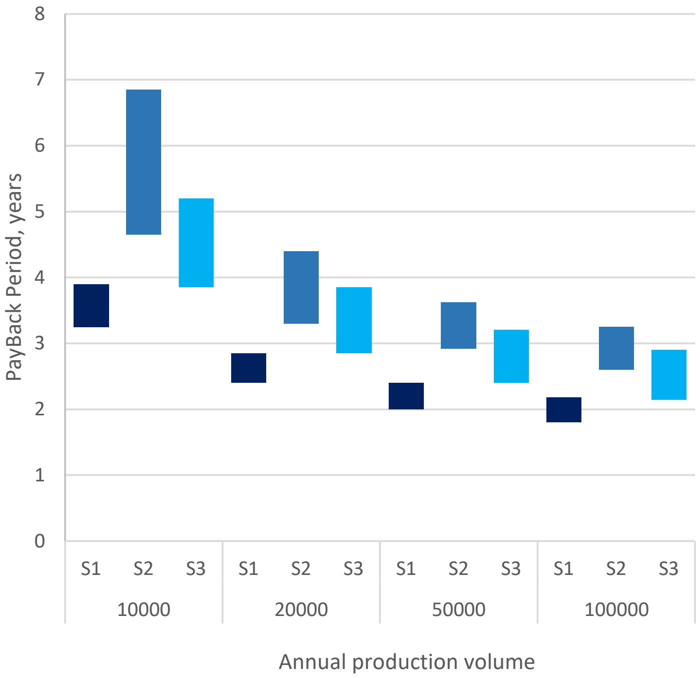


Figure 11: Estimated payback period versus annual production volume for a long-haul truck.

Finally, it is important to highlight that the calculated savings are related solely to long-haul trucks because their large fuel consumption makes the mini-ORC waste heat recovery solution more cost effective. However many other vechicles powered by combustion engines, such as off-road vehicles, ships and boats, trains, etc., could benefit from ORC waste heat recovery solutions and this would lead to an enormous impact on the global energy and CO_2 emissions scenario, even if carbon-free fuels were to substitute fossil fuels completely. Given the rather high economic viability of waste heat recovery for mobile engines, a proper regulatory framework would greatly facilitate the uptake. The societal benefit is clearly enormous.

4.2.2 Inland and Coastal Vessels Engines

As another example of the potential of waste heat recovery from propulsive engines, Table 7 shows the temperature-dependent potential of waste heat recovery in European inland and coastal vessels: again, it is differentiated between total wasted thermal energy (theoretical potential), wasted thermal energy that is convertible into additional mechanical energy (technical potential) and the total power capacity that could be installed (installable capacity). Also in this case, ORC systems would improve energy efficiency, even if hydrogen or other environmentally friendly fuels (carbon-based synthetic fuels or ammonia) will be adopted. The theoretical potential is based on Eurostat data related to energy input for domestic navigation and the technical potential has been obtained similarly to how values in Table 3 are calculated.

Table 7: Potential for waste heat recovery by means of ORC systems from engines of European inland and coastal vessels. Theoretical potential= total wasted thermal energy, technical potential = wasted thermal energy that is convertible into additional mechanical power or electricity, and Installable capacity = total power capacity that could be installed. The Installable Capacity is calculated assuming 3000 hours of operation per year.

Temperature level	Theoretical Potential	Technical Potential	Installable Capacity
Below 100 °C	16.8 TWh$_{th}$	1.3 TWh$_{el}$	0.42 GW$_{el}$
200 to 500 °C	16.8 TWh$_{th}$	3.8 TWh$_{el}$	1.27 GW$_{el}$
Total	33.6 TWh$_{th}$	5.1 TWh$_{el}$	1.69 GW$_{el}$

A number of nationally funded research and demonstration projects have been completed with the purpose of increasing the TRL of ORC Waste Heat to Power for ship propulsion. Seemingly, no European funded R&D project has addressed this efficiency improvement technology despite the potential for significant CO$_2$-emmission reduction for inland barge transport and coastal ship transport activities.

Table 9, taken from the report of a study funded by the European Regional Development Fund, reports that the European cargo fleet counted 19 099 inland motorized transport vessels in 2013, with about 73% located in the Rhine basin. Furthermore, the study shows that more than 64% of the vessels were older than 37 years. This indicates a significant opportunity for engine retrofitting solutions. Dedicated research and development on retrofittable ORC waste heat recovery systems are in great need, particularly when considering that a large part of the inland vessels are eligible for subsidized fossil fuel.

Table 9: Inland motorized transport vessels in Europe (2013) [87]

Active European cargo fleet in 2013	Rhine countries	Danube countries	Elbe countries	Total	Other EU countries
Dry cargo vessels	6340	383	115	6838	660
Tank vessels	1846	45	0	1891	
Pushboats/slow boats	1895	691	298	2884	N/A
Dry cargo barges	2843	2371	645	5859	461
Tank barges	197	309	0	506	
Total	13121	3799	1058	17978	1121
Total without Pushboats/slow boats	11226	3108	760	15094	
Active European fleet+ other EU countries					**19099**

5 Policy and Regulation: Current Situation and Proposals for Improvement

5.1 Introduction

As documented in this report, organic Rankine cycle (ORC) technology is arguably the best solution for the conversion into electrical or mechanical power of a large part of the huge amount of thermal energy that industrial processes and thermal engines currently release to the environment. This can result in an enormous societal benefit. Hence, related regulation should be rationally related with the technical and economic opportunities brought forth by this technology.

In the energy-intensive industry, the utilization of the various streams of thermal energy which are currently wasted should be rationally prioritized [10]. Figure 12 shows schematically how available thermal energy from industrial processes can be utilized and how its utilization should be prioritized/incentivized, namely

- first, previously wasted thermal energy should be reused as much as possible within the industrial process, for heating, hot water production or cooling (with, e.g., absorption chillers);
- if that is not possible, but district heating networks, other factories, large buildings, tertiary sites, green houses, or any other facilities are in the vicinity of the waste-heat generating plant, and they need thermal energy, this opportunity should be considered with the second level of priority;
- Finally, conversion of otherwise wasted thermal energy into electrical power is the third option, whereby the electrical power can be consumed within the industrial site generating the waste heat and/or exported to the grid. The indisputable advantage of this solution is that electrical power can be used for a myriad of different purposes, and its dispatchment is simple and economically attractive.

