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Review

Waste Energy Recovery and Valorization in Internal Combustion Engines for Transportation

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Abstract: Internal Combustion Engines (ICE) are experiencing a transition era in which research and innovation are mainly pushed by environmental issues: emission reduction and fuel saving are indispensable requirements of the new technologies, otherwise the end of ICE is proposed in Europe. Modifications, in reality, are under discussion by 2026 but the environmental issues are anyway welcomed. In the transportation sector, today dominated by ICEs, it appears that the reduction in the propulsion power, hybridization at various degrees, and exhaust post-treatment improvements will guarantee technological solutions able to support the transition in the next couple of decades toward full electric propulsion. Waste Heat Recovery (WHR) is a very interesting opportunity since almost two-thirds of fuel energy is not converted into mechanically useful energy. Moreover, the integration with other thermal streams on board (cooling and lubricating mediums, EGR cooling) can add further value to the recovery opportunity as well as the concept of managing the engine thermal management which can produce a sensible contribution that is appreciated mainly during urban driving. A huge scientific effort is underway, and a great expectation is perceptible. More generally, the technological options that can achieve a reduction in overall fuel consumption and, thus, the improvement of global engine efficiency, are the most valuable when they can be introduced without massive changes to the engine layout. This happens in all the energy applications in which ICEs are involved since the recovery unit can be introduced in the exhaust line. The mechanical energy recovered can be easily transformed into electrical energy, so represents an interesting integration with the hybrid propulsion powertrains. In this paper, a review of the most important technologies referred to the WHR is presented, outlining advantages and drawbacks, and setting up the presently available technologies referred to the transportation sector.

Keywords: waste heat recovery; internal combustion engines; efficiency

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1. Introduction

In the framework of reducing fuel consumption and related CO_2 emissions, energy recovery plays a crucial role, having the possibility to fulfill the same final energy requests with a reduction in the overall primary energy needed.

In fact, the worldwide total final consumption is about 10 Gtoe in 2019, and the main sectors involved are residential, transportation, industry, and commercial (Figure 1, where the values of each curve are cumulated to that of the bottomed ones [1]). In particular, the transportation sector is responsible for 29% of this value, with related carbon dioxide emissions which overcome 8 Gt/y in 2019, with a reduction experienced in the last two years due to the Covid pandemic [2]. Within this sector, road transportation is more than 77%, while aviation and shipping stand at around 11% and rail slightly overcomes 1% in 2021 (Figure 2, [2]). A recent European directive [3] aims to switch road transportation to rail and inland waterways, in order to improve the sustainability of the system and contribute to carbon neutrality [4]. Despite the great technological effort reversed toward decarbonization and the political pronunciations agreed by international agreements today binding, the fossil fuel economy seems to be still stronger. Carbon emissions significantly have grown inexorably, even during the last decade, when the awareness of climate change was increased and evidence of it on the ecosystems can no longer be denied.

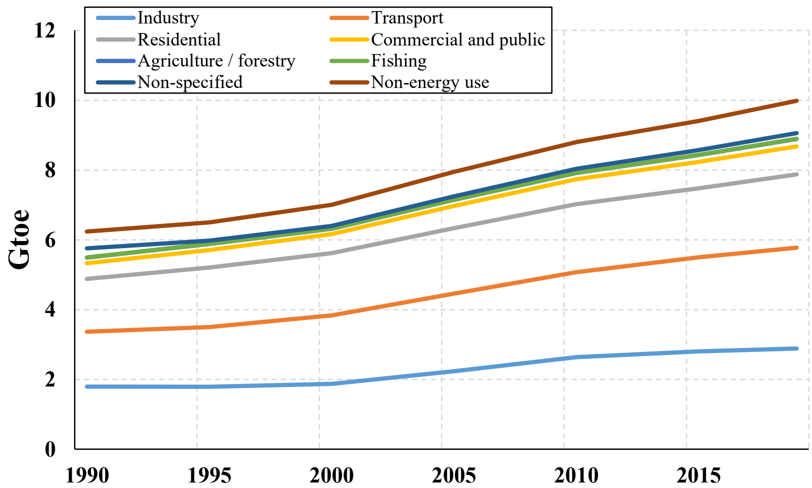


Figure 1. World total final consumption by sector: each curve is stacked with the bottomed others [1].

