Thermal Energy Harvesting

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

Version 2.0

KCORC
KNOWLEDGE CENTER
ORGANIC RANKINE CYCLE

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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. Today, KCORC is formed by approximately 400 registered members.

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 the ecosystem 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 without utilization 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 where fossil fuels are replaced by carbon-neutral alternatives, industrial processes and engines will continue to produce significant amounts of thermal energy, as dictated by the laws of thermodynamics. Utilizing this energy efficiently is crucial for preventing resource depletion.

A mature technology suitable for the use of this valuable asset **allows to convert thermal energy into electricity or useful mechanical energy: Organic Rankine Cycle (ORC) power plants. A prudent estimate** leads to the conclusion that **if only a portion of the wasted thermal energy from industrial processes in EU27 countries** were recovered with ORC power plants, this would generate as much as **150 TWh_e/year of electricity**. According to some **conservative calculations performed by KCORC**, the electricity generated may amount to about **5% of the total electricity currently produced** in European Union countries. Notably, such electric power is generated, daily and seasonally, at times of peak industrial activity, thereby reducing corresponding peak loads. Importantly, electricity from otherwise wasted thermal energy is generated within the perimeter of industrial facilities, therefore in most cases no additional grid capacity is required.

An ORC power plant works according to the same principle of steam power stations, but instead of water, the working fluid in the closed loop is an organic substance, like so-called refrigerants, hydrocarbons, and carbon dioxide. The fluid is selected according to the temperature level at which the thermal energy source is available and its amount. 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 thermal energy, 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 ℃to 1000 ℃. The thermal energy that is released at low temperature (40–80 ℃) can be used for cogeneration, that is to heat urban, industrial or agricultural (greenhouses) networks, 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 electric grid. The high-density population is one of the causes of the “not-in-my-backyard syndrome” against large power stations of any kind, while **ORC power plants can be easily integrated in existing industrial sites**, distributed, or embedded aboard means of transportation.

Europe is in a leadership position when it comes to ORC technology, as the majority of all 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 at least **45,000 to 50,000 new qualified jobs over a period of 10 years**. The necessary workforce is already available, as the required skill set closely aligns with that of workers in power plant manufacturing. 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 propulsive engines, those of 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, nonmetallic 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 currently 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 **propulsive thermal 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-neutral fuels like hydrogen. These fuels will likely be much more expensive, and this will also push for the adoption of waste heat recovery technology 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 waste-heat-to-power technologies has been summarized, pitfalls and barriers analyzed, and **a number of changes and improvements to related policy and regulations proposed, such that the role and value of waste-heat-to-power are properly recognized,**

and hopefully rational regulation is implemented in Member States in a consistent and effective way.

Furthermore, the European scenario of support to ORC 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 technology – ETIPoRc** is proposed.

In conclusion, this position document about ORC technology is to be intended as a dynamic repository (this is its second version, the first was publish in 2022) of convincing information and ideas brought forward by an enthusiastic and vibrant 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 Union and society at large.

Power generation from industrial waste heat in Europe could result in **150 TWh** of electricity per year

Equivalent to:

19 1 GW_e nuclear plants

electricity consumption of **20 million** homes

annual electricity consumption of **Netherlands** and **Denmark**

Background image courtesy of Exergy International.

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 process is called *cogeneration*.

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

- **chemical energy**, the energy of fossil fuels and carbon-neutral fuels like hydrogen or biofuels. It can be converted into thermal energy and subsequently into electricity or mechanical energy;
- **solar radiation energy** that can be converted into electricity using photovoltaic panels or into thermal energy for heating. This thermal energy can also be converted into electrical energy;
- **thermal energy in geothermal reservoirs** that Can be converted into mechanical energy or electricity;
- **thermal energy from combustion or by-products**, which Originates from fossil fuel combustion or as a by-product of other processes, and it can be converted into mechanical or electrical energy;
- **mechanical energy**, which useful for propulsion, or to drive machines or electric generators. It can also result from the conversion of chemical energy or renewable energy sources like wind.
- **electrical energy** that can be used directly for purposes such as lighting, computing, heating, propulsion, or driving machines.

All processes converting energy into a useful form result in some additional thermal energy at moderate or low temperature, which is often discarded without further use. The use of thermal energy currently released into the atmosphere provides a remarkable opportunity to generate large amounts of CO_2-free electricity in Europe and worldwide. This document is concerned with organic Rankine cycle (ORC) power plants, a prominent technology to realize this objective.

1.1 Manufacturing Processes

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

- (petro) chemical processes,
- material production processes (e.g., production of metals, 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 in gas turbines.

Thermal energy generated as a by-product of many processes should be utilized rather than discarded into the environment. Various options for its use include:

- **heating**;
- **heat upgrading**, that is, increasing the temperature of the thermal energy input using a heat pump;
- **refrigeration**, which can be achieved with an adsorption or absorption system;
- **conversion into electricity** using technologies such as thermoelectric devices, Stirling engines, steam power plants or Organic Rankine Cycle power systems.

Electricity is the primary and often preferred form of energy because it is easily transportable and directly usable for a wide range of applications. Conversely, discharged thermal energy is difficult and costly to transport and can only be utilized if it meets local demand in terms of temperature and timing.

In a recent study it was estimated that the industrial sector in EU28 countries discharged approximately 980 TWh/yr of thermal energy in 2015 [1]. From other literature it can be deduced that the potential for electricity generation from this energy ranges between 280 TWh_e/yr [1] and 300 TWh_e/yr [2]. This corresponds to nearly 10% of the 3050 TWh_e/yr of electricity generated in EU28 countries during the same year [3].

Usable thermal energy can be categorized based on the temperature at which it is available. **Members of KCORC conducted independent and conservative calculations to estimate the potential for electricity generation from currently discarded thermal energy.**[1] Thermal energy discharged at low temperature (< 100 ℃) 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_e/yr. The potential for electricity generation is 9.5 TWh_e/yr at moderate temperature (100 – 200℃), 61.7 TWh_e/yr at intermediate temperature (200 – 500℃), and 47.2 TWh_e/yr at high temperature (> 500℃). Therefore, the estimation of the total amount of electricity that can be generated adds up to approximately 150 TWh_e/yr. Taking into account the potential for electricity generation reported in recent literature, 280 TWh_e/yr in Ref. [1] and 300 TWh_e/yr in Ref. [2], it is hence reasonable to conservatively assume that at least 150 TWh_e/yr of electricity could be generated by harvesting currently untapped thermal energy; therefore, this figure is used in the following.

150 TWh_e/yr of electricity is the yearly electricity consumption of more than 40 million households [5], or the annual electricity production of 19 nuclear power plants of 1 GW_e capacity each, or the combined annual consumption of electricity of the Netherlands and Denmark. It can be generated without emissions of additional CO_2 or any other harmful substance; consequently, it should be treated as renewable electricity. In terms of CO_2 emissions, 150 TWh_e/yr generated from unused thermal energy allow avoiding the emission of 123 Mton/yr of CO_2 if the electricity were generated by burning coal, of 75 Mton/yr of CO_2 if it were generated by burning natural gas, and of around 45 Mton/yr of CO_2 if the emissions were calculated by considering the average emission factor of the electricity grid in the EU28 in 2017 (294 g/kWh_e, including electricity generated from renewable energy sources [6]). In addition, a reduction of nitrogen oxides (NO_x) emission can be accounted for at a rate of approximately 107 kton/yr, whereby the emission factor (0.71 g/kWh_e) is derived from various international sources.

As this untapped thermal energy is most often continuously available because of the nature of its sources, such 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.

1.2 Natural Gas Infrastructure

Organic Rankine cycle power plants can also be used for thermal energy harvesting from the natural gas infrastructure. A very large amount of thermal energy could be recovered from exhaust gases released by gas turbines installed in gas pipeline recompression stations, where they are used to 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 elevation, 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_e range), thus a very large amount of thermal energy at relatively high temperature (400 – 600 ℃) is available for conversion into mechanical or electrical power and ORC

[1] These calculations are based on 2018 Eurostat statistics, following Regulation (EC) No. 1099/2008 for EU27 countries. The estimates assume the use of conversion technologies described in Ref. [4] and a cold sink temperature of 17 ℃, as well as a lower temperature limit of exhaust gas streams of 120 ℃. Such temperature limit is due to the so-called dew-point constraint to avoid duct acidic corrosion.

power plants are the most suitable technology for this purpose [7].

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_e [8]. Several years ago, Baker Hughes commissioned in Canada an ORegen™ waste heat recovery system (15 MW_e) featuring a two-stage integrally geared turbine [9]. In Spain, Enagás has operated since 2009 a natural gas compression station comprised of five Solar Centaur 50 gas turbines and a 5.1 MW_e bottoming ORC waste heat recovery plant [10]. A more recent example is the largest high-temperature waste heat recovery ORC power plant supplied by Turboden to recover thermal energy from four existing gas turbine trains and from a new high efficiency gas turbine supplied by Siemens Energy and powering the GASCO Dahshour (Egypt) compression station [11], [12]. This 28 MW_e ORC power plant is coupled with electrically driven compressors, also supplied by Siemens Energy, and will generate 192 GWh_e/yr of fuel-free electricity powering two 10 MW_e compressors, and will save 65 million m^3 of natural gas per year, thus avoiding the annual emission of 120 kton of CO_2. At the time of publication of this document, this innovative combined cycle power plant is in the commissioning phase.

Liquefied natural gas (LNG) plants are another large source of thermal energy currently unutilized. At the production site, natural gas is compressed and then cooled down and liquefied at cryogenic temperature. Power for natural gas compressors is provided by aeroderivative gas turbines. Depending on the site, the amount of thermal energy that can be recovered is in the range of 45 – 70 MW_{th} at temperatures of 400 – 600 ℃ [13]. After transportation in cryogenic conditions (ambient pressure and – 160 ℃), LNG is vaporized at regasification terminals by means of different technologies involving the use of electric power and/or fuel combustion, thus offering additional possibilities for the installation of ORC power plants.

One of the most promising options to increase the energy efficiency of regasification plants, thus reducing the associated emissions of CO_2, is the integration of an unconventional ORC power plant operating with seawater as thermal energy source and the vaporizing LNG as thermal energy sink. Studies on this type of ORC power plants have been carried out since 1980 and several pilot plants have been commissioned in Japan [14], [15]. More recently, researchers have investigated various configurations to further increase the efficiency of the process [16], [17]. Ormat applied for a related patent [18] and installed the first ORC power plant based on this patented configuration at the Huelva regasification site in Spain [19].

The potential for thermal energy harvesting from regasification stations can be estimated considering that the global annual production of LNG was around 1030 Mton/yr in 2024 [20] and that a reference ORC power plant for waste heat recovery from an LNG terminal plant could generate approximately 22 kWh_e/yr per ton of vaporized natural gas [21]. Considering that the worldwide annual trade of LNG is equal to approximately 1000 Mton [20], this would result in the production of approximately 22.5 TWh_e/yr, corresponding to CO_2 emission savings of around 5.64 Mton/yr.

Also gas-to-liquid plants waste large amounts of medium-grade thermal energy that could be converted into electricity or mechanical energy. For example, the gas-to-liquid plants operated by Shell in Qatar and Malaysia discharge to the environment amounts of thermal energy ranging from 5 to 600 MW_{th} at temperatures between 130 and 185 ℃ [13].

1.3 Propulsive Engines

Propulsive engines of all sorts and used for a wide variety of purposes discharge to the atmosphere an enormous amount of thermal energy currently untapped. Internal combustion engines, independently from the fuel, release about two thirds of the chemical energy of the fuel to the environment. For example, the energy of the exhaust gas of truck engines amounts to approximately one third of the energy input and is at approximately 330 ℃, while the water and oil cooling systems discharge to the environment the remaining one third of the input energy at temperatures slightly lower than 100 ℃. Gas turbines, depending on their size and application, release 50% to 70% of the chemical energy of the fuel to the environment, in the form of a hot exhaust gas stream at temperatures between approximately 400 and 600 ℃.

The recovery of thermal power for the generation of additional mechanical or electrical power by means of ORC systems has been already demonstrated on board long-haul trucks [22]–[25] (see, e.g., Figure 1.1), ships [26]–[30], and trains [31], while it is being studied as one of the options for next-generation aircraft engines [32]–[37].

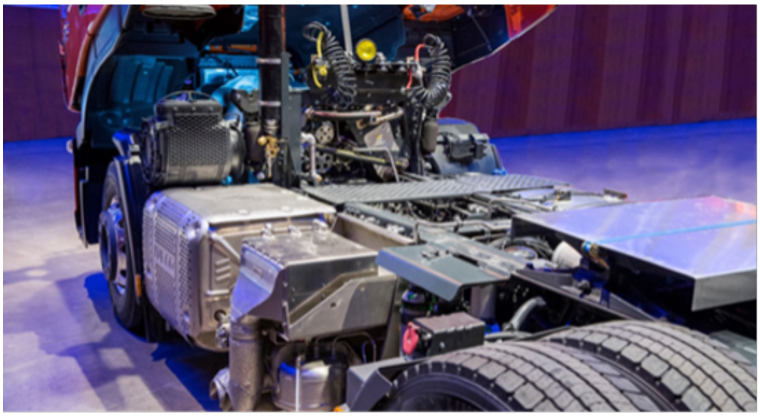


Figure 1.1: The prototype of a waste heat recovery ORC-system on board of a long-haul truck. Courtesy of AVL GmbH.

Trucks are powered by diesel engines and it is possible that soon natural gas and even hydrogen become widespread fuels for truck engines [38]. Ships can be powered by i) diesel engines (either large, low-speed 2-stroke engines, or smaller medium-speed or high-speed 4-stroke engines), ii) gas turbines or, iii) many possible hybrid combination of engines. Alternative fuels – i.e., liquefied natural gas (LNG), liquefied petroleum gas (LPG), ammonia (NH_3) and H_2 – have already been tested in various marine engines for ship propulsion. In addition, many modern marine diesel engines, especially those of the main propulsion system of large and fast ships (e.g., container ships, LNG/LPG tankers, etc.), can operate in dual-fuel mode, that is by combining conventional heavy fuel oil (HFO) with natural gas. Trains can also be powered by diesel engines in case the line is not electrified and, similarly to trucks, could benefit from a propulsion system featuring waste heat recovery by means of an ORC unit.

The potential to reduce CO_2 and other emissions, as well as to enhance efficiency, by converting a portion of the thermal energy wasted by all types of thermodynamic engines into additional power, is enormous. As an example, in 2019, more than 270,000 heavy-duty commercial vehicles over 16 ton were registered in Europe (EU25, excluding Cyprus and Malta) while the same figure rises up to over 370,000 if commercial vehicles, coaches and heavy buses above 3.5 ton are also considered [39]. In 2018, there were around 6 million trucks on the roads of the European Union (excluding United Kingdom); with more than 1.1 million trucks, Poland has the largest truck fleet, followed by Germany (946,541) and Italy (904,308) [40]. Almost all the heavy-duty vehicles in the European Union (98.3%) are powered by diesel engines [40], and they were responsible for 27% of the CO_2 emissions of the transport sector and almost 5% of the total greenhouse gas emissions in the EU in 2016 [41]; these CO_2 emissions amount to approximately 200 Mton/yr [42]. The recent Green House Gas emission study of the International Maritime Organization (IMO GHG) indicates that worldwide emissions of CO_2 due to international shipping totaled 796 Mton in 2014 [43].