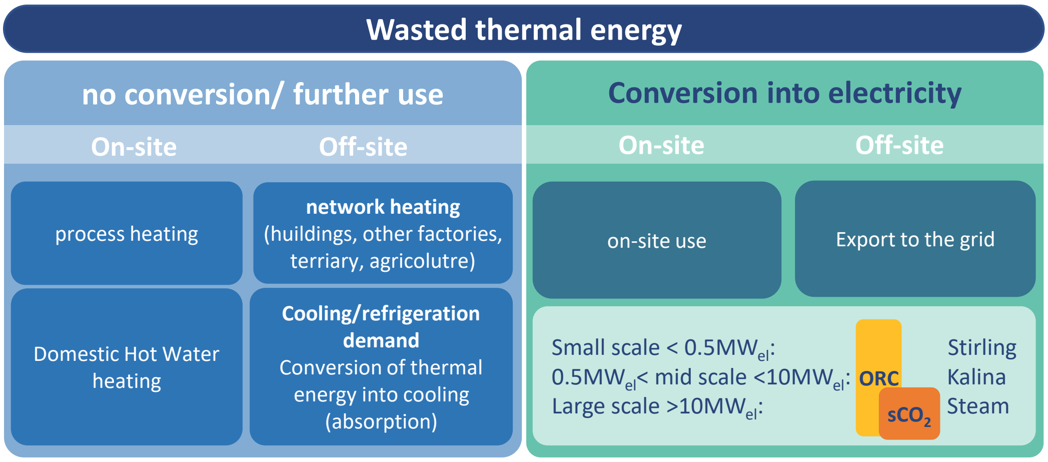


Figure 12. Rational approach to waste heat recovery in energy-intensive industry.

Currently, the feasibility of ORC power plants to recover industrial waste heat is influenced by various sets of policies and regulations, including

- greenhouse gas (GHG) emission policies,
- renewable energy targets,
- energy efficiency policies,
- levies and taxes for general purposes.

Policies and regulation that support waste heat recovery include

- energy efficiency policy,
- environmental regulations,
- incentives to the sustainable generation and use of heat [88].

Four foundational policy documents determine the future development of waste heat recovery technology in the EU: the Renewable Energy Directive [89] (RED 2), the Energy Efficiency Directive (EED 2) [90], the Emission Trading System (ETS) and the EU Taxonomy for Sustainable Activities. In the following, the current treatment of waste heat recovery in those documents is analysed, and some improvements are proposed.

5.2 Status and Proposals

5.2.1 Renewable Energy Directive (RED)

The current status of waste heat recovery technology regulation within the RED 2 is completely unsatisfactory because of a basic conceptual reason: waste heat and cold, as defined in Art.2, clause 9, is not considered as a potential source of renewable energy, see Art. 2, sect. 1. Throughout the document, waste heat and cold is only considered for direct use in the heating and cooling sector, see point (49) in the preamble; Art.15, sections 4 and 7; Art. 20, section 3; Art. 23; Art. 24, sections 4 and 5.

The potential of waste heat recovery for the production of clean electrical power is simply not recognized at all in this fundamental document, which of course seriously undermines the present and future development of this clean energy technology in the EU.

According to a recent report of the Joint Research Center of the European Commission [91], waste heat can be considered as a renewable energy source from a regulatory point of view if the waste heat

- is utilized off-site,
- is sold,
- is utilized in a heating network.

This definition of waste heat is clearly too restrictive and such definition negatively affects the possibility of making rational use of this humongous resource. **Waste heat is an unavoidable by-product of most industrial processes, including future processes using renewable electrical power, hydrogen or synthetic fuels as primary sources, and it can be utilized also as an emission-free and reliable energy source for electricity production, exactly as all other renewable energy sources**, as it complies with the principle of circular economy. Notably, waste-heat-to-power is already treated as a renewable energy conversion technology in 17 States of the United States of America, and as an efficiency improvement technology in 4 additional states [92].

The current draft of the proposed amendment of the RED 2, released on 14 July 2021, also known as RED 3, does not address this issue at all.

PROPOSAL

Waste heat should be considered as a renewable energy source, as it does not consume any finite resource and does not cause additional carbon dioxide emission. Electrical energy generated from waste heat recovery must be considered as renewable energy *from a regulatory point of view*, as long as incentivizing it does not result into promoting non-renewable or non-sustainable upstream processes. For example, as a general rule, the generation of any kind of solid or liquid waste must be reduced as much as possible; therefore, incentives on waste heat recovery should not end up hampering the reduction of the upstream waste production.

Waste-heat-to-power must be considered as a renewable energy conversion technology.

Amendment #1: Article 2 section 1 of the RED should be revised as follows (in bold):

'energy from renewable sources' or 'renewable energy' means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, ***waste heat****, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas.*

Amendment #2: Article 2 section 9 of the RED should be revised as follows:

'waste heat and cold' means unavoidable heat or cold generated as by-product in industrial or power generation installations, or in the tertiary sector, which would be dissipated unused in air or water without access to a district heating or cooling system**, or without being used by a waste-heat-to-power system.**

Amendment #3: A new definition should be added immediately afterwards:

'waste-heat-to-power' denotes technologies that utilize waste heat, that would otherwise be lost to the ambient, to generate electrical power. This power is considered as renewable, as long as incentivizing it does not result into promoting non-renewable or non-sustainable upstream processes.

5.2.2 Energy Efficiency Directive (EED)

Waste Heat Recovery Cogeneration

The Energy Efficiency Directive (EED 2) defines cogeneration as "the simultaneous generation in one process of thermal energy and electrical or mechanical energy", Art. 2 definition (30). However, the implicit assumption, which is made clear by the methodologies laid out in Annex II, is that the main goal of a cogenerator is the production of electrical power from a primary thermal energy source, such as natural gas. The cogeneration setup allows to recover the waste heat *of the electrical power generation process*, making it available for heating or cooling purposes, thus achieving an overall efficiency of the combined power and heat generation process from the primary thermal energy source which is higher than what could be achieved by two separate generation processes providing the same electrical and thermal power output.

All the references to cogeneration in the EED 2 only make sense, and thus implicitly refer, to this cogeneration scenario.

In fact, waste-heat-to-power technology makes an additional cogeneration scenario feasible: primary energy source is actually waste heat from some upstream industrial process, *which is not electrical power generation*. In this case, a waste heat recovery unit can well operate in cogeneration mode, by taking high-temperature waste heat from an industrial process, using it to produce some electrical power, and then discharging heat at lower temperature, which is still usable for heating purposes, e.g., in a district heating system.

As an example, consider an industrial process discharging flue gases at 350 °C, which is located near a district heating network working at 80 °C. A first option is of course to use these flue gases directly to heat up the working fluid of the district heating system. This option is already covered by the provisions of the RED 2 directive, see for example Art. 24, which allows member states to count the share of waste heat used to feed district heating systems together with renewable energy used for the same purpose. A waste heat recovery cogeneration system is another and possibly better solution. An ORC power plant is fed with the hot flue gases, produces electrical power, that could be used internally for the purposes of the upstream industrial process or exported to the grid, and then heat at 80 °C can be transferred to the district heating system through its condenser unit. In this case, a cogeneration configuration is put into effect. The amount of otherwise wasted thermal energy which is recovered is the same as in the first scenario, but some of it is converted into electrical energy, which is more valuable and more easily distributed and dispatchable than thermal energy.

PROPOSAL #1

A primary energy savings index analogous to the one defined in Annex II should be defined, comparing the primary energy required to produce the recovered heat in the first scenario with the primary energy required to produce the combined electrical and thermal energy output of the second one, which will be lower. The difference could be counted as an additional savings obtained by means of waste heat recovery, and should be recognized, accounted for, and incentivized as such.