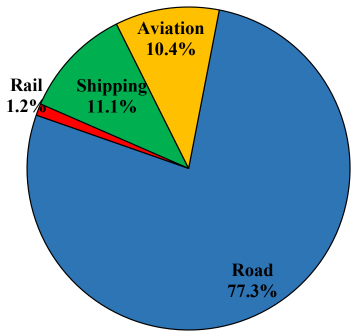


Figure 2. Breakdown of CO_2 emissions in the transportation sector [2].

Internal combustion engines (ICEs) are still widely used in transportation both for conventional and hybrid vehicles, and, in particular, for heavy duty ones, both for freight and passenger transportation. Moreover, it is also the main propulsion system for marine applications [5]. Moreover, also about 40% of the European railways still have diesel locomotives and its substitution with electrified rail will need a significant great infrastructure effort that requires several years and huge resources [6]. The sectors cited for technological reasons are the ones more resistant to a fast technological change belonging to those sectors defined as *hard to abate*, together with a wide series of industrial needs.

Hence, the need to increase engine efficiency and recover wasted energy is mandatory in the transition era for more sustainable transport, rightly matching technology availability and political commitments. In this regard, Waste Heat Recovery (WHR) finalized to mechanical/electrical conversion is seen as a viable way to reduce energy consumption and related CO_2 emissions in the transportation sector, [7]. It is just worth observing that WHR has a multiplicity of applications of reduced power sizes in the industrial sector at various temperature levels, achieving the same if not superior benefit, with basically the same technology. ICEs, in fact, are also used in industrial applications and residential, too, thanks to their high flexibility and modularity. In the first case, usually, the recovered power can be huge, since industrial streams have high flow rates and powers; in the second case, residential applications are characterized by very low recoverable powers (<10 kW), making the challenge to have reasonable efficiencies and suitable components very strong [8]. For streams above 500 °C several viable solutions have been set in the industry and significant examples of waste heat recovery options are implemented also for lower temperature streams and to face the need for energy efficiency improvement [9,10]. In this regard, the thermal energy recovery can be accounted also for Combined Heat and Power (CHP) opportunity [11]. Combination with solar and, in general, renewable energies, gives another degree of sustainable application [12,13], opening also to solar cooling and trigeneration [14], and integration with other energy systems (hydrogen production and storage, desalination, drying, etc. [15,16]). More recently, the integration of the waste heat recovery section to mitigate the penalty on Carbon Capture and Storage technologies has also been explored [17,18]. Industrial streams usually discharged into the atmosphere are, as well, very frequent and could be a source of significant recoverable energy.

Summarizing, the possibility to exploit different fluids as upper thermal sources, and with different temperature levels, make ICEs (Internal Combustion Engines) the most used device for energy recovery and CHP applications [19]. Indeed, roughly only one-third of the fuel energy is converted to mechanical power, one third is disposed to the environment as sensible heat, and one-third is wasted through exhaust gases (Figure 3).

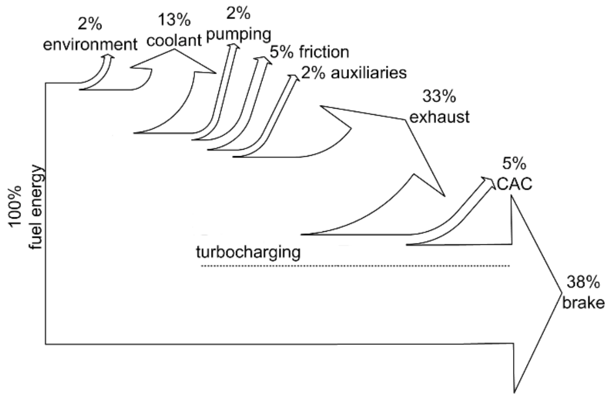


Figure 3. Sankey diagram of conventional ICE [20].