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, and similar regulation for ships is currently under discussion [44]. Thermal energy recovery is technologically easier to implement in large engines, such as those used to propel trains and ships, and is further simplified if cooling water is readily available, as is the case with ships.

1.4 Hydrogen Combustion and Electrochemical Reactions

In order for the current *Green Deal* policy of the European Union [45] to succeed, a wide range of combustion processes critical to numerous industrial sectors–including steel and metal production, cement and glass manufacturing, chemical processes, refining, food processing, pulp and paper production and construction–must transition from relying on natural gas and other fossil fuels to hydrogen or other decarbonized energy carriers [46]–[49]. Even with the electrification of many industrial heating processes, a large amount of thermal energy will still be generated by processes that continue to rely on combustion, albeit by burning carbon-free fuels.

Solar and wind energy are intermittent and fluctuating energy sources,[2] therefore it is to be expected that wind and solar farms will be complemented by thermal power stations fueled by hydrogen and powered by gas turbines or fuel cells.[3]

Hydrogen is likely to be a relatively expensive fuel, given the costs involved in the processes to produce it [50]. The cost of hydrogen production is projected to range between 1

[2]Solar thermal energy can be stored, enabling the production of dispatchable electricity. However, the capacity of solar power plants that generate electricity by converting thermal energy from concentrated solar radiation remains and will likely remain marginal compared to photovoltaic (PV) power plants. Conversely, electricity storage for PV power plants is challenging.

[3]Fuel cells for stationary electricity generation operate at intermediate to high temperature, thereby discharging the gaseous products of the electrochemical reaction at a temperature of approximately 80 – 200 ℃ (LT/HT-PEMFC), 500 – 600 ℃ (MCFC) and > 900℃ (SOFC).

and 2 USD/kg by 2050 [51], provided several technological challenges are successfully addressed. For comparison, the average price of natural gas was approximately 0.3 USD/kg during the period from October 2020 to May 2021 [52]. From an economic perspective alone, it is logical to recover the inevitable thermal energy contained in the exhaust of any hydrogen-based reaction (combustion or other thermochemical processes) to enhance efficiency and cost-effectiveness, thereby reducing overall costs. Timely incentives and regulations promoting thermal energy recovery technologies are likely to yield benefits both during the transition to carbon-free fuels and in the long term.

Advantages of waste heat to power using ORC

- no additional emission
- not weather dependent
- dispatchable
- less reliance on imported fuels
- electricity is easy to distribute
- suitable for a wide range of temperatures and powers

2 Organic Rankine Cycle Technology and its Advantages

Untapped thermal energy can be converted into electricity or mechanical energy using a well-established principle, the same one underlying the operation of steam power plants, namely the Rankine thermodynamic cycle. 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 whose capacity ranges 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 thermal energy sources.

The working fluid of ORC power plants consists organic molecules, which are molecules that contain at least one carbon atom. Examples include hydrocarbons, refrigerants, siloxanes, and carbon dioxide. Working fluids are commonly pure but also mixtures can be used. With reference to Figure 2.1, the pressure of a liquid fluid is increased in a pump, the fluid is then evaporated using the energy of an external thermal energy source, the vapor is expanded in a turbine possibly connected to an electrical generator, and liquefied 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 most suitable working fluid for large-capacity and high temperature thermal energy sources, other fluids make it possible to realize power plants with capacity from few kW to hundreds of MW (multiple turbines) and to efficiently and cost-effectively convert energy from sources at temperatures as low as 100 ℃ [53].

An ORC power unit is arguably the most economically viable and efficient technology for the conversion of otherwise wasted thermal energy into electrical or mechanical energy whenever [53]

- the thermal energy source is in the temperature range 100 – 600 ℃, 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 [54], [55].

Moreover, it is possible to operate ORC plants if:

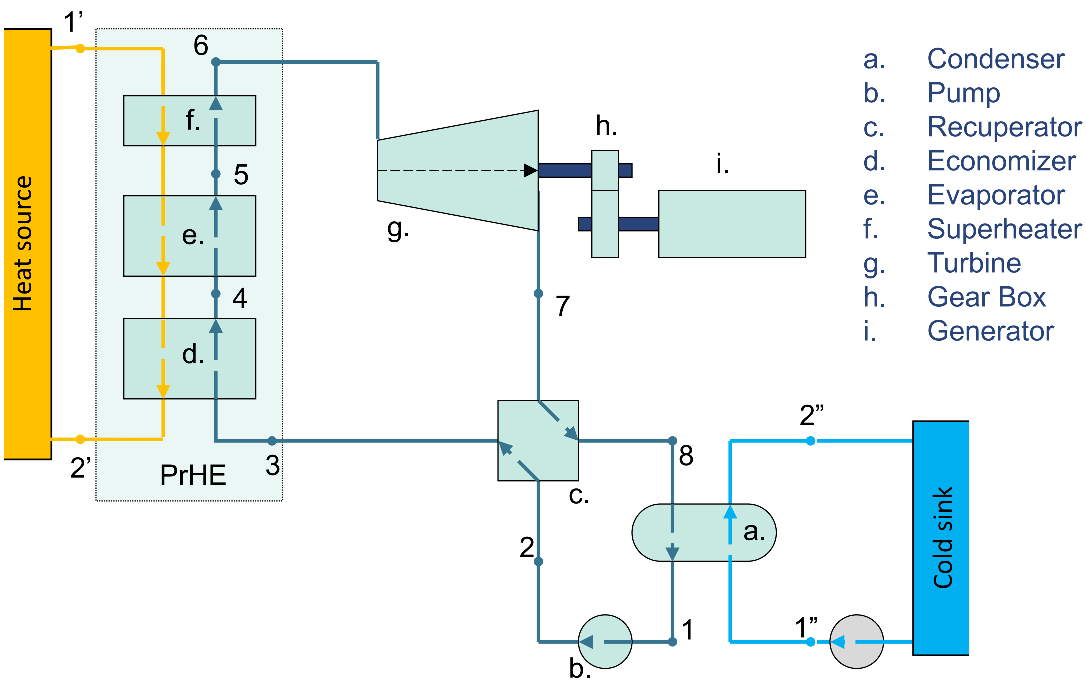


Figure 2.1: Simplified process flow diagram of an ORC power plant.

- 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 2.1, 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 designed based on specific requirements 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.

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 and their advantages are mainly the absence of moving parts and compactness.

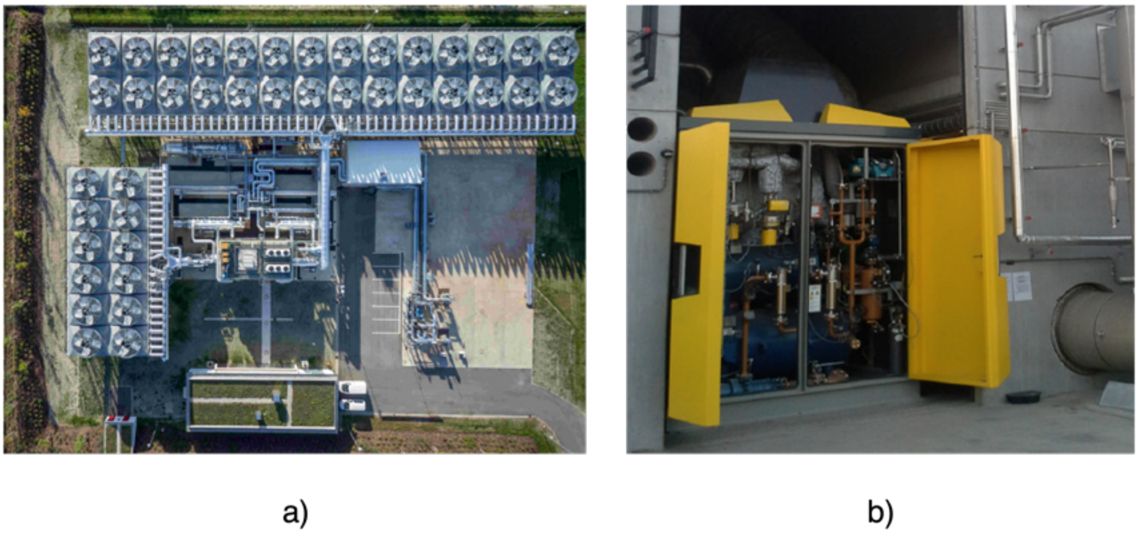


Figure 2.2: a) aerial view of a 6 MW_e ORC power plant (Courtesy of Turboden); b) the power block of a 150 kW_e ORC unit (Courtesy of Triogen).

However, they work only with high temperature differences, are suitable only for small-capacity power conversion, are rather inefficient if compared to thermodynamic engines, and they are rather expensive [56], [57].

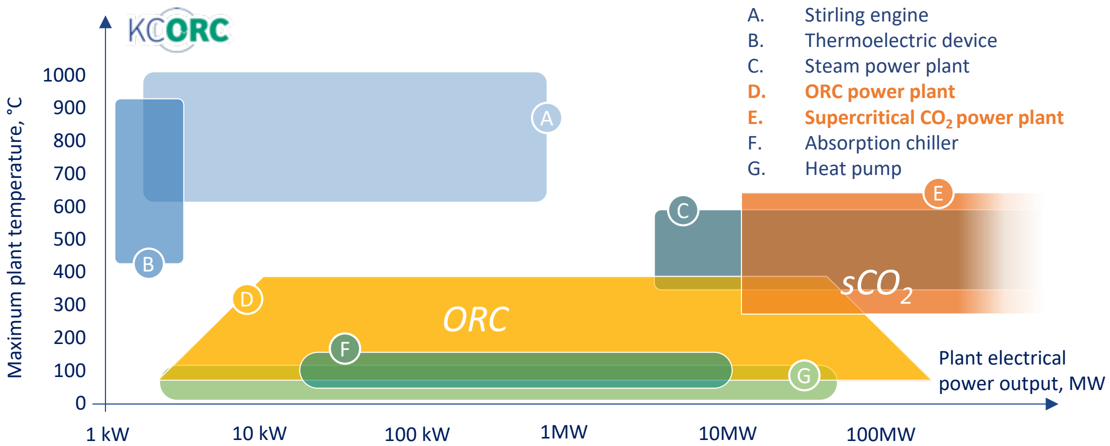


Figure 2.3: Range of applicability of various technologies for thermal energy harvesting.

The so-called inverse Rankine cycle or vapor compression 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 of 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 is a local demand for thermal energy at higher temperature [58]–[60].

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 units of cooling energy 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 [61], [62].

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 expander, but it is based on the alternating motion of one or more pistons, similarly to 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 for many applications, reliability is often an issue, given the relatively large number of moving parts, the complex kinematics, and the working fluid leakage issues [63], [64]. 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 2.3. The diagram outlines the large range of applicability of ORC technology, which arguably includes sCO_2 power plant technology, which is based on the same working principle and utilizes carbon dioxide as working fluid, thus also an organic compound.

Europe is a leader in ORC technology, in terms of both the manufacture & installation of ORC technology and in R&D activities

Doubling the annual growth rate from 7.5% to 15% could create **45,000 new jobs** over the next 10 years

Background image courtesy of Exergy International.

3 European Leadership

Since the end of the 18th century, Europe has been the epicenter of the development of thermodynamics 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 of ORC power plants hold a strong position in the market, making it essential to further advance technological and commercial leadership within Europe.

3.1 Stationary Power Plants

The largest number of ORC power plant suppliers and industrial innovators in this field are located in Europe. Againity (Sweden), Atlas Copco (Sweden), Climeon (Sweden), Dürr Cyplan (Germany), Enogia (France), Exergy (Italy), GMK (Germany), Nuovo Pignone (Part of the Baker Hughes company, Italy), Orcan (Germany), Ormat (USA, but part of the manufacturing occurs in Europe), Rank (Spain), Siemens Energy (Germany), Star Energy (Italy), Triogen (Netherlands) Turboden (part of the Mitsubishi Heavy Industries group, Italy) and Zuccato (Italy) are almost the totality of the established worldwide suppliers, and their ORC power plant products are 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 to move the technological frontier forward for the benefit of the transition to a CO_2-free society.

ORC power plant (courtesy of Atlas Copco).

European companies offer ORC units with a rated power output as small as 20 kW_e and as large as 20 MW_e for the conversion into electricity of renewable or renewable-equivalent energy sources as diverse as geothermal reservoirs, biomass combustion, and already industrial waste heat, including the exhaust of gas turbines and stationary 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 charts of Figure 3.1 allow to appreciate the comparably large success of ORC technology. It can also be inferred that the potential of using ORC power plants to recover otherwise wasted thermal energy is not exploited yet, given that the trends related to the waste heat recovery application are positive and that of number of installed power plants steeply increases, starting from recent years.

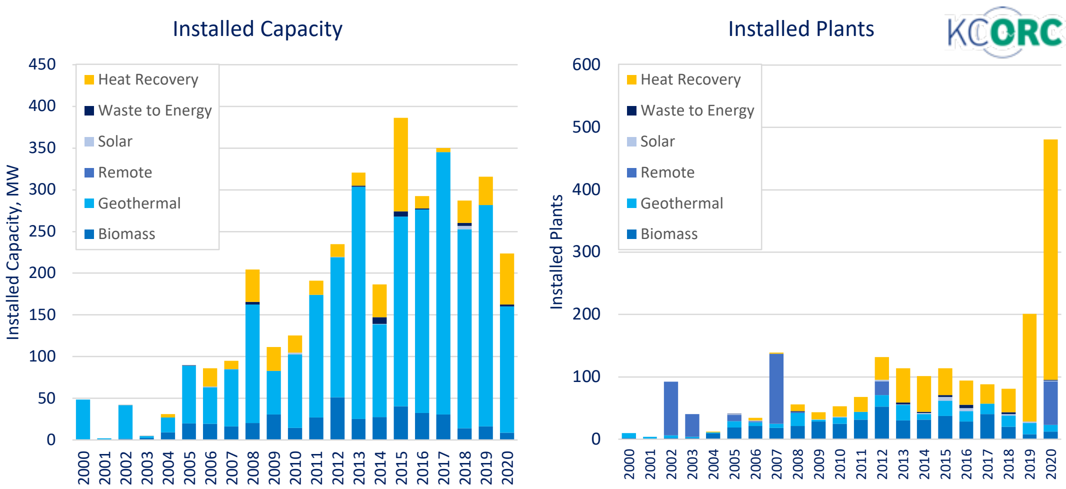


Figure 3.1: Total electric capacity (left) and number (right) of ORC power plants installed annually since 2000. The thermal energy source (e.g., biomass combustion, geothermal reservoir, waste thermal energy, solar radiation) is also indicated [65].