PROPOSAL #2

Concerning the promotion of efficiency in the heating sector, Art. 14(10), Art. 22(1) and Art. 23(2) of the current EED refer to the harmonised efficiency reference values for separate production of electricity and heat. In particular, EED refers to Regulation EU 2015/2402 where waste heat is included in the O14 category. In this category, the current reference value for the efficiency of the generation of electricity is 30%. This value is excessively high for technologies in the O14 category, especially because the efficiency of the electrical power production strongly depends on the fluctuations of the waste heat of industrial processes and on the waste heat temperatures. The reference efficiency value of 30% of the technologies belonging to the O14 category must be lowered; alternatively, sub-categories based on the temperature values at which waste heat is available (the fist up to 350°C and another > 350°C) must be introduced.

Harmonization of Waste Heat Recovery National Regulations

Heat recovered from an industrial process can be used in different ways. One of the best ways to valorize it, is to convert it into electricity.

The Energy Efficiency Directive (EED 2), implemented in the regulatory framework of Member States, already recognizes waste-heat-to-power technology; however, the current regulatory framework is fragmented, hampering the development of a EU-wide market for such solutions, and thus needs to be harmonized. As an example, the Italian incentive scheme is an excellent example of waste-heat-to-power valorization at national level, but unfortunately it is not consistent with the incentive schemes of other EU countries (see the following examples for more details).

PROPOSAL #3

The policies regarding waste-heat-to-power documented in the EED 2 have been implemented in the regulatory framework of the Member States through national incentive schemes (Article 7 and article 7a of the EED 2). Unfortunately, the EU incentive framework for waste-heat-to-power is too heterogeneous and fragmented among different Member States. Establishing a common EU incentive policy framework and implementing the energy efficiency projects as mandatory, especially for energy-intensive industrial sectors, is a must if the objectives of the Green Deal are to be pursued rationally and consistently.

Examples of Waste Heat Recovery National Regulations

The policy laid out in the EED has been implemented in all Member States regulations through national incentive schemes. A brief summary of national regulations is reported in the following paragraphs related to some exemplary European Countries. It is important to highlight that the analysis does not cover all European Countries.

FRANCE

In the French system, the number of certificates generated by each action (Certificat d'Economie d'Energie or CEE) is calculated based on cumulated primary energy savings over the duration of the operational lifetime of the investment. If the energy is recovered as electricity, a thermodynamic coefficient applies in order to take into consideration *the CO_2 emission intensity of the electrical mix* in Europe. This coefficient is defined as the amount of electricity that is generated from an amount of primary energy. Currently, it is assumed that for each kWh of electricity 2.58 kWh of primary energy are consumed.

These certificates are purchased by the energy providers from the companies implementing the energy efficiency actions, creating therefore a market-based value of the certificates. Today, ORC power plants do not benefit from a standard template with agreed calculations of energy saving, but are treated on a project-to-project basis. First waste-heat-to-power projects involving the installation of ORC power plants are expected to establish the rule for these calculations.

ITALY

In the Italian system, White Certificates or Energy Efficiency Certificates (TEE - Titoli di Efficienza Energetica) promote energy efficiency in the industrial sector, network infrastructure, etc. White certificates are documents certifying the achievement of a certain reduction of energy consumption. One white certificate corresponds to saving one Ton of Oil Equivalent (toe) energy due to the implementation of the energy efficiency intervention.

Every year, electricity and natural gas distributors with at least 50 000 customers are obliged to obtain a number of certificates corresponding to their energy efficiency target. In most cases, the white certificates are tradable and can be combined with an obligation to achieve a certain target of energy savings. In this regulatory framework, producers, suppliers or distributors of electricity, gas and oil are required to undertake energy efficiency measures for the final user that are consistent with a pre-defined percentage of their annual energy deliverance.

Since 2011, with the introduction of the EEN 9-11 norm, the Italian Energy Management Authority (ARERA) has included the eligibility of Waste Heat Recovery into the White Certificates scheme, allowing for a 5-year benefit. In 2017, thanks to the Decree DM 11 of January 2017, a specific incentive scheme for waste heat recovery by means of Organic Rankine Cycle systems has been introduced, allowing for a 10-year benefit.

GERMANY

In Germany, waste-heat-to-power is considered only if it is part of a cogeneration power plant. The first policy and regulation supporting cogeneration was reviewed in August 2012. ORC power plants can be considered as part of a cogeneration system and, as such, are eligible for incentives, but only if the thermal energy used to produce electricity is further used for heating purposes.

The first law about large cogeneration power plants dates back to 2002 and considered only fossil-fuels-fed power plants which could not receive support from laws related to renewable energy sources. It foresaw different incentives according to the kind of intervention (retrofitting or new plant) and to the plant capacity.

A second version of the cogeneration power plants law was issued in 2009. The last revision of this law, launched in August 2012 and foreseen to run until 2020, set as a goal for 2020 that 25% of the total electricity production should be obtained from cogeneration power plants. As an incentive, the law states that cogeneration power plants have priority of connection and dispatch to the grid, therefore with the same priority of renewable power plants. Moreover, it established a budget of up to 750 million €/year as incentives for cogeneration. A new capacity category was introduced (50 – 250 kW_{el}) to include small power plants. Further incentives are assigned to heat storage infrastructures and to cogeneration characterized by flexible operation, because they contribute to the realization of the so-called 'smart grid'.

Waste-heat-to-power is incentivized only if the installation can be considered a demonstration project within the "Environmental Innovation Program" of the Ministry of Environment. This program supplies low-interest loans for a period of up to 30 years to projects for which environmental impact reduction can be demonstrated.

SWEDEN

The Swedish variant of green certificates is the establishment of the *Elcertificate* market: a market-based support scheme for renewable electricity generation. Electric power generated for internal industrial use only is taxed in the same manner as if it were sold on the market. The rule allows up to 100 kW_{el} of internally produced electric power to be tax-free, only if the thermal energy input is generated from biofuel.

5.2.3 Emissions Trading Systems (ETS)

Electricity produced by waste heat is not eligible for free allocation in the EU Emissions trading system (ETS). Carbon pricing can play a key role in emissions reduction from industry, given that investment decisions are highly cost-sensitive and the EU ETS is well suited to accelerate the clean energy transition in the power sector. Carbon pricing can make energy efficiency improvements at scale more cost-effective, encouraging investments in less carbon-intensive technologies and it can be a key incentive for investments in innovative technologies.

PROPOSAL

The EU ETS Directive - Annex I should include a new category of activity for waste heat gases recovered to produce electricity by means of ORC technology. Such waste gases should be eligible for free allocation within the ETS mechanism, since they can be exploited by an ORC waste-heat-to-power system to produce electricity without additional CO_2 emissions into the atmosphere.

5.2.4 EU Taxonomy for Sustainable Activities

Power generated from waste heat recovery technologies is carbon-neutral: no additional CO_2 emissions are produced for the new energy carrier originated from waste heat and it can be considered as clean as renewables. Waste-heat-to-power valorization represents an opportunity for the optimization of circular-economy systems into a more integrated energy system.