Typical exhaust temperature ranges for different kinds of internal combustion engines are shown in Table 1: natural gas and gasoline-fueled engine are those that have higher values, are very close to each other and always in an air/fuel ratio close to stoichiometric one [21]. In diesel compression ignition engines, the load is controlled by changing the air/fuel ratio, and, so, they have lower average gas temperature and higher range of variation [22]. The strategy of fuel injection has also an influence on the temperature of the exhaust gases [23]. On the other hand, the exhaust mass flow rate is strongly dependent on the overall displacement of the engine, the charging technique of the intake air (i.e., naturally aspirated, turbocharging, supercharging), and the rotational speed [24].

Table 1. Exhaust temperature of different engine types.

Engine Type	Gasoline SI Engine	Natural Gas SI Engine	Diesel CI
Exhaust temperature range	*600–650 °C*	*550–600 °C*	*200–450 °C*

Hence, the enthalpy content owned by the exhaust gases can be calculated as in Equation (1).

$$P_{th,exh} = m_{exh} \cdot c_{p,exh} \cdot (T_{exh} - T_{env}) \quad (1)$$

Other energy flows in internal combustion engines from which WHR can be conducted are represented by the cooling circuit, the lubricant and the charge air (including EGR cooler) [25]. In vehicular applications, also the air conditioning circuit for cabin cooling is a thermal utilization opportunity. The condenser must be cooled and it can be treated as a thermal source for further recovery, while the evaporator produces a useful cooling effect.

Its integration in a more complex architecture of thermal management can involve overall optimization and it can act as a thermal sink in particular operating conditions [26,27].

The temperature level of the engine should be kept under control, in order to avoid thermal distortions of the block and to guarantee optimal temperature for the engine head, avoiding quenching on the cylinder wall, but keeping the intake air manifold and runners at a sufficiently low temperature level [28]. This is usually realized by a cooling circuit, controlled by a three-way thermostat. It is closed when the engine is warming up, recirculating the coolant (usually water/glycol mixture 50/50) in the engine; while, when the temperature rises over the optimal threshold value, it gradually opens towards a branch of the circuit where the excess thermal power is disposed in a radiator crossed by environmental air [29]. In marine applications, the cooling medium can be seawater, oil, or other fluids, due to the higher amount of energy to be disposed of [30,31]. The operating temperature of the engine is within 70–90 °C, sometimes a little higher if the cooling circuit is slightly pressurized to avoid boiling. This temperature level can still be interesting for medium-low temperature heat recovery [32,33]. The thermal power disposed of in the radiator can be estimated as in Equation (2), by knowing the instantaneous coolant flow rate circulating in it and the external temperature, hypothesizing a temperature approach point equal to zero, thanks to the high external air flow rate [34].

$$P_{th,coolant} = m_{coolant} \cdot c_{coolant} \cdot (T_{eng} - T_{env}) \tag{2}$$

Coolant circuits will be needed also for electrical components: batteries, electronic power control devices, electric motors/generators, and fuel cells [35–37]. This opens the application of WHRs and overall thermal management, also, in electrified and hybrid vehicles [38,39]. This sensibly widens the applications of recovering wasting heat, sustaining the transition with gradualism sustaining the ICE improvement as is it needed considering the role it will still have in the future.

The lubricant oil plays a crucial role to reduce friction, but its viscosity is strongly dependent on temperature and it should be quickly warmed up, also by directly using the wasted heat [40,41]. On the other hand, higher temperatures lead to thermal degradation of the fluid, so its optimal temperature level lies in the range of 80–110 °C. It is usually cooled by the same engine coolant fluid in a dedicated heat exchanger and the mass flow rates involved are low, so its contribution to possible energy recovery is not often considered.