The demand for highly specialized and agile teams of engineers and professionals, combined with Europe's long tradition of technological development and access to proprietary technology, makes European companies highly competitive in the global market.

ORC test facilities at Technical University of Munich (left) and Delft University of Technology (right)

3.2 Waste Heat Recovery Systems for Long-Haul Truck Engines

While Rankine-cycle-based heat recovery systems are well-established in the power generation and industrial sectors, applying the ORC concept to mobile engines has only recently reached the demonstration stage, primarily due to its greater technological challenges. 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 project at that time was that run by Mack Trucks and the Thermo Electron Corporation (TECO) [66]. The project objective was to equip a truck with a 676 Mack diesel engine enhanced with a small ORC system generating 10 kW_e of power. The concept consisted into recovering exhaust gases by means of a high temperature regenerative Rankine cycle system, using a high-speed turbine as expander. The research program was divided in three 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 technology development were made during the following decades and notable projects are partly documented in Refs. [67], [68], but most of the related information was not made public.

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 reduce 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 [69]–[71]. 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 [72], Mercedes Trucks [73], and CNH Industrial [74]. The *NoWaste* European project, part of the FP7 research program, is an example of public support [75]. The development efforts of European truck manufacturers have been significantly supported by their supply base, particularly in terms of component development.

Figure 3.2 lists 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 suppliers and main locations. 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. The future of this technology is uncertain due to the availability of alternative approaches for improving fuel efficiency and reducing emissions. Currently, most of the development effort are dedicated to battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). However, waste heat recovery could be highly beneficial if high-efficiency / high temperature fuel cells and/or if hydrogen-fueled internal combustion engines are adopted to power trucks. Waste heat recovery would be beneficial also in case LNG- or LPG-fueled internal combustion engines will become transition technologies towards the envisaged use of zero-carbon fuels. 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.

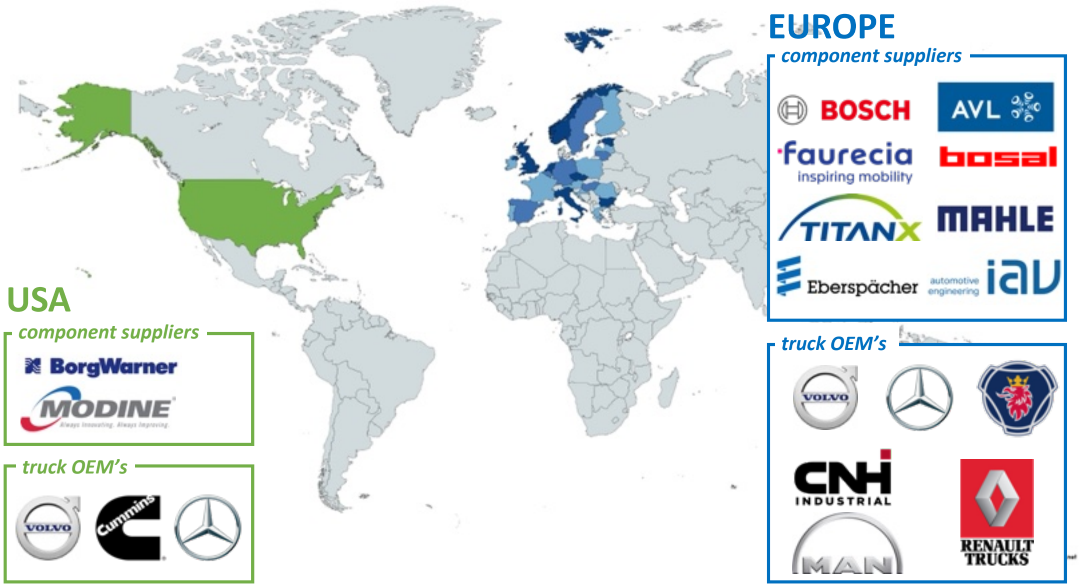


Figure 3.2: Companies that have been developing mini-ORC technology for waste heat recovery from long-haul truck engines and their location in the world.

3.3 Indexing of the European Technological Leadership

Scientific and industrial leadership is often assessed through the indexing of scientific publications and patents, respectively. Figure 3.3 shows the number of publications retrieved with Scopus using the search string *Organic AND Rankine AND Cycle AND Power* and published between 2000 and 2022. Europe leads the ranking ahead of China, with almost 50% more scientific documents. The United States lags behind, with one fourth of the scientific literature production.

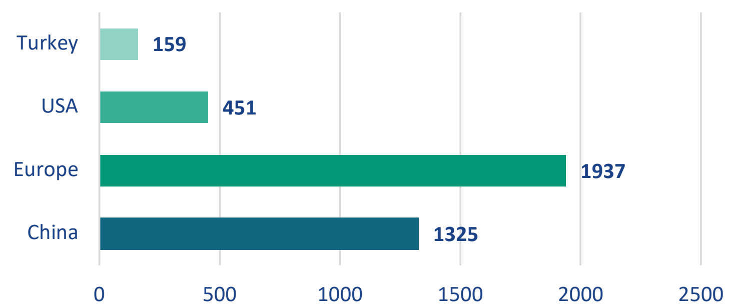


Figure 3.3: Number of scientific publications issued between 2000 and 2022 retrieved with Scopus (www.scopus.com) using the search string 'Organic AND Rankine AND Cycle AND Power' in the period 2000-2022.

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 industrial products, thus benefiting society. This can be ascertained to a large extent from the charts of Figure 3.4, presenting the number of patents granted in different areas of the world [76]. 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*[1] patents are concerned. This confirms that EU development programs effectively contribute to the leadership of European ORC OEMS's.

Global leadership in the development of Organic Rankine Cycle (ORC) technology is a valuable asset from points of view. First, it positions Europe as a hub for generating the knowledge crucial to achieving carbon neutrality by 2050. Second, it equips European industry with the expertise, skills, and infrastructure needed to meet the ambitious objectives of the European Green Deal in a cost-effective manner. Third, it creates extensive opportunities for high-end, high-value jobs in STEM fields. Finally, it strengthens efforts to ensure the sustainability, reliability, and security of the European energy market.

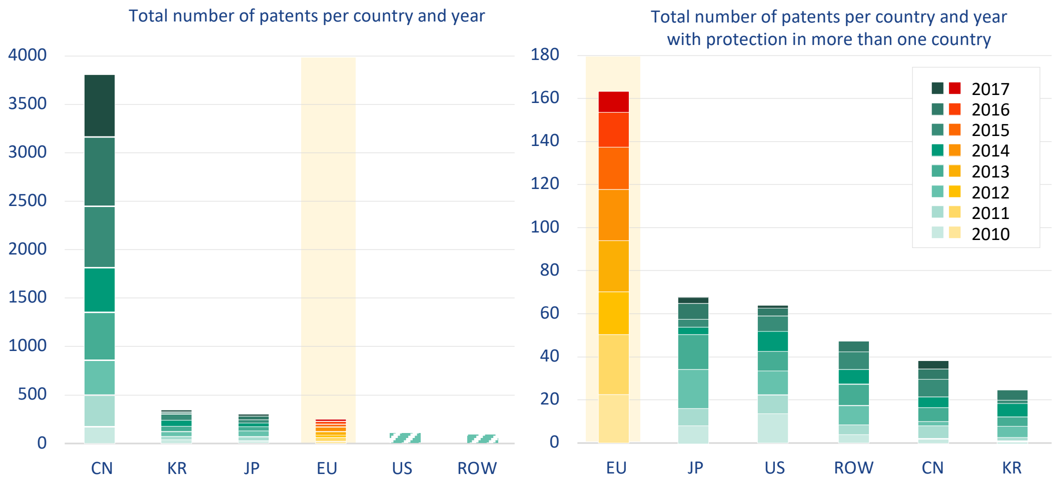


Figure 3.4: (left) Total number of patents per country and year related to industrial waste heat recovery technologies. (right) Total number of patents per country and year, with protection in more than one country, related to industrial waste heat recovery technologies [76].

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

Key application areas and technology potential

- industrial waste heat recovery
- natural gas supply networks
- waste heat recovery form long-haul trucks
- waste heat recovery from inland and coastal vessel engines

Background image courtesy of Exergy International.

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 4.1, which shows the temperature level at which the energy is released to the atmosphere and the fraction of the total wasted thermal energy pertaining to each industrial sector. In general, the higher the temperature of the energy source and the greater the amount of available energy, the more economically attractive it becomes to convert otherwise wasted thermal energy into electricity using ORC technology. It can therefore be argued that the industrial sectors providing the most economically advantageous opportunity for the immediate installation of ORC power plants are:

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

Figure 4.1 shows the distribution of industrial sites over EU27 countries plus the UK with significant potential for thermal energy harvesting. It is therefore self-evident that

Table 4.1: Wasted thermal energy per industrial sector and per temperature range at which it is available. Wasted thermal energy per industrial sector is reported as as percentage of the total wasted thermal energy (listed in the rightmost column if reported in the literature). The shade of blue of cells indicates the fraction of the total wasted thermal energy available at the given temperature range: light < 20%, medium < 50%, dark > 50%. Data are taken from Refs. [2], [77]. The light gray cells indicate additional potential resulting from technologies involved in the conversion process as described in Ref. [4].

	Temperature range of waste heat [°C]								
	<100	100–200	200–300	300–400	400–500	500–600	600–1000	>1000	TWh/y
Iron and Steel									73.0
Non-metallic minerals									91.2
Clinker									N/A
Glass									N/A
Non-ferrous metals (Primary aluminum)									32.3
Chemical and petrochemical									141.7
Pulp, paper and printing									125.5
Others									263.0
Refinery									N/A
Food and beverages									115.2
Gas and diesel engines									2013.5

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.

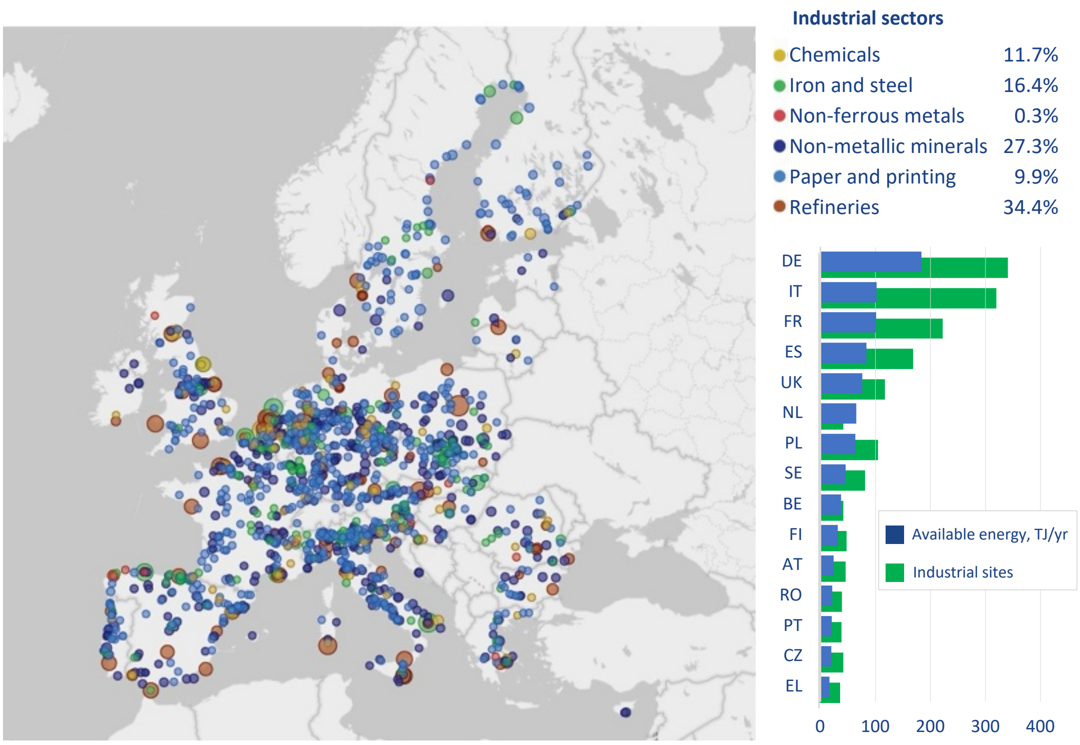


Figure 4.1: Map of industrial sites with significant waste heat recovery potential in Europe. Data are taken from Ref. [78].

According to the analysis in Ref. [78], these energy-intensive industries utilize thermal energy 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 electricity conversion). The article reports that a total of 1175 sites feature a waste heat potential of more than 50 MW_{th}, and these sites cause the emission of approximately 713 Mton/year of CO_2.

Unfortunately, an established approach for accurately assessing the potential for thermal energy harvesting in European countries is not available and the evaluation reported here 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 about these data is therefore strongly proposed, also because it would support the appropriate policy and regulatory actions.**

Arguably, the most reliable information about the potential for thermal energy harvesting by means of ORC power plants is reported in Ref. [77]. 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 study has been limited to seven European countries for which sufficiently reliable data were available. The starting points for the analysis

Table 4.2: Estimated potential for installation of ORC power plants in terms of total power capacity per selected country and per industrial sector. All values are in MW_e. Adapted from Ref. [77].

Country	Clinker	Container glass	Flat glass	Paper	Primary steel	Secondary 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**
The Netherlands	13	0	0	11	20.6	0	666.8	193.5	19.8	**925**
United Kingdom	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**

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 also considered. In order to obtain a realistic estimate, economic viability has also been assessed by taking into account specific electricity prices, regulations, and ORC power plant installation costs. For these reasons, only thermal energy sources at temperature higher than 250 °C have been considered. Table 4.2 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. It is remarkable that, just for these seven EU countries and with this conservative approach, power plants for a total power capacity of 6.6 GW_e could be installed. Such power capacity is approximately equivalent to that of three large nuclear power stations. Ref. [77] reports also a similar analysis for extra-European countries and the results demonstrate that the worldwide potential for waste-heat-to-power is enormous. Given the European leadership regarding ORC technology, it is clear that large economic benefit would arise not only directly from the exploitation of the large potential provided by the enormous amount of thermal energy that is wasted in Europe, but also from the opportunity of exporting European ORC technology worldwide.

450 kW_e ORC power plant (courtesy of Againity).

Another assessment of the potential for the utilization of wasted industrial heat is reported in Ref. [79]. It is estimated that the total thermal energy at various temperature levels that is available every year in European countries is more than 850 TWh/year (see Table 4.1. More than half of this energy is rejected to the environment from sites located in Germany, France, Italy, Spain and the United Kingdom, as showcased in Figure 4.2.