Waste-heat-to-power should be present within the Platform on Sustainability Finance.

The production of heat/cold using waste heat is already considered in the European Taxonomy (Delegated Act, Annex I and Annex II, point 4.25) as one of the environmentally sustainable economic activities, according to several criteria (Climate change adaptation, Transition to a circular economy, Pollution prevention and control, Protection and restoration of biodiversity and ecosystems).

Unfortunately, as of today, only the production of heat using waste heat is considered in the Taxonomy. Electricity production using waste heat is not mentioned, although it represents a sustainable opportunity to reduce greenhouse gasses emissions and it is compliant with the circular economy principle. Furthermore, electrical power is more easily transported and utilized than heat/cold, giving waste-heat-to-power technologies more potential for the generation of clean, sustainable energy.

PROPOSAL

Waste heat is properly reported in the EU Taxonomy, Delegated Act, as one of the carbon-free opportunities, but is currently limited to the production of heat/cold only. Waste-heat-to-power is currently missing from the document.

The following amendment to activity 4.25 is proposed, which, in addition, should be renamed to “Production of heat/cool and/or power using waste heat”.

TEXT OF THE EU TAXONOMY, DELEGATED ACT	PROPOSED AMENDMENT (IN RED)
Annex II to the Commission Delegated Regulation (EU) …/… supplementing Regulation (EU) 2020/852	Annex II to the Commission Delegated Regulation (EU) …/… supplementing Regulation (EU) 2020/852
4.25 Production of heat/cool using waste heat *Description of the activity* Construction and operation of facilities that produce heat/cool using waste heat. The economic activities in this category could be associated with NACE code D35.30 in accordance with the statistical classification of economic activities established by Regulation (EC) No 1893/2006.	**4.25 Production of heat/cool and/or power using waste heat** *Description of the activity* Construction and operation of facilities that produce heat/cool and/or power using waste heat. The economic activities in this category could be associated with NACE codes D35.30 and D35.1 in accordance with the statistical classification of economic activities established by Regulation (EC) No 1893/2006.
Technical screening criteria	*Technical screening criteria*
Substantial contribution to climate change mitigation	Substantial contribution to climate change mitigation
The activity produces heat/cool from waste heat.	The activity produces heat/cool and/or power from waste heat.
Do no significant harm (‘DNSH’)	Do no significant harm (‘DNSH’)
(2) Climate change adaptation: The activity complies with the criteria set out in Appendix A of Annex to the Commission Delegated Regulation (EU) …/… supplementing Regulation (EU) 2020/852	(2) Climate change adaptation: The activity complies with the criteria set out in Appendix A of Annex to the Commission Delegated Regulation (EU) …/… supplementing Regulation (EU) 2020/852
(3) Sustainable use and protection of water and marine resources: n/a (4) Transition to a circular economy: The activity assesses availability of and, where feasible, uses equipment and components of high durability and recyclability and that are easy to dismantle and refurbish. (5) Pollution prevention and control: Pumps and the kind of equipment used, which is covered by Ecodesign and Energy labelling comply, where relevant, with the top class requirements of the energy label laid down in Regulation (EU) 2017/1369, and with implementing regulations under Directive 2009/125/EC and represent the best available technology. (6) Protection and restoration of biodiversity and ecosystems: The activity complies with the criteria set out in Appendix D of Annex to the Commission Delegated Regulation (EU) …/… supplementing Regulation (EU) 2020/852	(3) Sustainable use and protection of water and marine resources: n/a (4) Transition to a circular economy: The activity assesses availability of and, where feasible, uses equipment and components of high durability and recyclability and that are easy to dismantle and refurbish. (5) Pollution prevention and control: Pumps and the kind of equipment used, which is covered by Ecodesign and Energy labelling comply, where relevant, with the top class requirements of the energy label laid down in Regulation (EU) 2017/1369, and with implementing regulations under Directive 2009/125/EC and represent the best available technology. (6) Protection and restoration of biodiversity and ecosystems: The activity complies with the criteria set out in Appendix D of Annex to the Commission Delegated Regulation (EU) …/… supplementing Regulation (EU) 2020/852

5.2.5 A Positive Example from China

The evidence of the success of policy strategy related to waste-heat-to-power is documented in a report of the International Finance Corporation (IFC –World Bank Group) titled “*Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis”* [93], which analyses how a favorable policy was implemented in China.

China, with more than 1000 installations in which steam power plants are integrated and its industrial policy, hold the waste-heat-to-power leadership for large-capacity sites. The Chinese success is due to a combination of regulatory framework involving the compulsory realization of waste-heat-to-power plants in any new cement production plant, some financial incentive and tax credit and a joint agreement for innovation.

The launch of a governmental policy aimed at supporting the cement industry and its technology chain has enabled the installation of numerous waste-heat-to-power plants in cement factories, with benefits for the energy-intensive industries themselves in terms of competitiveness and sustainability, as well as for the development of a technology supply chain that today competes in international markets.

6 Research and Development: Current Status and the Way Forward

6.1 Existing Programs

In the last five years, several European Commission R&D programs have been focused on energy recovery and waste heat utilization, mostly related to the industrial and civil sectors but also to other sectors, such as aerospace. The framework program of the European Commission for research and innovation is the most relevant of these programs. It is comprised of calls for proposals in thematic areas of interest, which are defined and renewed every five to seven years. Horizon Europe is the current framework program and runs from 2021 to 2027. Horizon Europe is the successor to Horizon 2020 which ran from 2014 to 2020.

Framework research and innovation programs of the European Commission are composed of subprograms, so-called pillars. For example, Horizon 2020 was formed by three pillars: *excellent science*, *industrial leadership* and *societal challenge*. The first pillar funded frontier research, capacity building and the creation of a large, international research infrastructure. The second pillar aimed at enabling and fostering the co-investment of industrial players in higher-risk innovation, with a special incentives for small and medium enterprises (SME’s). The *societal challenge* pillar stimulated seven areas where investment in specific research and innovation actions had the potential to yield societal benefits, namely:

- health, demographic change and wellbeing;
- food security, sustainable agriculture, marine and maritime research, and the bio-economy;
- secure, clean and efficient energy;
- smart, green and integrated transport;
- climate action, resource efficiency and raw material;
- Europe in a changing world - inclusive, innovative, reflective societies;
- secure societies.

Secure, clean and efficient energy and *smart, green and integrated transport* included most of the funding opportunities to support research and innovation in waste heat recovery technologies and applications, stationary and mobile. Horizon Europe is the successor to Horizon 2020 and adopts a similar structure, shown in Figure 13. This €95.5 billion program is comprised of four pillars. The first pillar is again *Excellent Science*. The second pillar, *Global Challenges and European Industrial Competitiveness*, supports research tackling societal challenges and includes the Joint Research Centre framework, which was independent from the third pillar in Horizon 2020. Pillar three is focused on market-oriented innovation and on the integration of the so-called *knowledge triangle* of education, research and innovation. The goal of a fourth horizontal pillar is to provide the EU member states with support to maximize the results of their national research and innovation programs through international collaboration in a European Research Area. The six clusters in pillar 2 of Horizon Europe play a similar role to the seven topical areas in the *Societal Challenge* pillar of Horizon 2020. Research funding for Thermal Energy Harvesting technologies and applications is allocated within Cluster 5 (*Climate, Energy and Mobility*).