In a supercharged engine, charge air is pressurized by a compressor in order to increase the volumetric efficiency of the engine and boost the power produced. So, compressed air must be cooled down before filling. Usually, an air-cooled heat exchanger (charge air cooler) is used for this purpose, and a WHR can be proposed also in this section. The temperature level is strictly dependent on the compression ratio (i.e., engine boost pressure), but it can reach 100–150 °C in some engine operating points [42,43]. A cooling down to 50–60 °C must be insured. The thermal power available for recovery can be calculated by knowing the charge air mass flow rate and the temperature at the compressor exit. Hypothesizing a full cooling down to the environmental temperature, Equation (3) gives the available heat:

$$P_{th,CAC} = m_{air} \cdot c_{p,air} \cdot (T_{Compressor\ exit} - T_{env}) \tag{3}$$

The great part of modern engines, finally, has an Exhaust Gas Recirculating (EGR) section, in order to reduce the NOx formation and its related tailpipe pollution. When a percentage of the exhaust gas is recirculated into the intake manifold, it should be strongly cooled down to not vanish the supercharging effect and to avoid abnormal combustions and reduced combustion efficiency. Therefore, an EGR cooler is always needed: the temperature of the gas from which a WHR can be conducted can be very high and variable (Table 1). The potential thermal power recoverable can be estimated according to Equation (4) considering as reference temperature the one of the environment:

$$P_{th,EGR} = m_{EGR} \cdot c_{p,exh} \cdot (T_{GAS} - T_{env}) \tag{4}$$

According to the previous equations, the heat available from the cited streams is transferred inside a heat exchanger, eventually favoring the vaporization and superheating of a low boiling fluid (i.e., Heat Recovery Vapor Generator, HRVG). The superheated fluid can perform a thermodynamic cycle and produce mechanical work. This WHR is said to accomplish an *indirect transformation* into mechanical power and this applies to a plurality of hot sources.

When the heat to be recovered is from exhaust gases, a *direct heat conversion into mechanical work* is also possible. The high enthalpy of the fluid can be used to favor an expansion thanks to the high temperature and a pressure level greater than the ambient one. This will produce direct mechanical useful work. The exhaust gas leaving the expander still has a high temperature and a useful pressure level to cross the exhaust pipe and to avoid water condensation.

In this paper, a review of both waste heat recoveries has been assessed, particularly focusing on ICEs used for on-road transportation. A further step is conducted considering the possible valorization of the energy recovered on board in mechanical and electrical form.

2. Waste Heat Recovery Opportunities

In this work, several opportunities to recover waste energy from ICEs have been reviewed, categorizing them, as already introduced, in two main different technological options according to the nature of the working fluid. Table 2 summarizes the different recovery options discussed in this paper and categorized as:

- Direct Heat Recovery, DHR, using the same exhaust gases to produce additional power.
- Indirect Heat Recovery, IHR, using a different working fluid as a heat transfer medium, following a sequence of transformations (cycle) whose result is the production of work.

Table 2. Summary of WHR technologies discussed in this paper.

Direct Heat Recovery Options	*Indirect Heat Recovery Options*
Turbocompound	Organic Rankine Cycle (ORC)
Thermoelectric	Stirling Cycle
Thermoacoustic	Combined Cycles
Inverted Brayton Cycle	Trilateral Flash Cycles (TFC)
Direct heat utilization	

2.1. DHR via Turbocompounding

Turbocompounding can be viewed as the most mature technology to recover waste energy directly from exhaust gases. It tries to exploit the residual enthalpy owned by the exhausts, which generally leaves the engine at high temperature and also a not negligible pressure (1–4 bar_{abs}, [44,45]), so making possible an expansion phase, usually realized by a dynamic turbine [46]. Hence, it behaves as a turbocharger stage [47], where the turbine is coupled to a compressor for engine intake air charging; alternatively, the recovery turbine can be mechanically linked directly to the engine crankshaft, giving power to the wheels [48,49], or a further energy conversion with an electrical machine can be introduced exploiting the energy recovered in the electrical form [50]. This configuration is interesting from a technical point-of-view since it consents to regulate the speed of the turbocharger in order to match the boost requirements of the engine, avoiding waste gate valves. It is particularly suitable for hybrid electric vehicles, where the optimization of a range extender engine can be maximized and the electrical energy recovered more easily stored and exploited [51,52].