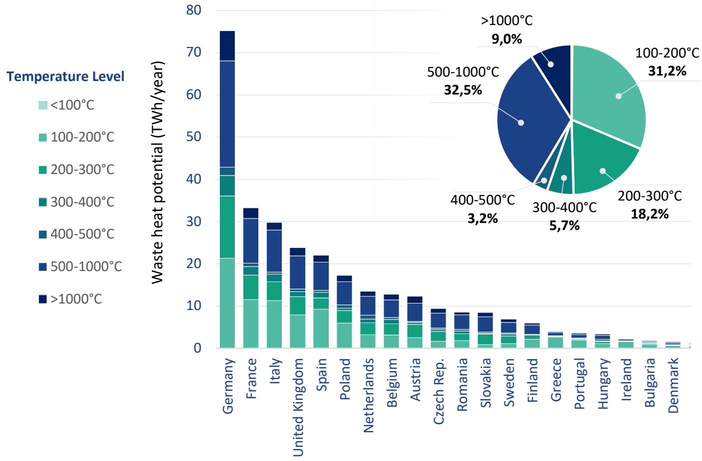


Figure 4.2: Distribution of waste heat recovery potential across Europe, reporting also temperature levels of available, unused thermal energy. Data taken from Ref. [78]

By year 2016, more than 40 waste-heat-to-power ORC power plants were installed in Europe, recovering thermal energy from cement, glass, iron or steel manufacturing processes for an overall installed capacity of 26 MW_e [80]. It is therefore evident that the opportunity for such installations has not been fully realized, and the potential offered by industrial sectors such as pulp and paper, non-ferrous metals, oil and gas, and food and beverages remains largely untapped.

In addition, Ref. [80] documents the evaluation of the waste heat recovery opportunity provided by the kraft pulp and paper sector in Sweden. Analysis of 2017 data shows that the sector utilized 50% of the total amount of energy consumed by the industry in Sweden, namely 72.4 TWh. The study analyzed in more detail kraft mills, which produce more than 60% of the total paper pulp and considered the installation of small- and medium-capacity ORC systems, concluding that 8 to 11% of the unused thermal energy could be converted into electricity, in spite of the low temperature at which it is available.

Ref. [81] documents that the largest share of the potential for waste heat recovery in Europe originates from the production of minerals and metals, which accounted for 24.7% and 45.8% of the total available waste heat in 2018. More specifically, furnaces discharge to the environment more than 50% of the total waste heat emitted by the metal industry, followed by coking and rolling, whose share is 10 to 15%.

Members of KCORC conducted an independent study on the potential of harvesting thermal energy from industrial processes in Europe in an attempt to provide more complete and consistent information. Table 4.3 shows the temperature-specific potential for waste heat recovery from industry by means of ORC power plants in Europe. Three different figures of merit are reported for each temperature level and these are defined as follows.

- *Theoretical potential*: total amount of thermal energy discharged to the atmosphere. It is termed *theoretical* because it cannot be utilized in its totality.
- *Technical potential*: amount of unused thermal energy that could be converted into

electricity.

- *Installable capacity*: cumulative rated power output of the ORC systems that could be installed. The amount of thermal energy powering these system is the *technical potential*.

Table 4.3: Temperature-specific potential for waste heat recovery from industry by means of ORC power plants in Europe. Theoretical potential (total unused thermal energy that is currently wasted); technical potential (electricity which could be obtained by efficiently converting the theoretical potential); installable capacity (total power capacity of the ORC systems that could be installed).

Temperature level [°C]	Theoretical Potential [TWh_{th}/yr]	Technical Potential[1] [TWh_e/yr]	Installable Capacity[2] [GW_e]
< 100	390.4	32.2	4.0
100 – 200	60.5	2.8	0.3
200 – 500	334.7	68.5	8.6
> 500	97.2	47.2	
Total	**882**	**150**	**18.8**

[1] The technical potential is estimated based on educated simplifying assumptions.
[2] The installable capacity is calculated by assuming 8000 operating hours per year.

As outlined in Section 1.2, in addition to the opportunity for waste heat recovery provided by energy intensive industries, large amounts of thermal energy are emitted to the environment from the natural gas supply infrastructure. Table 4.4 reports the estimation of the technical potential and of the installable capacity with reference to LNG and GTL liquefaction plants, and to regasification units / LNG terminals. It is remarkable that the estimated total installable capacity is as large as 18.4 TWh_e.

Table 4.4: Temperature-specific potential for waste heat recovery from the natural gas infrastructure by means of ORC power plants in Europe. Theoretical potential (total unused thermal energy that is currently wasted); technical potential (electricity which could be obtained by efficiently converting the theoretical potential); installable capacity (total power capacity of the ORC systems that could be installed). Data for the computation of these values are taken from recent publications reporting the worldwide production capacity [82] and plant-specific assessments [83].

Application	Technical Potential[1] [TWh_e/yr]	Installable Capacity[2] [GW_e]
LNG and GTL liquefaction plants	10.6	1.5
Regasification units / LNG terminals	7.8	2.1
Total	**18.4**	**3.6**

[1] The technical potential is estimated based on educated simplifying assumptions.
[2] The installable capacity is calculated by assuming 8000 operating hours per year.

Large-scale ORC power plant (courtesy of Turboden).

Finally, another source of industrial waste heat that could be converted into electricity by means of ORC power plants originates from air compression stations. In 2014, 31 million air compressors were installed in EU countries [84]. Compressor inter- and after-cooling systems discharge to the atmosphere a substantial amount of thermal energy. However, only one university project aimed at demonstrating the efficient conversion of this waste heat with an ORC unit has been identified to date [85].

Based on the information presented, it can be concluded that the widespread adoption of waste heat recovery technology would significantly enhance the efficiency of many industrial sectors. Improved process efficiency, in turn, is a critical factor for maintaining competitiveness in the anticipated global CO_2-emission-restricted scenario. This is of utmost importance not only in the current quest for decarbonization of industrial sector that are still relying on the combustion of fossil fuels for heating purposes, but also in a future scenario in which hydrogen or other environmentally friendly fuels (carbon-based synthetic fuels or ammonia) will be adopted.

4.1.1 An Exemplary Study: Economic Viability of Waste-Heat-to-Power in the Energy-Intensive Industry in Germany

In Germany, 25% of the total CO_2 emissions are caused by industrial processes. The main industrial sectors originating these emissions include the steel sector (basic oxygen furnace, electric arc furnace and reheating furnace for hot rolling mills), the cement sector, and the glass sector (hollow and container glass). Table 4.5 outlines the characteristics and volume of the unused thermal energy per sector. The values are calculated from information gathered from Refs. [86]–[98].

Table 4.5: Waste heat characteristics of three manufacturing sectors in Germany: cement, steel and glass. The efficiency of heat utilization is based on the maximum and minimum temperature of the heat source.

Sector & Process	Source Temperature Available [°C]	Source Temperature Minimum [°C]	Waste Heat Available [GJ/ton$_{prod}$@15 °C]	Utilization Rate [%]
Cement				
Clinker cooling air	300	100	0.52	70
Clinker preheater *(1000-2000 ton/d)*	390	100	0.92	64
Clinker preheater *(8000 ton/d)*	390	150	0.81	53
Steel				
Blast O_2 furnace off-gas	1,200	150	1.04	89
Electric arc furnace off-gas	1,200	150	1.02	89
Reheating furnace off-gas	400	150	0.30	65
Glass				
Glass melting furnace	400	200	2.64	52

The cumulative installed capacity of ORC power plants that could be deployed to harvest the unused thermal energy can be calculated from the information in Table 4.5, together with the associated annual generation of electricity. This information is shown in Figure 4.3 for two different conversion efficiencies of the ORC unit, namely 15% and 19%. *Economic potential* is defined in this analysis as the *cumulative capacity of ORC systems running at industrial sites where using waste-heat-to-power based on ORC technology yields a lower cost of electricity than the price of electricity imported from the grid*. This economic potential is therefore equal to or lower than the technical potential.

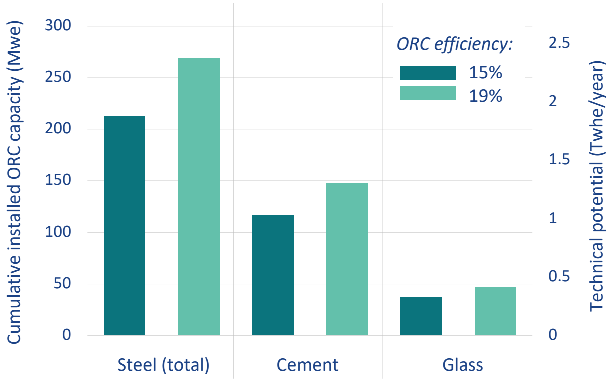


Figure 4.3: Cumulative capacity of ORC plants that could be installed to recover unused thermal energy in three industrial sectors in Germany (top) and corresponding annual electricity generation (bottom). The ORC power plants load factor is set to 95%.

The economic potential for industrial sites belonging to these three sectors in Germany can be calculated starting from the information provided in Table 4.5 and Figure 4.3, taking into account the reference capital (CAPEX) and operational (OPEX) expenditures of actual ORC power systems, as well as the price of electricity for industrial consumers in Germany in 2018. The result of this estimation is shown in Figure 4.4, assuming two exemplary values of the efficiency of the conversion from thermal energy to electricity. The main assumptions of these calculations include an interest rate of 4%, an amortization time of 10 years, and a price of electricity set to €51 /MWh$_e$. Under these assumptions, the economic potential is very close to the technical potential in the case of the steel sector (1.3–2.3 TWh$_e$/yr, 94–97% of the technical potential) and of the cement sector (685–1298 GWh$_e$/yr, 97–99% of the technical potential). However, in the case of the glass sector, the economic potential is significantly lower than the technical potential (0–228 GWh$_e$/yr, 0–56%).

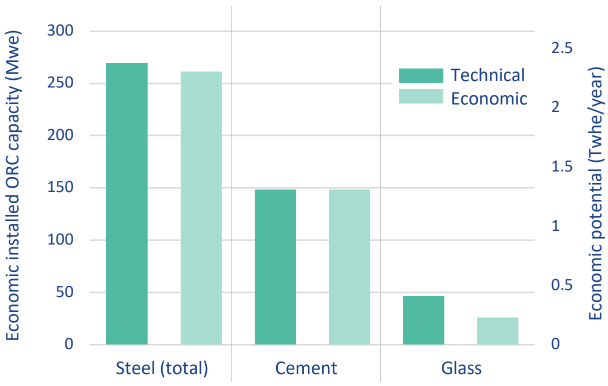


Figure 4.4: Technical and economic cumulative capacity of ORC plants that could be installed to recover unused thermal energy in three energy-intensive industrial sectors in Germany (top) and corresponding annual electricity generation (bottom). The efficiency of the ORC power plants is set to a reference value of 19%.

In summary, the cumulative capacity of the waste heat-to-power ORC power plants that would be economically viable in Germany according to the assumptions of this study are: 160–269 MW$_e$ for the steel sector, 78–148 MW$_e$ for the cement sector and up to 26 MW$_e$ for the glass sector. Furthermore, based on annual electricity generation, these ORC power plants can have a significant impact on the reduction of annual CO_2 emissions in

Germany. The emission reduction could be of 0.6–1.1 $Mton_{CO_2}$ for the steel sector, of 0.3–0.6 $Mton_{CO_2}$ for the cement sector and of 0–0.1 $Mton_{CO_2}$ for the glass sector. The total CO_2-emission reduction is 0.9–1.8 $Mton_{CO_2}$ (with data of 2018).

4.1.2 Economic Profitability of Waste-Heat-to-Power ORC Plants in Europe

The data on installed ORC plants with waste heat to power in Europe over the years reported in Table 4.6 arguably demonstrate that the owners of those industrial sites positively assessed the economic benefit. Data are take from the ORC World Map [99], therefore from an extensive database of references provided by manufacturers and following the methodology reported in Ref. [100]. Both the number and cumulative capacity of waste-heat-to-power ORC Plants increase sharply since 2013: the percentage of waste-heat-to-power ORC plants with respect to the total number of installations increased in Europe and globally to approximately 60% in the last decade, while in terms of power capacity it doubled. Importantly, it cannot be claimed that these data provide a comprehensive scenario because some ORC power plants manufactures have not reported about their installations. KCORC, based on private communication with ORC manufactures and other companies, estimates that the figures reported in Table 4.6 for both the installed capacity and number of units are too low by approximately 30%.

Table 4.6: Number of installations and cumulative capacity ORC power plants over the years. Both the values for the total number of units and the total capacity, independently from the thermal energy source, and those referred to waste-heat-to-power are displayed, together with the percentage fraction of the waste-heat-to-power installations with respect to the total.

	Any type		Waste-heat-to-power		% of Waste-heat-to-power	
	<2013	2013-2023	<2013	2013-2023	<2013	2013-2023
Number of units, world	1428	1849	110	1135	8%	61%
Number of units, EU	428	806	75	459	18%	57%
Capacity, world [MW_e]	1700	3250	165	377.1	10%	12%
Capacity, EU [MW_e]	353.4	284.8	41.7	92.3	12%	32%

Table 4.7 shows information on financial indicators related to waste heat to power ORC plants in Europe and for different energy intensive industries, based on data from a recent report prepared by CE Delft for KCORC [101]. Interestingly, internal rate of return in the range from 12% to 35% and short payback periods were calculated for all considered industrial sectors (note that the reference study is based on a limited number of installations and, therefore, even better business cases could result from other sets of boundary conditions).

Heat recovery plant installed at the Wittekind cement plant. The ORC plant produces 8,000 MWh of electricity per year (courtesy of ORCAN).

Table 4.7: Summary of financial indicators related to installations of waste-heat-to-power ORC plants depending on exemplary energy-intensive industrial sectors in Europe. Adapted from Ref. [101].

	Glass	Cement	Steel	Oil & Gas	Chemicals
Installed ORC capacity [MW_e]	1.0–2.0	1.0–8.0	1.0–5.0	5.0	0.4
NPV [M€]	6–13	3–34	2–17		2–4
Payback period [years]	3.0–4.8	2.8–6.7	4.-7.5	7.0	5.0–7.0
Internal Rate of Return IRR [%]	20–33%	14–35%	12–21%		1–20%

Estimating economic indicators for ORC power plant installations is challenging, as the calculations cannot be generalized. This is due to their strong dependence on economic, technical, and site-specific boundary conditions, which can vary significantly. A common metric used by the industry to estimate the total cost of an installation from the cost of the individual components is the Lang factor which is the ratio between the sum of the cost of the single components making up the installation and the total cost. For waste heat-to-power ORC plants, the Lang factor may vary significantly, depending not only on the technology of choice but also mostly on the boundary conditions that are specific to the site and the process providing the thermal energy. For instance, in an existing industrial site with strong requirements for high energy efficiency and involving explosive environments, installing a waste-heat-to-power ORC plant might imply a Lang factor higher than 10, whilst this factor can be close to 1 for a similar ORC power plant but installed in a non-explosive greenfield. Furthermore, if the ORC unit is fully integrated into the process during the design phase, the Lang factor can be negative (<0) since such solutions can minimize costly on-site activities. Such integration has already been developed for air compressors [85] and combustion engines [102]. It is straightforward to perform similar integration in electrical motors and generators (see Section 4.2).