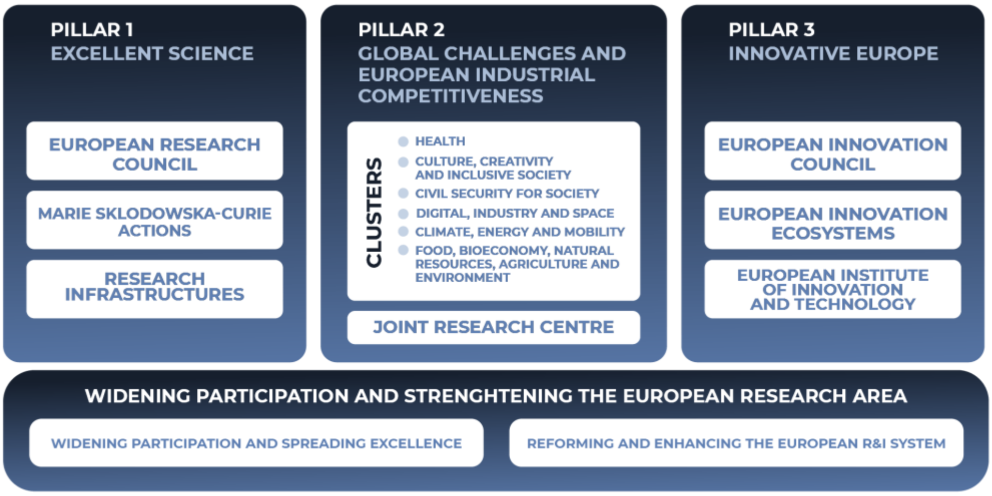


Figure 13. Research and Innovation funding framework of Horizon Europe (Source: https://www.horizon-eu.eu).

6.1.1 Waste Heat Recovery with ORC power plants

Table 8 lists twelve projects on waste heat recovery funded by the Horizon 2020 framework program, with a cumulative budget of €55M. Notably, only the two projects I-Therm and CO2OLHEAT are related to waste-heat-to-power technologies, while the others are related to the exploitation of waste heat for thermal purposes only (mostly process heat). In addition, only CO2OLHEAT targets electricity generation and includes the design, manufacturing and demonstration of a pilot plant. Funding for larger demonstration facilities has become more prominent in Horizon Europe.

The information in Table 9 suggests two observations. On the one hand, it is confirmed that the European Commission is aware of the importance of tackling energy inefficiency in the form of waste heat released to the environment across the industry and residential sectors, albeit the level of funding is modest compared to other renewable energy technologies and considering its potential. On the other, the potential of the conversion of wasted thermal energy into electrical (or mechanical) power is largely neglected. This is arguably a lost opportunity to expand waste heat recovery beyond low-grade heat applications, and to enhance research through the development of innovative solutions to foster the penetration of waste-heat-to-power units at different scales and in various sectors.

Reasons to support research and innovation for waste heat to power technologies are as follows.

- *Maximum performance and minimum environmental impact must be pursuit*. Research programs shall always push for the most efficient and integrated solutions, which must include the possibility to produce mechanical or electrical power thus contributing to the reduction of fossil fuels usage.
- *Power generation is not in competition with the thermal use of available heat*. Harvesting thermal energy to produce mechanical/electrical power does not preclude the direct utilization of thermal energy. In case of heat demand, all or part of the available waste heat should be used first, or, if possible, the heat rejected by the waste heat recovery power plant at a lower temperature should be used and this leads to the maximum efficiency.

Table 8: Projects on Waste Heat Recovery funded by the Horizon 2020 program of the European Commission.

Project	M€ funding	Topic	Power production
SPIRE PPP Valorization of waste heat in industrial systems Field: industrial - final / TRL: 6 - 7 / starting year: 2016			
Smartrec www.smartrec.eu	3.7	secondary aluminum recycler and/or ceramic processor	No
DryFiciency www.dry-f.eu	5	drying applications with heat pumps	No
ETEKINA www.etekina.eu	4.6	Heat recovery with heat pipes and HX in steel, aluminum, ceramic industry	No
Business case for industrial waste heat/cold recovery Field: industrial - final / TRL: 4 - 8 / starting year: 2018			
INCUBIS www.incub-is.eu	2	Industrial Symbiosis Incubator for Maximizing Waste Heat/Cold Efficiency in Industrial Parks and Districts	No
R-ACES www.r-aces.eu	2	Integration of renewables and exchanging surplus of energy between industries	No
EMB3Rs	4	Determining the costs and benefits related to excess HC utilization routes for industry and end users	No
SO WHAT www.sowhatproject.eu	3.4	Industrial waste heat and waste cold in industrial sector	No
Waste heat recovery from urban facilities and re-use to increase energy efficiency of district or individual heating and cooling systems Field: civil - Final / TRL: - / starting year: 2015			
ReUseHeat www.reuseheat.eu	4	Demonstrate first of their kind advanced, modular and replicable systems enabling the recovery and reuse of excess heat available at the urban level.	No
New technologies for utilization of heat recovery in large industrial systems, considering the whole energy cycle from heat production to transformation, delivery and end use Field: industrial - Final / TRL: 4 - 7 / starting year: 2015			
SusPIRE www.suspire-h2020.eu	3.7	Sustainable Production of Industrial Recovered Energy using energy dissipative and storage technologies	No
Indus3Es, Industrial Energy and Environment Efficiency www.indus3es.eu	3.9	Developing an innovative Absorption Heat Transformer (AHT) for this purpose, focused on low temperature waste heat recovery	No
I-Therm, Industrial Thermal Energy Recovery Conversion and Management www.itherm-project.eu	4	Investigate, design, build and demonstrate innovative plug and play waste heat recovery solutions to facilitate optimum utilization of energy in selected applications with high replicability and energy recovery potential in the temperature range 70°C – 1000°C.	Yes, ORC and sCO_2 power plants
Industrial (Waste) Heat-to-Power conversion Field: industrial - Final / TRL: 6 - 7 / starting year: 2020			
CO2OLHEAT	14	Design and testing of novel sCO_2 WHR power plant in the cement industry	Yes

Table 8: Continued

Project	**M€ funding**	**Topic**	**Power production**
Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries Field: industrial - Final / TRL: 6 / starting year: 2014			
Taasio	4	Develop solutions to recover the waste heat produced in industrial, energy-intensive processes -cement, glass, steelmaking and petrochemical- and transform it into useful energy	Yes
Boosting new Approaches for flexibility Management By Optimizing Process Off-gas and Waste use Field: industrial - Final / TRL: 6 / starting year: 2018			
BAMBOO	11	Develop new technologies for energy and resource efficiency in four intensive industries -steel, petrochemical, minerals and pulp and paper-. Scale-up, testing and validation under real production conditions.	Yes

- *Local power generation from renewable energy and waste heat recovery, even if the latter is originated from non-renewable energy sources, must be encouraged in future energy scenarios*. Generation of power from thermal energy that is otherwise wasted or used in applications with lower added value allows to limit the demand for primary energy and to reduce a number of concerns about distribution grids: reliability due to cyclic stress, distribution losses, maintenance labor and costs, etc.