In order to increase the exploitation of the enthalpy of the exhaust gas, an electric motor-generator on the turbocharger shaft can be placed (Figure 4a) building an easy direct recovery system. In this case, the increased complexity of the control system would correspond to the mechanical simplicity. In fact, the expansion should feed the compressor to reach the requested intake air boost pressure. The remaining power delivered by the turbine can be transformed into electrical power thanks to a motor/generator machine on the same shaft. During transient conditions, the electrical machine can boost the compressor, limiting the turbo-lag [53,54]. The control system should have the boost pressure requested by the compressor as a controlled variable by estimating the mechanical power requested and leaving the residual mechanical power eventually delivered by the turbine to the electrical generator. The same control system, when the turbo-lag is present, will dispatch the mechanical power delivered by the electrical machine which behaves as an electric motor, accelerating the compressor speed. Critical aspects related to the reliability and efficiency of the electrical machines can be present, considering their high speed of rotation (100–150 kRPM) and the high operating temperatures that limit the capabilities of the electronics [55].

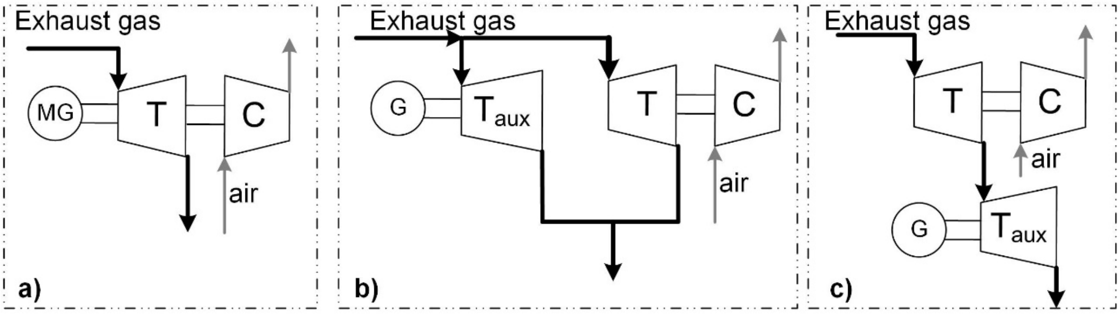


Figure 4. Direct expansion recovery configurations: (**a**) electrical motor-generator on turbocharging; (**b**) parallel turbine and (**c**) series turbine.

A parallel turbine can be proposed (Figure 4b), recovering also the enthalpy loss in the turbocharging control stage, conducted with a waste-gate or by varying the position of the inlet nozzle of the turbine (variable geometry turbine, VGT) [56,57]. The management of the turbo-lag reduction is not possible being the auxiliary turbine not mechanically linked with the one which drives the compressor. Additionally, in this case, a control system shares the two exhaust gas flow rates, giving priority to the boost pressure. An additional turbine placed downstream of the turbocharger (Figure 4c) seems the simplest possibility and it has the added value to be a kind of plug-in component, allowing a retrofitting system. The interference on the engine exhaust backpressure should not be neglected [58].

Generally speaking, turbocompounded engines improve fuel economy with low weight requirements and low encumbrances on board. In every configuration presented the recovery is strictly dependent on the engine displacement and its working point considered, while the turbocharger regulation strategy (waste-gate or VGT) influences more the operating condition. The introduction of two-stages or twin turbines can improve the recovery and the fuel consumption reduction, but further increase the complexity of the layout [59]. However, the final recovered power is demonstrated that could sum up to 18–20% of the engine's brake power [57,60,61].