4.1.3 CO_2-abatement cost

The cost of abating CO_2 emissions must be accounted for if comparing different waste heat recovery options, since the reduction of CO_2 emissions is required by regulations. Interestingly, the fact that the Net Present Value shown in Table 4.7 is always positive implies that **the cost of CO_2-abatement may become negative**. This implies that the plant operator would save money while reducing the carbon footprint of the installation. However, it is acknowledged that this may not be entirely feasible in the very short term, as public incentives would likely be needed to accelerate the deployment of ORC power plants within a limited timeframe. This could result in a cost to taxpayers, such as lost tax revenues associated with CO_2 emission reductions. Nevertheless, economic benefits are expected over the longer term. This is further discussed in Ref. [101], the source of the information shown in Table 4.8. These values suggest that the installation of waste-heat-to-power ORC plants would be highly beneficial in terms of CO_2 emissions reduction[1].

4.1.4 Jobs Creation Perspective

General ORC power plant installations in Europe and the export of technology outside of Europe are continuously creating many hundreds of jobs for highly skilled industrial workers and engineers and could easily generate many thousands of new jobs, if a proper policy (see Chapter 5) is in place to support the European market and the worldwide distribution. The clean energy transition requires a rapid expansion of the energy workforce,

[1] CO_2-abatement costs are strongly dependent on the CO_2-emission factor associated with the electricity generated by conventional power plants which would be replaced by waste-heat-to-power ORC plants.

Table 4.8: Summary of the CO_2-abatement costs associated with waste-heat-to-power ORC plants for different industrial processes wasting thermal energy. Negative means immediately profitable [101].

	Glass	Cement	Steel	Oil & Gas	Chemicals
CO_2 savings [$ton_{CO_2,eq}$/yr]	2,100–4,300	1,900–15,000	1,900–9,000	8,000	700
Abatement costs [€/$ton_{CO_2,eq}$]	–95 / +128	–52 / +104	–34 / + 71		–49 / +115

and the demand for new workers for the manufacturing of clean energy technologies is arguably the strongest. According to the latest Scenarios issued by the International Energy Agency [103], jobs for the manufacturing of electric vehicles, solar PV, heat pumps and wind turbines are going to increase by 220% between 2022 and 2030, while European legislative packages promoting clean energy technologies, such as the Net Zero Industry Act (NZIA), are expected to significantly increase the number of jobs share related to manufacturing, particularly for those sectors that are considered as strategic (i.e., geothermal power installations, heat pumps or other renewable energy technologies). European companies are well positioned to respond to this increasing market demand. High precision manufacturing companies, such as those supplying the aeronautical, power generation and transportation industries, are capable of growing quickly if the market demand increases, although there could be an initial mismatch between the skills required for the new workers and those currently available on the supply side. However, it is expected that this phase, as well as that of re-skilling of workers coming from other sectors like those related to fossil fuels, could last no longer than a few years and, in any case, with a higher absorption rate than the potential short-term deficit. Training programs could be designed to prioritize the development of the skills required by the ORC power industry along with those required by any other player in the supply chain, creating potential synergies, especially between university and industry.

A recent report on the evaluation of the value and trends of the waste heat recovery technologies market [104] states that the value of global sales of equipment is US$65 Bn/year. The market share of European companies is 38% . The global growth rate is 6.9%, however the current growth rate is lower than that of the market in North America, also due to the strong government support due to the US Inflation Reduction Act (IRA), which aims to provide direct loans for reequipping, expanding, or establishing the manufacturing facility. This is arguably a long-term strategic threat for the European waste heat recovery industry, especially with regard to the possible shift of investments from Europe to the United States. This negative possibility is partially balanced by the NZIA (Net Zero Industry Act) supporting the enhancement of European manufacturing capacity for net-zero technologies and their key components and addressing the barriers to the scaling up.

Two installed ORC units (courtesy of RANK).

The result of the analysis of the potential for job creation related to the expansion of the ORC power plant market published in the first version of this document is that approximately 45,000 new positions could be created over a minimum period of 10 years. In a recent report commissioned by KCORC [101] it is documented that 4,000 to 12,000 new full-time equivalent (FTE) positions in maintenance alone could be created and 38,000 to 41,000 new FTEs in direct labor related to design and manufacturing could be created. If FTEs required for R&D is included, a rough estimation is that 50,000 new FTEs could be required in Europe. The time frame for such job creation is linked to the speed of implementation of the planned expansion of the ORC power plant market. This period could be a few years only, but the duration is also driven by the development of related sectors, in a cascading effect.

4.2 Waste Heat Recovery from Propulsive Engines

4.2.1 Long-Haul Truck Engines

The possibility of increasing the efficiency of truck engines through ORC units powered by the exhaust of the engine can be analyzed from an economic perspective. The operational costs for different segments of the trucking industry are reported in Ref. [105]. According to this study, the average annual expenses of a truck operator are as follows:

- 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.

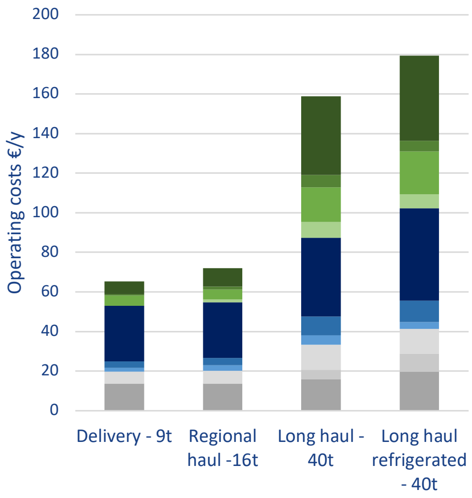
Figure 4.5 shows the yearly cost repartition of operating a truck per vehicle segment. As it can be seen, annual fuel costs range from 10% to 25%, depending on the vehicle tonnage (the lower the payload the lower the percentage). It is therefore clear that in case of long-haul trucks, a mini-ORC waste 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 4.9 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 increase with the improvement of the technology, which is still in its infancy, and with mass adoption.

Table 4.9: 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 [€]	6,540	9,362	39,704	43,053
Yearly savings [€]	164-327	234-468	993-1,985	1,076-2,153

Using previously published data [106], [107], Table 4.10 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).

Figure 4.6 shows, based on the data of Table 4.10, the dependency of the return on



	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 4.5: Yearly operating costs of trucks, per trucking segment.

Table 4.10: 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

investment (in years) from the ORC waste heat recovery system production volume (in units). The results have been obtained using an established cost model [108]. 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 56,000 Mton of CO_2 [109].

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 vehicles powered by combustion engines, such as off-road vehicles, buses, etc., could benefit from ORC waste heat recovery solutions and this would lead to an enormous impact on the global energy and 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.

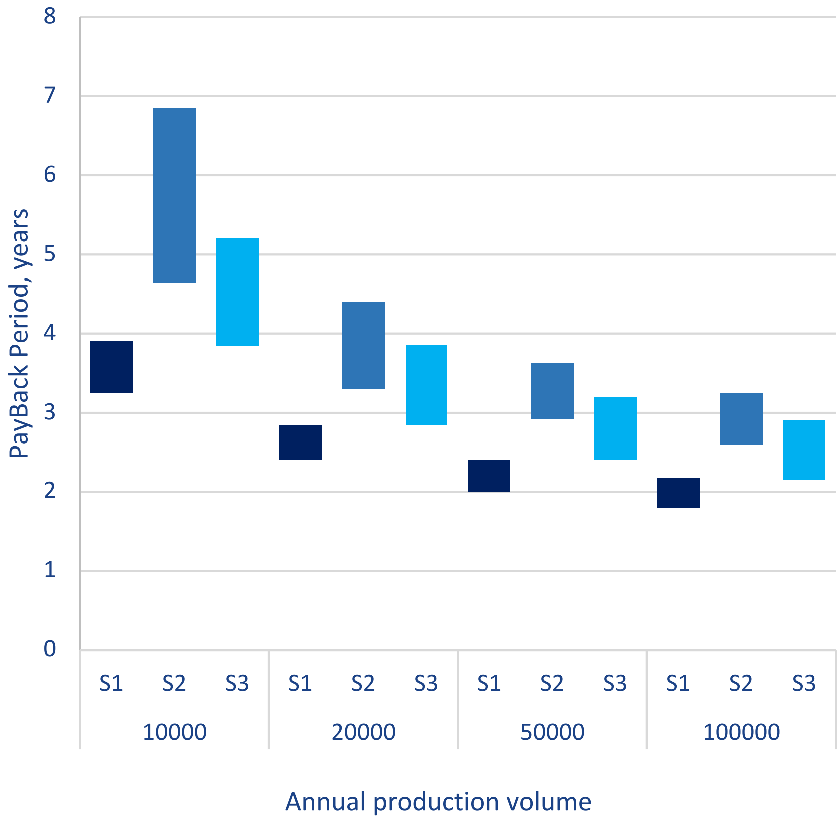


Figure 4.6: Estimated payback period versus annual production volume for a long-haul truck for the exemplary cases of Table 4.10.

4.2.2 Inland and Coastal Vessels Engines

Compared to ORC systems for the recovery of waste heat from industrial processes or truck engines, those for ship engines benefit from an inherent thermodynamic advantage, namely that cooling can be provided by ocean, river, lake or canal water. Air cooling is bound to occur at higher temperature, and air is a far less efficient cooling medium than water, thus requiring larger heat transfer surfaces. In general terms therefore, for the same specifications, an air-cooled ORC system is less efficient and more expensive than a water-cooled ORC system.

A recent study on the application of waste heat recovery on dredging vessels concluded that ORC systems can reduce the onboard fuel consumption by 3.5% to 4.5%, depending on the engine type, fuel type and resulting exhaust temperature [110]. Table 4.11 shows the potential for waste heat recovery in European inland and coastal vessels. The table lists the number of active vessels, their average fuel consumption, equivalent annual energy use and the energy that could be saved if ORC systems were utilized to harvest unused thermal energy (a fuel saving of 4% is assumed to estimate the anticipated annual energy saving potential). Also in this case, even if hydrogen or other environmentally friendly fuels (carbon-based synthetic fuels or ammonia) were adopted in the future, ORC systems would still improve energy efficiency by by the same amount. The underlying calculations are based on a list of operational profiles and fleet families reported as part of the PROMINENT project funded by the European Union [111].

A number of research and demonstration projects funded by national institutions in Europe have recently been completed with the purpose of increasing the Technology Readiness Level (TRL) of ORC systems for waste-heat-to-power applications in ship propulsive

Table 4.11: Potential for waste heat recovery from engines of European inland and coastal vessels by means of ORC systems. The values of the number of vessels and of the average annual fuel consumption are based on results obtained during the PROMINENT project [111] and refer to 2013. The equivalent annual energy consumption is calculated by assuming a fuel oil density of 860 kg/m^3 and a specific energy of 42.7 MJ/kg. A 3.5% to 4.5% fuel saving is assumed to estimate the annual saving potential.

European inland fleet	Number of vessels	Average annual fuel consumption [m^3]	Equivalent annual energy [GWh]	Annual saving potential [GWh$_{th}$]
Passenger vessels	2,553	54	1,406	56
Push boats <500 kW	890	32	291	12
Push boats 500-2000 kW	520	158	838	34
Push boats ≥ 2000 kW	36	2,070	760	30
Motor vessels ≥ 100 m	1,212	341	4,216	169
Motor vessels 80–109 m	2,449	182	4,542	182
Motor vessels <80 m	4,463	49	2,231	89
Coupled convoy	140	558	797	32
Total	**12,263**	**–**	**15,081**	**604**

systems. In addition, other similar R&D projects funded by the European Union have addressed the utilization of similar solutions for the enhancement of fuel economy onboard ship. For instance, an ORC demonstrator was developed and extensively tested in the JOULES project [112]. The data were used to verify simulation models, which were subsequently incorporated in simulations of various application cases to enhance the energy efficiency of ship, subject to realistic operational profiles. Furthermore, in addition to these research and innovation actions, ORC technology has successfully been applied commercially onboard several vessels; for instance, the marine unit developed by Orcan Energy has been installed onboard two LNG-fueled ferries operating in the North of the Netherlands [private communication with the company].

Table 4.12 reports data from a preliminary analysis of the potential of installing waste heat recovery ORC systems onboard motorized inland transport vessels in Europe [111]. The table provides detailed information about the average installed power of engines onboard these vessels, and it also reports estimates of the rated installed power of associated ORC units, assuming that the amount of additional mechanical/electric power that could be produced by these systems is approximately 4.25% of the rated capacity of the main engine. With this information, Table 4.12 also provides an estimate of the total market potential for ORC systems related to the active European inland fleet.

Heat recovery system installed on-board a shipping vessel (courtesy of Climeon).

Table 4.12: Average engine power per type of vessel, capacity of the associated ORC waste heat recovery system and cumulative electric power capacity of ORC systems per type of vessel [112]. The data for the fleets are the same as those in Table 4.11.

European inland fleet	Average installed engine power [kW]	Average net ORC power [kW_e]	Fleet ORC potential [MW_e]
Passenger vessels	482	20	52
Push boats <500 kW	247	10	9
Push boats 500-2000 kW	847	36	19
Push boats ≥ 2000 kW	3,458	147	5
Motor vessels ≥ 100 m	1,761	75	91
Motor vessels 80-109 m	814	35	85
Motor vessels <80 m	302	13	57
Coupled convoy	2,237	95	13
Total	**–**	**–**	**331**

Table 4.12 shows that the total market potential for waste heat recovery ORC systems is large. However, the total installed power is moderate and whether or not ship owners will eventually adopt this type of solution will likely depend on individual cost benefit analysis. It can be argued that small, standardized cost-effective ORC-modules tailored to inland marine market would be needed. Larger vessels with larger installed power and fuel consumption may provide a promising market niche, whereby ORC systems similar to those employed for industrial waste heat recovery could be employed [112].

4.2.3 Ocean Going Vessels Engines

With current environmental considerations about seaports as well as along major sea faring lanes, as well as with rising fuel costs, it is imperative that alternative green energy technologies are sought and applied to yield innovative, more sustainable propulsion systems. Given that ocean going vessels are inherently intercontinental, the analysis cannot be limited to the EU.

According to current estimates presented in the third IMO[2] Green House Gas Study [43], international shipping emitted 796 Mton of CO_2 in 2012, which accounts for no more than about 2.2% of the total emission volume (all sectors into account) for that year. Furthermore, the forecasted mid-term scenarios treated in the third IMO GHG Study showed that CO_2 emissions from international shipping could grow by between 50% and 250% by 2050, depending on the expected future economic growth, world maritime commerce, and energy developments.