- *Large room for technology improvement.* Even though waste heat recovery is a rather mature technology, there are still a number of technical challenges that will only be solved if an appropriate funding program supports technology development beyond the current state of the art. Only once these hurdles have been overcome, the full potential of waste to power can be exploited.

- *soaring scientific interest in 'waste-heat-to-power' applications*: the number of publications indexed with the keywords 'waste heat recovery' and 'power production' increased by an order of magnitude in the last ten years, as reported in Figure 16. Screening of these data reveals that most of this activity has been carried out in China (470 documents), followed by United Kingdom (100 documents) and Europe (34 documents).

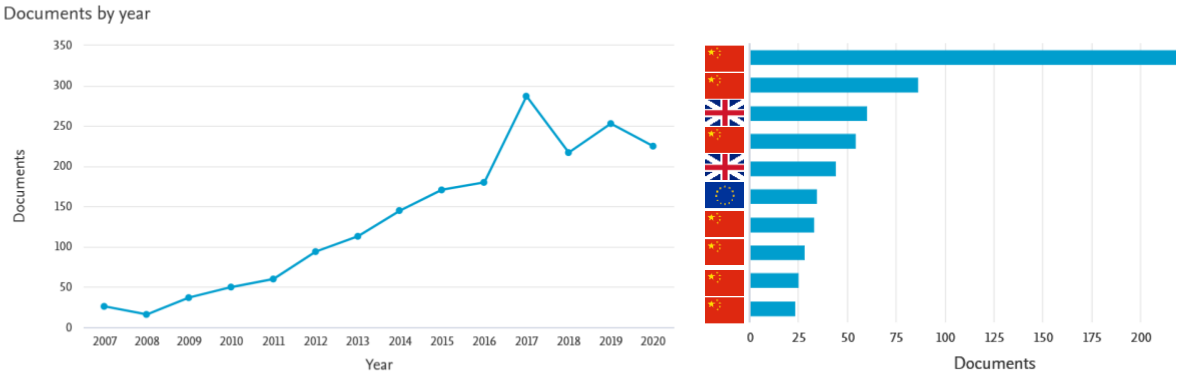


Figure 14. Results of searching the Scopus database for the keywords 'waste + heat + recovery': number of published documents (left) and affiliation of the leading author (right).

The European Commission is aware of the need to support research on waste heat recovery technologies, as proven by the list in Table 8, albeit the support is insufficient. However, waste heat recovery is most often conceptually associated to district heating or other uses of thermal energy. This is why the **difference** between **waste-heat-to-heat** and **waste-heat-to-power** and the relevance of waste-heat-to-power cannot be emphasized enough. These aspects have been made clearer in the recent *Clean Energy Transition – Technologies and Innovations Report* (CETTIR) [74], part of the *Report from the Commission to the European Parliament and the Council on Progress of Clean Energy Competitiveness* [94] adopted on 14 October 2021 as part of the State of the Energy Union Package. Here it is stated that "*the industry will play an important role in meeting the overall aim to transform the EU into a modern, resource-efficient and competitive economy with an economic growth decoupled from resource use and aiming at zero net emissions of greenhouse gases by 2050*". CETTIR categorizes industrial waste heat applications in three groups: a) thermal energy that is recuperated through appropriate heat exchangers and utilized at similar temperature in another process; b) thermal energy that is recuperated through appropriate heat exchangers and then upgraded to a higher temperature for the same or another process; and c) thermal energy that is recuperated through appropriate heat exchangers and then converted into mechanical/electrical power.

Category c) is of utmost importance, as it constitutes an opportunity for power consumers to reduce their primary energy consumption, but it is unfortunately overlooked by most existing organizations in the waste heat recovery sector, focusing mainly on category a). As for category c), Organic Rankine Cycle power plants are thus identified as the technology of choice for a large range of capacities and temperatures of the heat source, and it is remarked that "*the potential is still large for improvements of the techno-economic performance, as well as for its wider application to the conversion of more types of waste heat streams*[7]*, both in terms of capacity and temperature level*". According to CETTIR, the areas offering opportunities to improve the technology are:

- innovative thermodynamic cycle configurations, increasing efficiency and reducing capital and operating expenditures;
- new working fluids, free of problems related to thermal stability, sustainability or safety (i.e., flammability) and with lower costs;
- ad hoc heat exchangers (waste heat recovery evaporator, regenerator, condenser), tailor-made for specific applications, more efficient, less expensive, with improved maintenance characteristics.
- more efficient machinery: expanders, compressors, pumps. Although the performance of this equipment has improved significantly in recent times, thanks to the development of numerical design tools that are specific to organic working fluids, further experimentation is needed to validate these tools.
- secondary features of machinery: bearings, seals and balancing. Turbomachines for ORC systems rely on conventional hydrodynamic oil bearings and mechanical seals. CETTIR identifies opportunities for hermetic, self-lubricating bearings or even unlubricated bearings (gas and magnetic bearings). These features are very relevant for the efficiency, reliability and availability of organic Rankine cycle power plants.
- self-adaptive (machine learning) control algorithms for the management of transient conditions and the avoidance of misbehaviour and instabilities of plants already operational.

Within the Horizon Europe framework, the call for proposals HORIZON-CL5-2021-D4-01-05 was dedicated to technical solutions for *Industrial excess (waste) Heat-to-Power conversion based on*

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[7] CETTIR identifies the following business cases for the applications of ORC systems: cement, glass and steel industry, bottoming systems of reciprocating engines and gas turbines.

organic Rankine cycles, and it will fund up to two projects with a total financial support of € 14 million with the aim of bringing the technology to TRL 7. This call is complementary to a former call for proposals in Horizon 2020, namely LC-SC3-CC-9-2020 *Industrial (Waste) Heat-to-Power conversion*, which awarded € 14 million to the CO2OLHEAT project for the integration of an industrial waste heat-to-power conversion system using supercritical CO_2 technology and the subsequent demonstration of a MW-scale prototype in an industrial environment.

6.1.2 Waste Heat Recovery in Mobile Applications

Table 9 shows Horizon 2020 projects aimed at research and development for waste heat recovery system for propulsive engines. The number of projects is lower than number of research project related to stationary applications of ORC technology. Moreover, whilst most funding schemes for stationary applications are based on providing financial support to develop a specific technology, the activities listed in Table 9 are supported by instruments of a different type. For instance, DYNCON-ORC is funded through an individual fellowship of the Marie-Sklodowska-Curie program, aimed at fostering the creativity and innovation potential of post-doctoral researchers, and TORC is funded through an SME instrument scheme. Even if these instruments offer excellent opportunities for interested individuals and entities, the lack of a concerted and impactful effort is evident, if compared, for instance with that of the United States, where the SuperTruck research program of the Deaprtment of Energy has been ongoing since many years, and recently renewed (SuperTruck II). Yet, also in this case the potential is enormous (Section 4.2) and the leadership of Europe in the area of waste heat recovery technologies holds also for mobile applications (see Section 3.2) and demands for much greater attention.