On large ocean´going vessels (>100 GRT[3]), diesel engines are the dominating technology to produce propulsive power (>96% of global fleet) [113], featuring 2-stroke engines, large bores and low speed; therefore, opportunities for waste heat recovery are related to low-to-medium temperature sources. The Fourth IMO GHG Study 2020 [114] provides a global perspective for the fuel consumption of ocean-going vessels. As confirmed by data from the Janes Sea Module Global Shipping Database [115], global shipping is dominated by several types of vessels that account altogether for nearly two thirds (>66%) of the total global merchant vessel fleet (105,491 vessels): general cargo, bulk carriers, tankers (oil-, product-, chemical-, etc.), and container carriers. Table 4.13 summarizes these findings.

These vessels contribute the largest share (>86%) of the total fuel consumed by the

[2] The International Maritime Organization (IMO) is the specialized agency of the United Nations responsible for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.

[3] GRT: Gross Registered Tons.

global sea-going vessels fleet. The most widely used marine fuel is heavy fuel oil (HFO) -and its equivalents (HFO-equivalent)- and this is used to operate three power systems onboard each modern merchant vessel: main propulsion, auxiliary power, and steam generation. Of these three, the fuel demand for main propulsion is largest. Auxiliary power is needed for various loads (e.g., emergency power, main engine starting, marine auxiliary equipment, stand-by at port, etc.) and it is typically generated by smaller 4-stroke, medium/high-speed diesel engines. In addition, other power configurations are also possible, including various hybrid configurations (e.g., small gas turbines, electric storage devices, efficient power banks, etc.). The majority of newly built merchant ships are equipped with modern dual-fuel diesel engines, capable of operating not only on different fuel phases (i.e., liquid, gaseous/vapor, etc.) but also on newer cleaner varieties of liquid biofuels as well as green and blue fuels. It is therefore expected that the overall energy savings due to waste-heat-to-power ORC installations on ships will remain an attractive value proposition for ship owners and ship operators even when other fuels will be introduced, as it is the case for all other cases discussed in this report. Onboard steam is generated for several needs: preheating of cold/viscous HFO from the fuel holding tanks (prior to transferring and pumping to the fuel injectors of the main diesel engine); heating of cabin/work/cargo spaces; power for various marine auxiliary equipment, etc.

The annual estimates of fuel consumption [114] include the fuel needed for all three types of onboard power generation. However, by far the largest share of fuel consumption is associated with the main propulsion engines, accounting for nearly 97–98% of all fuel consumed onboard a modern merchant ocean-going ship [114]. Table 4.13 shows the ranking of merchant ships by specific ship type and its (HFO-equivalent) fuel consumption (in millions tons per year). Although container carriers account for only about 5.5% of the global merchant vessels fleet (based on 2018 data [115]), they are the largest fuel consumer at nearly 27% of the total fuel consumed per year [114].

Research and development of new technologies that optimize engine design in order to improve fuel efficiency should therefore be directed mainly towards these types of propulsion systems. Modern large container carriers require large, powerful 2-stroke low-speed diesel engines (50,000 – 75,000 kW) due to their large displacement and high operational speeds. The other ship types responsible for large amounts of fuel consumption–bulk carriers and oil tankers– consume 22.6% and 15.4% of the total HFO-equivalent fuel consumption per year, respectively [114]. Both bulk carriers and oil tankers are propelled by large 2-stroke, low-speed diesel engines. Thus, these three types of ship (i.e., container carriers, bulk carriers, and oil tankers) account for nearly two thirds (approx. 65%) of the aggregate annual fuel consumption of the total global merchant vessel fleet, a staggering value.

Figure 4.7 shows the energy balance (Sankey diagram) for a typical 2-stroke large-bore low-speed high-power diesel engine (in-line 12 cylinder) powering an ocean-going vessel (typically a fast container carrier) [116]. Nearly 50% of the total fuel energy is rejected as waste heat to the surroundings. The three largest streams of unused thermal energy are the exhaust gas, the air cooler (scavenge air), and the cooling water of the engine jacket. The remaining >3% of the waste heat comprises heat rejection to the lubricating oil and heat radiation. The three major waste heat streams are available at different temperature levels, namely 200–350 °C (exhaust gas), 100–160 °C (scavenge air) and 70–95 °C (engine jacket cooling water) [117]–[122]. Hence, most of the thermal energy available for waste-heat-to-power conversion is available in the 70–350 °C range.

The potential of powering ORC units with otherwise wasted thermal energy from ship engines propelling inland and coastal vessels (Table 4.12) is smaller if compared to ocean-

Table 4.13: Number of most common merchant ships and associated fuel consumption as percentage of total annual fuel consumption of sea-going vessels fleet (adapted from Ref. [114], [115]).

Ship type	Ships		Fuel consumption (main,aux, boiler)	
	Number [–]	Share [%]	Consumption [$Mton_{HFO,eq}$]	Share [%]
General cargo	16,321	15.5	12.7	5.3
Bulk carriers	13,182	12.5	54.4	22.6
Oil tankers	11,793	11.2	37.0	15.4
Product tankers	9,502	9.0	20.0	8.3
Offshore ships	9,042	8.6	1.7	0.7
Containers carriers	5,816	5.5	63.9	26.5
Chemical tankers	4,094	3.9	17.5	7.2
All others	35,741	33.9	–	–
Total	**105,491**	**100**	**–**	**–**

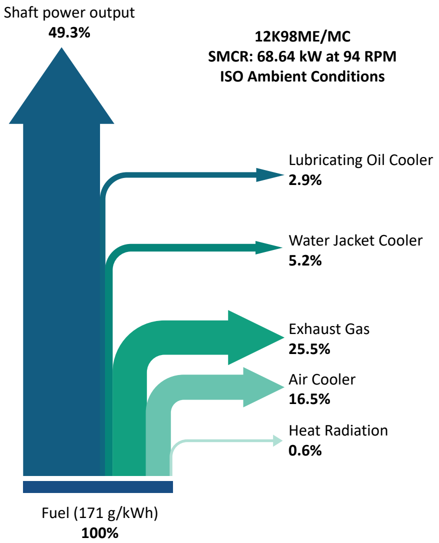


Figure 4.7: Energy balance (Sankey) diagram for MAN 12K98ME/MC marine diesel engine [116].

going vessels (Table 4.13), not only because the number of vessels is much larger but also because the rated power of the engines is much larger and the operational profile is characterized by more time spent at higher speeds.

Propulsion systems other than large 2-stroke engines equip other types of ships, like passenger ferries, cruise ships, etc. Examples of these propulsion systems are combined gas and steam cycle engines, hybrid gas turbine and diesel engine systems, advanced hybrid electric systems. Opportunities to increase the energy efficiency and reduce CO_2 emissions by means of ORC systems exist also for all these more complex propulsion systems. For example, many low-temperature waste heat streams could be used to generate additional electricity to be used onboard (and/or storage).

In all of these combined power cycles, the opportunity to extract energy from a waste heat stream exists and is optimal for the implementation of an ORC system for recuperating this "low-temperature" heat to produce additional useful electric energy for on-board consumption (and/or storage).

The investment quality for waste-heat-to-power ORC system onboard ships differ significantly from that of stationary power plants. Electric price onboard is not regulated and this implies that a stringent correlation between fuel and maintenance costs apply to the business case. Furthermore, ORC systems not only reduce the operating cost but they also increase vessel range, which is particularly important in naval fleet economics, as inventory can be reduced according to the increased range of each vessel. In addition, a significant incentive to the marine industry is the regulation of CO_2 emissions, which can bring savings to ship owners and operators because it implies an increase in engine efficiency. A variety of penalties (CO_2 tax, FuelEU tax, etc.) have been introduced or are about to be introduced, as well as possible bans on entering emission control areas (ECA's) if current IMO environmental regulations are not followed.

Lang factors in maritime applications can be very large. On the one hand, retrofitting is associated to very high Lang factors because a ship is typically highly optimized and adding new systems is, therefore, complex and expensive. On the other hand, integrating an ORC waste heat recovery system into the original ship design leads to an extremely small or even negative Lang factor.

CE Delft [101] investigated one specific business case for a maritime application recently. The calculated IRR[4] is in the range between 25% and 47%, at a discount rate of 8%, providing an extremely advantageous investment opportunity even for small-capacity ORC systems (>200 kW_e. The CO_2 abatement cost could not be estimated because it is not clear how to allocate any public cost for investments in the reduction of CO_2 emissions in case of international sea vessels. A larger ORC system onboard a larger vessel is expected to provide the opportunity for an even more profitable investment.

Table 4.14: Main values related to an exemplary business case related to a small capacity waste-heat-to-power ORC system onboard a vessel [101].

ORC system capacity	[MW_e]	0.1–0.2
NPV	[M€]	0.4–0.5
Payback period	[Year]	2.1–3.8
IRR	[%]	25–47%

[4] Internal Rate of Return.

Existing EU Regulations and Directives can support and promote the deployment of ORC technology

- Regulations and directives that are directly relevant are identified
- Some directives unfortunately do not mention waste heat-to-power explicitly
- Actions for KCORC in this area are proposed

5 Policy and Regulation: Situation and Proposals for Improvement

5.1 Introduction

As outlined in the previous chapters, waste-heat-to-power technology, enabled by ORC power generation systems, provides the European Union (EU) with an enormous opportunity to reduce CO_2 emissions. Unfortunately, this potential is still largely ignored in EU policies, affecting therefore national legislation in all EU countries.

While waste heat recovery and cogeneration are frequently cited in EU regulations, ORC technology is rarely mentioned explicitly and when it is, it is always related to cogeneration rather than to waste-heat-to-power applications. There are thus many opportunities to improve current EU regulations and policies by lobbying to explicitly introduce ORC-based waste-heat-to-power technology in the relevant documents.

This Chapter is a short guide to relevant EU regulations and policies, providing a summary of the current status for each of them, as well as recommendations for actions to improve the current situation. The content of this Chapter is largely based on Ref. [101], to which the interested reader is referred for more details.

5.2 EU Decision-Making

There are three main actors in the EU decision making process. The **European Commission** is the executive branch of the EU, with 27 Commissioners, nominated by the national governments. The **Council of Europe** is one of the legislative bodies of the EU and is composed by 27 national government ministers, each representing one member state. The **European Parliament** is the other legislative body, with members elected by EU voters.

The most common types of EU legislative acts are the **Directives**, which establish general objectives but need to be incorporated into national legislation by each member state, and the **Regulations**, which instead feature binding legal force throughout every Member State. The decision-making process in the fields of climate, energy, and industry is initiated by the Commission, which publishes a new legislative proposal. This is scrutinized and possibly amended by the Parliament and Council of Europe in a process known as the *trilogue*, which typically takes one to two years from the initial proposal to the moment the new legislation enters into force.

As far as technical or implementation details of the legislation are concerned, the legislative bodies can delegate the Commission to issue so-called **Implementing Acts** and **Delegated Acts**, which cannot be amended by the Parliament and Council, but only accepted or rejected, thus requiring a much shorter process. Delegated Acts are mostly used to establish technical measures, so they can be quite relevant for ORC advocacy.

In 2021, the European Climate Law Regulation [123] was adopted, setting binding targets of 55% reduction of greenhouse gas emissions by 2030 and full climate neutrality of EU countries by 2050. To achieve the 55% target, the Commission presented an extensive set of legislative proposals, which is referred to as the **Fit for 55** package. Most of the proposed measures have been adopted by the Parliament and Council by the end of 2023. Moreover, following the invasion of Ukraine by the Russian Federation, the Commission issued the *REPowerEU Plan* with the goal of further increasing energy saving and diversifying the EU energy supply; however, not all these amendments were ratified.

5.3 EU Directives, Regulations, Acts and Plans

EU directives, regulations, acts, plans, and policies that are relevant for the promotion of ORC-based waste-heat-to-power technology are outlined by mentioning for each of them who takes decisions, when the last decision was taken, when a new decision may be due, what is relevant for ORC technology, and what the ORC community can do. The legislative items offering the greater potential for action are listed first.

5.3.1 Industrial Emissions Directive (IED): BREFs and BATs

The IED was first approved by the EU Parliament and Council in 2010 [124]. All industrial installations listed in Annex I require a permit to operate, granted by national authorities and with conditions set in accordance with the Directive. The permit conditions, in particular the emission limit values, are based on the Best Available Technology (BAT). The process to define the BATs involves experts from member states, industry, research institutions, non-governmental organizations and the European Commission. The process is coordinated by the European IPCC Bureau (EIPCCB), which sets up working groups per sector or industry, resulting in BAT Reference documents, or BREFs[1], which summarize the state of the art of what is technically and economically available to improve the environmental performance. The conclusions of these BAT documents are adopted by the European Commission as Implementing Decision. The IED requires that the references for issuing permits are based on the BATs.

BREFS are grouped into so-called *sectoral BREFs*, covering specific agro-industrial sectors, and *horizontal BREFs* dealing with cross-cutting topics such as energy efficiency, industrial cooling, etc. The process of producing a BREF takes two to three years by a group of up to 100 experts, mediated by the EICPPB. BREFs are revised according to a rolling program, with a expected revision after eight years from its publication. Once finalized, BREFs are presented to a forum established by the IED, comprising representatives from member states, industries and non-governmental organizations; they are endorsed by the *IED Article 75 committee* and finally published as Implementing Decisions on the official journal of the EU.

In 2022, the European Commission adopted a proposal to revise the IED by increasing the focus on energy efficiency, material efficiency and reuse, and the use of safer and less toxic chemicals in industry; such proposal should inherently favor ORC-based waste-heat-to-power technology. In addition, it was proposed to establish the Innovation Centre for Industrial Transformation and Emissions (INCITE), a strategic innovation in the

[1] For an updated list of BREFs check the website of the European Bureau for Research on Industrial Transformation and Emissions **BREFS**.

revised Industrial Emissions Directive, with the goal of identifying and evaluating emerging technologies linked to decarbonization, resource efficiency, and circular economy, from both environmental and economic perspectives, eventually listing them as BATs if they are commercially available. Trilogue negotiations towards the final adoption of the revised IED started in 2023 and concluded with the approval of IED II on April 2024. Soon after, INCITE set sail in June 2024 and the revised version of the Industrial Emissions Directive entered into force on August 4th [125].

Despite the recommended eight-year update cycle, many BREFs for which ORC technology is relevant were never revised after their first publication for a much longer time interval. For example, the following the following BREFs were not revised after the year of publication: Energy efficiency (2009), Manufacture of Glass (2012), Iron and Steel Production (2012), Production of Cement, Lime, and Magnesium Oxide (2013). The revision of these BREFs in the near future provides a unique opportunity for KCORC to get involved through the EIPCCB in the technical working group for future revision of those documents. Waste-heat-to-power technology could be made compulsory for new or possibly even existing installations, as a means to reduce greenhouse gas emissions.

5.3.2 FuelEU Maritime Regulation

The FuelEU Maritime Regulation [126], part of the *Fit for 55* initiative, entered into force at the end of 2023. It mandates a cut of the so-called greenhouse gas emission intensity (grams of carbon dioxide released per megajoule of energy generated) on board all ships above 5000 t entering EU ports. The emission reductions are: 2% by 2025, 6% by 2030, 20% by 2035, 38% by 2040, 64% by 2045, and 80% by 2050. Although it is not mentioned in this regulation, one way achieving these targets is by installing ORC modules that are powered by the exhaust gas of engines, by saturated steam, by hot thermal oil, or by engine cooling water, thus reducing the amount of fossil fuel that need to be burned for a given purpose.

Annex III of the regulation sets general requirements for zero-emission technologies, and it includes a *non-exhaustive* list of suitable technologies (onboard fuel cells, onboard electrical energy storage, and onboard power generation from wind and solar energy). Moreover, it is mentioned that power technologies that are not listed but do not emit greenhouse gases, can be added to the list by means of delegated acts, which require a much leaner process than new directives or regulations.

50 kWe ORC plant (courtesy of ENERBASQUE).

KCORC therefore should get involved in the formulation of delegated acts related to the FuelEU maritime regulation and promote the inclusion of ORC technology into the list of suitable zero-emission technologies.

5.3.3 EU Taxonomy Regulation

The EU Taxonomy Regulation entered into force in 2020 [127]. Article 9 sets out six environmental objectives: climate change mitigation, climate change adaptation, sustainable use of resources, transition to a circular economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems. Article 3 sets criteria for economic activity to qualify as environmentally sustainable: making a contribution to at least one environmental objective, doing no significant harm to any of the environmental objectives, complying with minimum safeguards related to business and human right, and, last but not least, complying with screening criteria set out in the **Taxonomy Delegated Acts**. The Taxonomy is technology-neutral and does not introduce mandatory obligations–it is rather a voluntary instrument to steer financial decisions towards more sustainable investments.

Under this regulation, the Commission is delegated to define technical screening criteria through the **Environment Delegated Act**, related to sustainable use of resources, circular economy, pollution prevention, restoration of biosystems, and the **Climate Delegated Act**, related to climate change mitigation and adaptation. The Climate Delegated act was first published in 2021 [128] and since then amended twice, the first time with the Complementary Climate Delegated Act in 2022, and the second in 2023 with an amendment establishing additional screening criteria.

As with most other EU policy documents, the Climate Delegated Act (Delegated Act, Annex I and Annex II, point 4.25) mentions waste heat utilization as one of the environmentally sustainable activities for heating or cooling generation, but does not mention waste-heat-to-power technology. However, as past experience also shows, the Climate Delegated Act is meant to be updated frequently and this does not require the laborious *trilogue* process, but rather only an executive act by the Commission. This leaves ample room for KCORC to lobby to get waste-heat-to-power explicitly mentioned in a future amendment issued in the near future, thus improving its chances of being considered for sustainable investments in the industry. Power generated from waste heat is indeed a carbon-neutral technology, especially for hard-to-abate sectors: the additional electricity (or mechanical energy to drive machinery) derived from waste heat does not produce additional CO_2 emissions and is as clean as useful energy generated from renewable sources. Waste-heat-to-power valorization offers a chance to enhance circular-economy systems, leading to a more integrated thus more efficient energy system.

5.3.4 European Union Emission Trading System (ETS)

The EU ETS [129] is a cap-and-trade system setting an upper limit to the total greenhouse emissions by the subjected sectors. The cap is expressed in equivalent tons of CO_2. All companies responsible for emissions must procure emissions allowances in order to operate. The cap is meant to be progressively reduced; this makes buying the allowances increasingly expensive, thus incentivizing low-emission activities and making high-emission activities more expensive.

The system was set up in 2005 and progressively included more sectors, until basically all industrial activities were included in 2020. Since 2020, the rate of reduction of the cap increased: it is currently fixed at −4.3% from 2024 to 2027 and will further increase to −4.8% from 2028. Additionally, starting from 2024 the ETS system also regulates emissions from maritime transport entering EU ports. All large vessels above 5000 gross tonnage, no matter what flag they fly, must comply with the regulation.

ETS allowances had a small impact until 2021, with values below €20/t_{CO_2}, but values started increasing sharply since 2021, peaking around €100/t_{CO_2} in 2023, see Figure 5.1. Given the accelerating pace at which the cap is shrinking, the cost of allowances is expected to remain high in the future, or possibly to increase even more.

Figure 5.1: Market price of ETS emissions allowances over the years in €/t.

The production of 1 MWh of electricity with a combined-cycle plant emits about 400 kg of CO_2, while the emission is about 600 kg if marine diesel engines are used to generate it. At €100/t_{CO_2}, the ETS allowance corresponds to an indirect incentive to waste-heat-to-power of €40/MWh for stationary power and €60/MWh for marine propulsion. In the future, higher prices of the ETS emission allowances will correspond to higher indirect incentives. Together with the mentioned FuelEU Regulation, these measures will make the use of ORC for waste-heat-to-power systems on board ships particularly attractive, making it convenient to invest in such power plants even in the short term, when the emission limits prescribed by the FuelEU Regulation are still very mild.

Six ORC modules with a total output of 1 MW_e (courtesy of ORCAN).

5.3.5 Energy Efficiency Directive (EED)

The EED was first adopted in 2012, setting goals for 2020, in particular 20% efficiency improvements, within the so-called 20-20-20 program. The EED was revised in 2018, with the adoption of the EED II which established the goal of saving 32% of primary energy by 2030, with 0.8% annual improvements between 2024 and 2030.

As a part of the Fit for 55 initiative, in 2021 the Commission proposed another revision, known as EED III [130], further increasing efficiency improvements targets; EU countries are required to achieve cumulative end-use energy savings for the entire obligation period (from 2021 to 2030), equivalent to annual savings of at least 0.8% of the final energy consumption in 2021-2023, at least 1.3% in 2024-2025, 1.5% in 2026-2027 and 1.9% in 2028-2030. In addition, it made it binding for EU countries to collectively ensure an additional 11.7% reduction in energy consumption by 2030; the EED III was published in September 2023 and entered into force on 10 October 2023. Given that these directives do not mention obligations for revisions, a further amendment or revision of directive act is not expected anytime soon.

The EED II and EED III mention ORC power plants as a cogeneration technology in part II of Annex II. Unfortunately, extensions to include the use of ORC power plants for waste-heat-to-power, which were proposed in the first version of this White Paper, did not end up in the revised EED.

> Being a Directive, the EED needs to be implemented by member states through national legislative acts. This still leaves room for lobbying activity at national level, since ORC waste-heat-to-power systems can help achieving the national energy efficiency goals mandated by the directive. In the long term, a further EED revision may be in the making, and at that point KCORC should be ready to propose the explicit inclusion of waste-heat-to-power among the technologies listed in Annex II.

5.3.6 Renewable Energy Directive (RED)

Similarly to the EED, the RED was first adopted in 2009 as part of the 20-20-20 initiative, mandating a minimum share of 20% of renewable energy by 2020 for the whole EU. The directive was reviewed in 2018 with the RED II, fixing a minimum objective of 32% renewable energy share in 2030. In 2021 the Commission put forth the Fit for 55 initiative, initially proposing an increased target of 45% renewable share for 2030, which was later reduced to 42.5% during the *trilogue* process, leading to the final publication of the RED III [131] in October 2023.

As with the EED, the RED III extensively mentions the direct use of waste heat and cold, but does not explicitly consider waste-heat-to-power as a form of renewable energy. Waste heat is not considered renewable if it is originated from a process for which fossil fuels are burned. Therefore, under this directive ORC-generated electricity in such cases does not comply with the definition of renewable energy. Unfortunately, the provisions of the RED III from this point of view remained the same as those of the RED II, despite the proposals laid out in the first version of this White Paper. However, the progressive decarbonization of primary energy sources will inherently solve this problem in the future.

The European Commission has prepared a guidance document about waste heat in relation to the RED III, after noting that Member States have different interpretations of the waste heat definition and different ways of accounting for it in their national statistics. The guidance document aims to provide directions on how to account for waste heat more uniformly. Article 22a focuses on mainstreaming renewable energy in industry. The guidance document was published on September 2nd, 2024 [132]. As with the EED, a further revision of this directive is not expected soon. However, KCORC should be ready to propose suitable amendments, should the Commission initiate a revision process, particularly within the new mandate.

5.3.7 Strategic Energy Technology (SET) Plan

In 2007, the EU Commission launched the SET Plan [133], with the goal of providing a common vision, goals, and coordination in accelerating the development and deployment of efficient and cost-competitive clean technologies. The related work is led by the SET Plan Steering Group and Bureau, which set up 14 Implementation Working Groups (IWG) tasked with monitoring and reporting progress towards the SET Plan targets. The activities and targets published in the implementation plans generated by the IWGs are identified in cooperation with national governments and stakeholders (industry and research bodies); the implementation plans are the reference documents of the SET plan.

In 2021, a revised implementation plan on energy efficiency in industry–of which KCORC was one of the contributors–was published. In this implementation plan, ORC technology is explicitly mentioned (in the Annex, among the *Heating and Cooling Activity Fiches*) as a suitable waste-heat-to-power technology. The revision of the SET plan of October 2023 refers explicitly to this implementation plan. Given that Member States report on their activities in relation to the SET Plan through National Energy and Climate Plans (NECPs)–which play a key role in the climate and energy policy of Member States–the contribution of KCORC to this revision increases the chance that ORC systems are brought to the attention of national policy makers.

5.3.8 F-Gas Regulation

Fluorinated greenhouse gases (F-gases) are fluorinated compounds featuring a very low ozone-depletion potential (ODP) but a very high greenhouse gas potential (GWP). F-gases are widely used in the refrigeration industry. At EU level, F-gases currently account for about 2.5% of total GHG emissions. The F-Gas Regulation, first issued in 2006 and subsequently updated in 2014 [134], limits the total quantity of such gases that can be sold in the EU, with a current goal of reducing the sales in 2030 to one-fifth of those in 2014. A revised version of this Regulation was adopted in February 2024 and started to apply in March 2024 [135]. The replacement of those ORC using fluorinated compounds as working fluids with natural refrigerants such as CO_2 or hydrocarbons is doable but involves some development work and can be considered in the medium-to-long term.

5.3.9 Net-Zero Industry Act (NZIA)

The NZIA, proposed in March 2023, is one of the initiatives under the umbrella of the Green Deal Industrial Plan, announced by the EU Commission in January 2023. The NZIA is aimed at issuing a Regulation strengthening the European manufacturing capacity of net-zero technologies and at overcoming barriers to the scaling up of the manufacturing capacity in Europe. The measures included in the act should increase the competitiveness of the industrial sectors related to net-zero technologies and improve the energy resilience of EU countries.

The NZIA creates the necessary conditions to facilitate investments in net-zero manufacturing technologies and makes it easier for project promoters to build up net-zero industrial manufacturing. It does so by addressing the core drivers of investments in net-zero technology manufacturing through measures such as lowering administrative burdens and ensuring access to information.

The proposal of the European Commission sets a benchmark for the manufacturing capacity of strategic net-zero technologies to meet at least 40% of the EU annual deployment needs by 2030, creating favorable conditions to facilitate investments in net-zero technology manufacturing projects. The current list of 19 technology categories covers renewable energy technologies to a large extent, but unfortunately ORC power plants are not mentioned explicitly. The list also mentions "Renewable energy technologies, not covered under the previous categories" without a clear reference to waste heat recovery technologies or to ORC technology. As the Regulation is still in the making, suitable lobbying activity could be undertaken by KCORC. The Commission will have to examine the need to modify the list after each revision or update of the National Energy and Climate Plans (NECPs). While the regulation mainly aims to strengthen the production capacity of "net zero" technologies in the EU and therefore does not cover the deployment of these technologies, projects for decarbonizing energy-intensive industries (steel, aluminum, non-ferrous metals, cement, paper, ceramics, glass, lime, chemicals) have nonetheless been included in its scope.

To support future R&D activities KCORC proposes two key actions

1. To create a European Technology & Innovation Platform on organic Rankine cycle (ETIPoRC)

2. Creation of Joint Programs within EERA that are specific to ORC technology

6 Research and Development: Status and Way Forward

6.1 Existing Programs

In the last five years, several R&D funding programs of the European Union have been focused on energy efficiency and waste heat utilization, mostly related to the industrial and civil sectors but also to other sectors. The EU framework program for research and innovation is the most relevant of these programs. Within this program, several calls for proposals are issued in thematic areas of interest for which grants are made available, which are defined and renewed every five to seven years. *Horizon Europe* is the current framework program and runs from 2021 to 2027. This program is the successor to *Horizon 2020* which ran from 2014 to 2020.

EU Framework research and innovation programs 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 was aimed at enabling and fostering the co-investment of industrial players in higher-risk innovation, with special incentives for small and medium enterprises (SMEs). 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 well being;
- 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 for R&D activities related to waste heat recovery technologies and applications, stationary and mobile. Horizon Europe adopts a similar structure, shown in Figure 6.1. 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. The third pillar funds market-oriented innovation and promotes 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 role similar to the role of 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*).

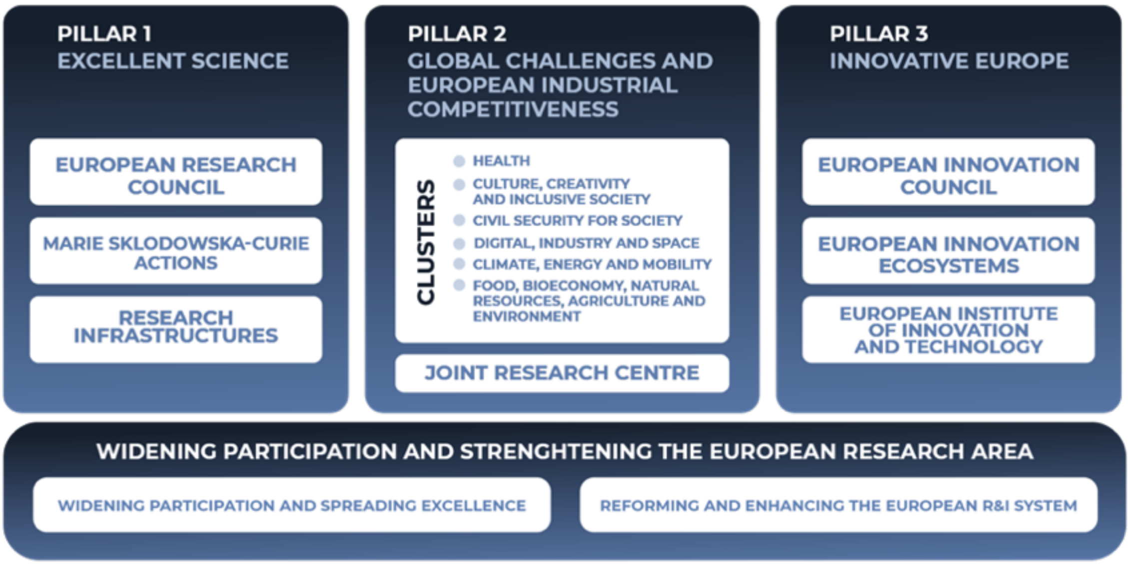


Figure 6.1: Research and Innovation funding framework of Horizon Europe (Source: https://www.horizon-eu.eu).