Table 9: Selected projects on Waste Heat Recovery funded by the Framework VII and Horizon 2020 programs of the European Commission.

Project	**M€ funding**	**Topic**	**Power production**
Small business innovation research for Transport and Smart Cities Mobility (H2020) Field: transportation (freight) - final / TRL: 6 - 7 / starting year: 2016			
TORC https://cordis.europa.eu/project/id/733460	2.1	Truck with and Organic Rankine Cycle	No
Individual fellowship (H2020) Field: general - final TRL: NA - starting year: 2017			
DYNCON-ORC https://www.dyncon-orc.mek.dtu.dk/about	0.2	Dynamic performance modelling and controller design of a mini-scale organic Rankine cycle unit for heavy duty vehicles	No
Sustainable surface transport Field: civil/industrial - Final / TRL: 6 / Starting year: 2011			
NOWASTE www.nowasteproject.eu	2.7	Engine Waste Heat Recovery and Re-Use	No
LC-MG-1-13-2020: Decarbonising long distance shipping Field: marine/long distance shipping - Final / TRL: 5+ / Starting year: 2021			
ENGIMMONIA www.engimmonia.eu	9.5	Focus on shipping with NH_3 as energy vector and technology demonstration for efficiency increase (ORC is side topic)	Yes
CHEK www.projectchek.eu	10	Focus on H_2 as energy vector and technology demonstration for efficiency increase (ORC is side topic)	Yes

6.2 Ideas for Improved Support of Technology Development

Even though various research and development projects were funded during the last decade, a consistent and prolonged effort like the one that, for instance, sustained the birth and expansion of solar and wind energy technologies is arguably lacking for organic Rankine cycle technology, and for waste heat recovery technologies in general. As an example of successful energy technology development support, it is useful to consider the trends followed during the development and widespread adoption of wind turbines and solar photovoltaic panels.

Analysists worldwide agree on the fact that, today, these technologies are self-sustainable economically and do not need further economic support [95] [96]. However, this did not happen overnight. Taking the United States as a relevant example, a very large and sustained economic effort by the Government was needed before cost-effectiveness in free-market conditions was achieved. Over US$ 100 billion were invested overall to support the development of renewable energy technologies and this proved to be the right approach: the installation costs of onshore wind and solar photovoltaic panels dropped by more than 40% and by 80% between 2010 and 2020, reaching cost-competitiveness without subsidies in several regions worldwide [96]. It can be argued that incentivizing the ignition of a dynamic market for wind and solar technologies brought about lively research and development activities which were also supported in a substantial and structured way [97].

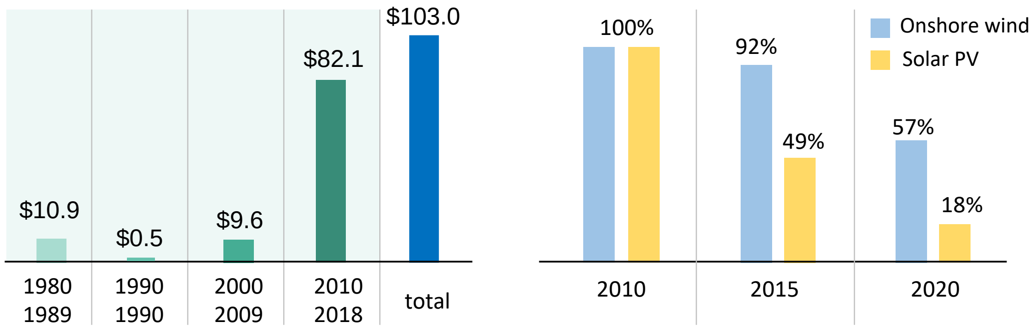

Figure 15. Tax subsidies (billions of US$) for renewable energies (all technologies) in the United States of America (left) and overnight capital cost of onshore wind and solar photovoltaic (right) over the years [96].

Given the techno-economic and societal benefits that the widespread adoption of waste heat recovery technologies could bring across many industrial sectors with both stationary and mobile applications, and given that it is instrumental to attaining the Sustainable Development Goals of the United Nations, the lack of a larger R&D program to support waste heat recovery in general and waste-heat-to-power in particular, from both an economic and regulatory point of view, is unjustified. In particular, ORC technology fulfills all the key principles of the Clean Energy Transition as stated in the European Green Deal, namely:

> “ 1. ensuring a **secure** and **affordable** EU energy supply**;**
> 2. developing a **fully integrated**, interconnected and digitalised EU energy market;
> 3. prioritising **energy efficiency**, improving the energy performance of our buildings and developing a power sector based largely on renewable sources. ”

Currently, the calls for proposal related to waste heat recovery and waste-heat-to-power in Horizon Europe and earlier programs (See Section 6.1) come as part of a somewhat scattered and insufficient approach. The urgency to achieve the final goal of a widespread adoption of this technology and the vast amount of unused thermal energy across Europe (equivalent to over 19 large nuclear power plants if only stationary power from manufacturing processes is accounted for, see Sec. 1.1) demands for a larger and wider support plan in term of both duration and budget. It is therefore mandatory to resort to a different approach which can tackle the critical gaps of the technology in an organized, holistic way, by leveraging on the vast skills and knowledge held by the scientific community and industry in Europe, as already stated in the *Clean Energy Transition – Technologies and Innovations Report (CETTIR)* [74], attached to the European Green Deal.

In order to better coordinate the efforts of all stakeholders of waste-heat-to-power technologies, the creation of a framework similar, for example, to the European Technology & Innovation Platform on Wind Energy – ETIPWind, namely the **European Technology & Innovation Platform on organic Rankine cycle – ETIPoRc is proposed.** This platform will be responsible for placing in the correct evidence the role that waste heat recovery must have in the clean energy transition and will make sure that policymakers know how the global European leadership in organic Rankine cycle technology can be sustained and augmented in accordance with the objectives of the European Union regarding the goals related to the mitigation of Climate Change and, related to that, its Energy Policies. ETIPoRc will support the implementation of the Sustainable Energy Technology plan and will provide a roadmap regarding the Research and Innovation actions that are needed to accomplish the goals of the plan. The platform will be led by a Board of members belonging to industry, academia and research institutes and will be supported by an Advisory Board with a similar composition. Additionally, not only would ETIPoRc provide the right framework for collaborative R&D initiatives, but it would also make use of a rigorous *metric of success* such that the effect of R&D on the progress of the various technologies can be evaluated, and, if needed, corrective action taken. The evaluation shall be used to decide upon the continuation of the program and also in the years following the completion of the program, an effort should be made to quantify the impact, which will arguably be measurable only after five to ten years from its ending.

ETIPoRc will liaise with the **European Energy Research Alliance (EERA),** a membership-based, non-profit association bringing together 250 universities and public research centres in 30 countries (some even outside the European Union) to yield the largest energy research community in Europe. EERA's joint research programs cover the whole range of low-carbon technologies as well as systemic and cross-cutting topics, with the mission to catalyse European energy research to attain the objectives defined in the EU’s SET-Plan and its clean energy transition strategy. EERA is comprised of 18 Joint Programmes (JP) focusing on a wide variety of themes that range from energy materials over technologies to systemic topics. Each JP is a permanent structure which allows EERA members working on defined topics to collaborate, exchange knowledge and network to apply for funding opportunities. JP’s do not provide funding but, rather, streamline common interests of R&D institutions across and outside Europe to build up economies of scale. Such economies of scale then yield multiple benefits: wider and interdisciplinary sets of skills, exchange of knowledge, more competitive applications for funding schemes such as those of Horizon Europe, cost-effective management of resources, accomplishment of more ambitious objectives. The EERA Joint Programs that are relevant for ETIPoRc are:

- *Energy efficiency and industrial processes*
- *Economic, Environmental and Social Impacts of the Energy Transition (e3s)*
- *Energy systems integration*:
- *Geothermal energy*

However, none of them provides the specific framework for research on organic Rankine cycle technology, therefore an additional JP is proposed regarding both ORC technology topics and applications.

6.3 Concluding remarks

The *Clean Energy Transition – Technologies and Innovations Report* (CETTIR) acknowledges that the industry will play a very important role in the transformation of the EU into a "*modern, resource-efficient and competitive economy with an economic growth decoupled from resource use and aiming at zero net emissions of greenhouse gases by 2050*". This will not be accomplished without a key contribution from waste-heat-to-power technologies, which will become instrumental to the reduction of the consumption of primary energy through a much better utilization of the current energy resources. These renewable technologies not only need support at policy level, but proper R&D support is needed so that they can achieve their full potential and full economic viability.

The fulcrum of the lever for R&D in Europe is the framework program for research and innovation, the last of which has just started under the name of Horizon Europe and will run from 2021 to 2027. Horizon Europe provides funding opportunities for Waste Heat Recovery technologies. However, most of the allocated resources focus on waste-heat-to-heat, some to waste-heat upgrade and just a handful to waste-heat-to-power. This is a shortcoming for it restrains the unleashing of the true potential of thermal energy harvesting.

Two main actions in this respect are proposed:

- **European Technology & Innovation Platform on organic Rankine cycle – ETIPoRc (ETIPoRc)** representing all the stakeholder of ORC technology and having as its mission supporting policy makers and contributing to implementation of the Sustainable Energy Technology plan by providing a roadmap regarding the Research and Innovation actions that are needed to accomplish the goals of the plan, together with a metric to verify the results.
- **Creation of Joint Programs** within EERA that are specific to organic Rankine technology, which is now absent. These JP's will leverage the infrastructure of EERA and will be linked to ETIPoRc (leaders of the specific JP's will likely be members of the ETIPoRc board)

7 Conclusions and Recommendations

The main takeaways of this document, resulting from the close collaboration of several members of the *Knowledge Center on Organic Rankine Cycle technology – KCORC* in consultation with the whole constituency, are:

- The amount of thermal energy that is squandered by industrial processes and stationary or mobile thermal engines is enormous. Such waste contravenes the principles of modern and responsible societies and hampers the mitigation or solution of the global climate problem. A technology to convert a large portion of this energy into electricity exists and is proven, namely organic Rankine cycle power plants. The electricity generated in this way is CO_2-free, distributed and dispatchable. ORC technology is the most flexible and efficient waste-heat-to-power technology as it is suitable for all sorts of waste heat sources, at vastly different temperature and capacity levels.
- Recent literature states that the potential for electricity generation from waste heat from industrial processes is approximately 300 TWh_{el}/yr. With data for 2018, this amounts to almost 10% if compared with approximately 3050 TWh_{el}/yr of electricity generated in EU28 countries. The analysis performed independently by KCORC shows that, if only waste of thermal energy from stationary sources is considered, at least 150 TWh_{el}/yr of electricity could be generated. The estimate is very, perhaps excessively, cautionary. This is equivalent to the annual electricity production of 19 large nuclear plants of 1 GW capacity each, or to the summation of the yearly electricity consumption of the Netherlands and Denmark.
- The CO_2 emitted by propulsive engines (long-haul trucks, off-road vehicles, ships of all kinds, internal combustion engine driven trains, aircraft, etc.) can also be considerably reduced by means of ORC waste heat recovery systems. This technology, albeit more challenging than its stationary power counterpart, has already been demonstrated successfully on board of trucks and ships, for example, and it is actively researched for other applications.
- Waste heat recovery by means of ORC technology can be greatly beneficial to reduce the dependency of EU countries from imported fossil fuels, and can improve penetration of carbon-free and more expensive fuels like hydrogen as it increases the efficiency of any thermodynamic process discarding heat.
- European companies and research and development institutes are already in the lead worldwide. The market is already growing at a sustained pace. However, the share of the ORC market for waste-heat-to-power is very small compared to the potential. If the potential is fulfilled, it would result also in the creation of many qualified jobs every year. The main barriers to the achievement of the envisaged results are identified as: 1) lack of proper, coherent and consistent policy and regulation, and, 2) lack of sufficient R&D support to make ORC power plants more efficient and less expensive. The overcoming of both these hurdles would lead to rapid technology adoption, which would ignite the well-known virtuous cycle of economy of scale and production.
- Policies about the utilization of thermal energy that is otherwise wasted do not correctly account for the possibility of converting such energy into electricity, but only for the direct re-utilization of heat and cold. Moreover, current regulation does not consider waste-heat-to-power as a renewable energy technology, even if it does not consume any finite resource and does not cause additional carbon dioxide emissions. Amendments to the *Renewable Energy Directive* and to the *Energy Efficiency Directive* are proposed such that the important contribution of organic Rankine cycle technology is appropriately taken into consideration. Moreover, a more consistent and uniform approach to the implementation of

these directives in the regulatory framework of Member States is put forward for consideration.

- The importance of research and development about ORC technology for waste-heat-to-power is testified by several calls for proposals in both the Horizon 2020 and the Horizon Europe frameworks, albeit at a level that is deemed grossly insufficient if the potential benefit is correctly accounted for. Two initial actions to solve this issue are proposed:
  - Creation of a *European Technology & Innovation Platform on organic Rankine cycle* (ETIPoRc), representing all the stakeholders of ORC technology, and with the mission of supporting policy makers and of contributing to the implementation of the *Sustainable Energy Technology Plan* by providing a roadmap of the Research and Innovation actions needed to accomplish the goals of the plan, together with metrics to verify the results.
  - Creation of Joint Programs within European Energy Research Alliance (EERA) that are specific to organic Rankine technology, which are now absent. These JP’s will leverage on the infrastructure of EERA and will be linked to ETIPoRc (leaders of the specific JP’s will likely be members of the ETIPoRc board).

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