6.1.1 Waste-Heat-to-Power with ORC Power Plants

Table 6.1 lists sixteen projects on thermal energy harvesting funded by the Horizon 2020 and Horizon Europe framework programs, with a cumulative budget of €55 million. Only around one third of these projects (I-Therm, CO2OLHEAT, DECAGONE, TAASIO, BAMBOO and EPHYRA) 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). Nevertheless, in spite of this imbalance, funding of topics for which the primary objective is power generation, or it is at least included in the scope, has become more prominent in Horizon Europe compared to previous framework programs. Moreover, research on new waste heat applications such as the utilization of the thermal energy discharged by electrolyzers are being funded, as is the case for the EPHYRA project.

Table 6.1: Research projects on waste heat recovery funded by the Horizon 2020 and Horizon Europe programs.

Project	Funding in M€	Topic	Power production
SPIRE PPP Valorization of waste heat in industrial systems Sector: industry / Final TRL: 6 to 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.etenika.eu	4.6	Heat recovery with heat pipes and HX in steel, aluminum, ceramic industry	No
Business case for industrial waste heat/cold recovery Sector: industry / Final TRL: 4 to 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 Sector: building / Final TRL: 4 to 5 / 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
RESTORE www.restore-dhc.eu	5.7	Demonstrate Thermo-Chemical Energy Storage coupled to reversible Heat Pump - ORC system for District Heating and Cooling	Yes

Table 6.1 - Continued

Project	Funding in M€	Topic	Power production
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 Sector: industry / Final TRL: 4 to 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 70ºC – 1000ºC.	Yes, ORC and sCO2 power plants
Industrial (Waste) Heat-to-Power conversion Sector: industry / Final TRL: 6 to 7 / Starting year: 2020			
CO2OLHEAT	14	Design and testing of novel Waste-Heat-to-Power facility, based on sCO_2 power cycle technology, in the cement industry (2 MWe gross power output)	Yes
DECAGONE www.decagone.eu	14	Design and testing of novel Waste-Heat-to-Power facility, based on ORC technology, in the steel industry industry (2 MWe gross power output)	Yes
Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries Sector: industry / Final TRL: 6 / Starting year: 2014			
TASIO	4	Develop solutions to recover the waste heat produced in industrial, energy-intensive processes -cement, glass, steel making and petrochemical- and transform it into useful energy	Yes
Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries Sector: industry / Final TRL: 6 / Starting year: 2021			
HI4S www.hi4s-life.eu	1.5	Develop and validate an innovative cost-effective combined heat and electricity production plant from the waste heat contained in the off-gas of an electric arc furnace within the steel making industry	Yes
Energy and Resource Flexibility in Highly Energy Intensive Industries Sector: industry / Final TRL: 7 / Starting year: 2018			
CIRMET	7	Design, develop and validate (in three relevant sectors) an innovative solution to provide energy and resource flexibility to Energy Intensive Industries	Yes (mechanical)

Table 6.1 - Continued

Project	Funding in M€	Topic	Power production
Boosting new Approaches for flexibility Management By Optimizing Process Off-gas and Waste use Sector: industry / Final TRL: 6 / Starting year: 2018			
BAMBOO https://bambooproject.eu	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
Integration of multi-MW electrolysers in industrial applications Sector: industry / Final TRL: 8 / Starting year: 2023			
EPHYRA https://www.ephyraproject.eu	24.6	demonstration of an innovative hydrogen production facility (30 MW) at industrial scale, from renewable energy sources, by employing improved electrolysis technology. Use of waste heat from the electrolyzer and refinery streams by means of an ORC system	Yes

The information in Table 6.1 suggests two observations. On the one hand, it is confirmed that the European Commission and other European decision-taking actors are aware of the importance of tackling energy inefficiency also by promoting the utilization of waste heat released to the environment across the industry and building 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 still 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 pursued*. 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. If there is a demand for thermal energy, all or part of the available waste heat should be used first to satisfy this requirement, or, if possible, the heat rejected by the waste heat recovery power plant at a lower temperature should also be utilized. This cascading exploitation of energy leads to the most efficient energy utilization (unused thermal energy is minimized).
- *Local power generation from renewable energy and waste heat recovery (even if originated from non-renewable energy sources), must be promoted 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- heat-to-power can be exploited.

90 kW_e ORC power plant (courtesy of Againity).

- *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 6.2. Screening of these data reveals that most of this research has been carried out in Europe, closely followed by China, while the United States, United Kingdom and India are far behind.

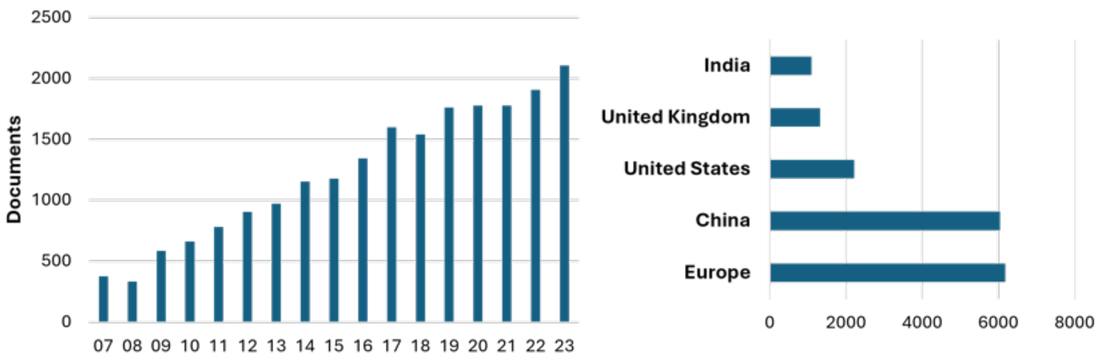


Figure 6.2: Results of searching the Scopus database with the search string 'waste AND heat AND recovery': number of published documents (left) and affiliation of the leading author (right).

The European Commission is aware of the need to support research on waste heat recovery technologies, as proven by the information provided by Table 6.1, 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) [136] to which KCORC contributed. This report is part of the *Report from the Commission to the European Parliament and the Council on Progress of Clean Energy Competitiveness* [137] 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), ORC 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*[1]*, both in terms*

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

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.
- auxiliary machinery components: bearings and seals. 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). Advantages of these technologies 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 in operation.

Within the Horizon 2020 and Europe framework programs, two complementary calls for proposals were launched, each one granting €14 million to one project developing a pilot plant for the conversion of industrial (waste) heat into power: H2020-LC-SC3-CC-9-2020 for *Industrial (Waste) Heat-to-Power conversion*, and HORIZON-CL5-2021-D4-01-05 for *Industrial excess (waste) Heat-to-Power conversion based on organic Rankine cycles*.

ORC power plant (courtesy of Atlas Copco).

6.1.2 Waste Heat Recovery from Propulsive Engines

Table 6.2 shows the projects funded by the Horizon 2020 and Horizon Europe programs that are aimed at research and development of waste heat recovery system for propulsive engines. The number of projects is lower than the number of those related to stationary ORC power plants, see Table 6.1. Moreover, whilst most funding schemes for stationary applications are based on providing financial support to develop a specific technology, the activities listed in Table 6.2 are supported by instruments of different types. 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 (Small and Medium Enterprise) 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 Department of Energy has been ongoing for many years: SuperTruck I (2010–2016, US$284 million), SuperTruck II (2017–2021, US$160 million) and SuperTruck III (2022–2025, US$100 million). Yet, also in this case, the potential is enormous 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. The recent funding efforts of the European Union to develop low-carbon solutions for marine vessels, where the versatility and adaptability of ORC systems are unique, are worthy of note.

Table 6.2: Selected projects on Waste Heat Recovery from propulsive engines funded by the Framework VII, Horizon 2020 and Horizon Europe programs.

Project	Funding in M€	Topic	Power production
Small business innovation research for Transport and Smart Cities Mobility (H2020) Sector: transportation (freight) / Final TRL: 6 to 7 / Starting year: 2016			
TORC `https://cordis.europa.eu/project/id/733460`	2.1	Truck with an Organic Rankine Cycle	No
Individual fellowship (H2020) Sector: 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 an organic Rankine cycle unit for heavy-duty vehicles	No
Sustainable surface transport Sector: transportation / Final TRL: 6 / Starting year: 2011			
NOWASTE `www.nowasteproject.eu`	2.7	Engine Waste Heat Recovery and Re-Use	Yes
Decarbonizing long-distance shipping Sector: marine/long-distance shipping / Final TRL: 5+ / Starting year: 2021			
ENGIMMONIA `www.engimmonia.eu`	9.5	Focus on shipping with NH_3 as an energy vector and technology demonstration for efficiency increase (ORC technology is a side topic)	Yes
CHEK `www.projectchek.eu`	2.7	Focus on H_2 as an energy vector and technology demonstration for efficiency increase (ORC technology is a side topic)	Yes
ZHENIT `www.zhenit.eu/`	4.4	Integrate ORC systems for WHR onboard vessels for 25% energy consumption reduction	Yes

6.2 Ideas for Improved Support of Technology Development

Even though several 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.

Analysts worldwide agree on the fact that, today, these technologies are economically self-sustainable and do not need further economic support [138], [139]. 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%, respectively, between 2010 and 2020, reaching cost competitiveness without subsidies in several regions worldwide [139]. 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 [140].

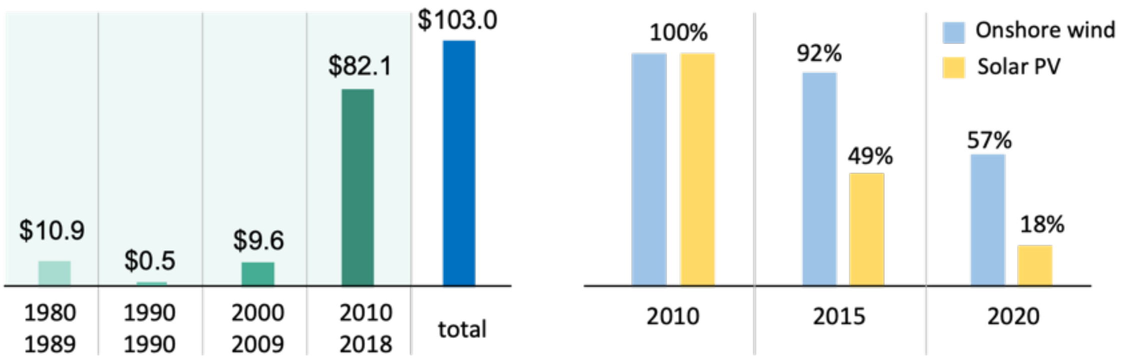


Figure 6.3: Tax subsidies (billions of US$) for renewable energies (all technologies) in the United States of America (left) and overnight capital cost of onshore wind and solar photovoltaic (right) over the years [139]

Skid mounted ORC unit (courtesy of RANK).

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 digitalized EU energy market;
3. prioritizing 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) [76], 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 technology – ETIPoRc is proposed**. This platform would be responsible for placing in the correct evidence the role that waste heat recovery must have in the clean energy transition and would make sure that policy-makers 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. ETIPoRc would support the implementation of the Sustainable Energy Technology plan and would provide a roadmap regarding the Research and Innovation actions that are needed to accomplish the goals of the plan. The platform would be led by a Board of members belonging to industry, academia and research institutes and would 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 actions would be 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 would arguably be measurable only after five to ten years from its ending.

ETIPoRc would liaise with the **European Energy Research Alliance (EERA)**, a non-profit, membership-based association bringing together 250 universities and public research centers 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 catalyze European energy research to attain the objectives defined in the SET-Plan and its clean energy transition strategy. EERA is comprised of 18 Joint Programs (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 in Industrial Processes*,
- *Economic, Environmental and Social Impacts of the Energy Transition (e3s)*,
- *Energy Systems Integration*,
- *Geothermal Energy*.

However, none of these JP's provides the specific framework for research on organic Rankine cycle technology.

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 RD support is required 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 started in 2021 under the name of Horizon Europe, and will run until 2027. Horizon Europe provides funding opportunities for Waste Heat Recovery technologies. However, most of the allocated resources focus on waste-heat-to-heat, some on waste-heat upgrade and just a handful on waste-heat-to-power. This is a shortcoming for it restrains the unleashing of the true potential of thermal energy harvesting.

The main action proposed is the creation of the European Technology & Innovation Platform on organic Rankine cycle technology – ETIPoRc (ETIPoRc), representing all the stakeholders and having as its mission the support of policy makers and the contribution to the 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. ETIPoRc would thus inform policymakers on how to maintain Europe's global leadership in the area of flexible (waste) heat-to-power conversion technology with the ultimate goal to accomplish the Climate and Energy objectives for decarbonization and sustainability.

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 propulsive 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 generated electricity is CO_2-free, decentralized and dispatchable.
  - ORC power plants are the most flexible and efficient waste-heat-to-power technology as they are suitable for all sorts of waste heat sources, at vastly different temperature and capacity levels.
- Data reported by recent literature states that the potential for electricity generation from waste heat from industrial processes is approximately 300 TWh_e/yr in 2018. This amounts to almost 10% of the 3050 TWh_e/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_e/yr of electricity could be generated[1]. This estimate is very, perhaps excessively, cautionary. This is equivalent to the annual electricity production of 19 large nuclear plants of 1 GW_e capacity each, or to the summation of the yearly electricity consumption of the Netherlands and Denmark in 2023 (155 TWh_e, according to Eurostat).
- The CO_2 emitted by propulsive engines (long-haul trucks, off-road vehicles, ships of all kinds, trains driven by internal combustion engines, 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 it can also improve the penetration of carbon-free and more expensive fuels like hydrogen

[1] Based on data reported in Table 4.3. It is assumed that *all* the unused thermal energy available at different temperature levels in Europe is converted into electricity by waste heat-to-power systems whose estimated conversion efficiencies are based on educated simplifying assumptions derived from the laws of Thermodynamics.

inasmuch as it increases the efficiency of any thermodynamic process discarding heat.

- European companies and research and development institutes working on the development of ORC technology and applications 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 still very small compared to the potential. If the potential is fulfilled, this will also result 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. Actions that KCORC and any other interested party should undertake in relation to all the relevant EU body of directives, regulations and plans are proposed. Opportunities for improvements have been identified for the following regulatory and policy making documents: Industrial Emissions Directive (IED), with its Best Available Techniques (BAT) definitions and Best Available Techniques Reference Documents (BREF), FuelEU Maritime regulation, EU Taxonomy regulation, European Union Trading System (ETS), Energy efficiency directive (EES), Renewable energy directive (RED), Strategic Energy Technology (SET) plan, Net-Zero Industry Act (NZIA).
- 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. The creation of a *European Technology & Innovation Platform on organic Rankine cycle* (ETIPoRc) is proposed, representing all the stakeholders of ORC technology, and with the mission of supporting policy makers and 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.

ORC power plant (courtesy of Turboden).

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ORC turbine rotor (courtesy of Exergy International).