Turbocompounding can also enable the engine to introduce delayed ignition timing, a higher EGR rate with reduced NOx, and faster time response during transients [62]. The degree of freedom in engine design is increased by turbocompounding: several parameters can be optimized in the system, such as size, expansion ratio, efficiency and rotational speed of recovery turbine, exhaust manifold geometry, air-fuel equivalence ratio, engine boost pressure, engine compression ratio, intake and exhaust valves timings, the start of combustion timing, EGR systems, and exhaust after-treatment placement. In the development of turbocompounded engines and for the selection of the configuration, increased attention should be paid to the turbine efficiency and the augmented pumping work on the engine [63]. In fact, when turbocompounding is considered, turbine efficiency plays a crucial role. Turbine design should consider variable geometry and revolution speeds to be set up to deal with various working conditions. The main limitations, indeed, are related to the low efficiency of the recovery turbine, which limits the useful power. The additional exhaust back-pressure on the engine represented by the crossing of the exhaust gas through the turbines leads to higher pumping loss seen by the engine which increases PMEP and reduces engine efficiency [62,63] vanishing part of the recovery. The problem with the turbine efficiency is real since usually during engine operations its efficiency is sensibly low [64]. Electrical machines also suffer low efficiencies when they rotate at high speed; hence, a gear or a Continuous Variable Transmission (CVT) could be used to reduce the shaft speed [49,63] at the electrical machine side.

2.2. DHR via Inverted Brayton Cycle (IBC)

The inverted Brayton cycle is a novel recovery option not yet fully explored in the literature and with very few experimental tests [65]. It makes use of the exhaust gases as a working fluid, so acting as a direct recovery. The gases are under-expanded below atmospheric pressure in a recovery turbine (sections 1–2 in Figure 5). They are cooled down (sections 2–3 in Figure 5) before the re-compression is required to bring them again at a pressure slightly higher than the environment to make their evacuation possible in the atmosphere (transformation 3–4 in Figure 5). Hence, an IBC-based unit is composed of a recovery turbine, coupled to the same shaft with a compressor, and an IBC cooler between them (Figure 5) [66,67]. T_{gas} (or T_1) is the temperature of the gas considered for direct energy recovery (i.e., to be expanded): its value depends on the exhaust stream considered and the specific operating point. In order to be suitable for this kind of energy recovery, it should be higher than about 400 °C [68], otherwise, the energy produced during the expansion is not sufficient to drive the IBC compressor and to have net positive energy recovered. T_{env} is the environmental temperature and represents the low boundary limit of the IBC: T_3 is the lower temperature of the gas reached within the IBC and it should be as close as possible to T_{env}, in order to reduce the power requested by the compressor as much as possible to bring the gas to environmental pressure. Therefore, the cooling phase from IBC sections 2 to 3 is crucial, but it is usually constrained by the thermal sink availability [68]. Pressure after re-compression p_4 is close to the environmental one: only a slightly higher value (5–10 mbar) is needed to be sure of the evacuation of the gases. On the other hand, p_1 usually ranged from 1.2 to 2 bar_{abs} and depends on the specific layout of the engine exhausts (for instance, the presence of the turbocharging with its control device) and it is surely modified by the presence of the IBC turbine, which definitively imposes backpressure on the engine exhaust. p_3 is the subatmospheric value, and it cannot be pushed down to 0.3–0.4 bar_{abs}. Hence, from an energetic point of view, the low-pressure ratio in the turbine represents a drawback and limits the cycle efficiency and, finally, the overall IBC unit recovery efficiency, which is not higher than 8% [69].

From a technological point of view, the efficiencies of both the turbine and compressor have a great influence on the final recovery, as well as the effectiveness of the IBC cooler [68,70]. The need for a reliable control strategy on the rotational speed of the IBC turbine-compressor shaft is mandatory to guarantee gas evacuation to the environment, maximize efficiency and minimize the impact on engine backpressure and eventual turbocharging regulation [71,72]. The vacuum management on board can represent an issue, but the possibility to exploit mature technology for machinery and other components makes this recovery option competitive with other opportunities with similar theoretical final recovered energy (in the range between 2 and 5% of the engine brake power) [73,74]. Other concerns can be related to the presence of water condensation before final compression, but it can be managed quite easily considering the low pressure profiles [75,76]. Moreover, the IBC does not prevent the possibility to introduce a cascade indirect recovery on the IBC cooler, combining two different recovery options [77] or introducing a regenerative heat exchanger to improve the applicability to low temperature hot sources [78,79]. Definitively, IBC applications are suitable for energy recovery in steady applications from internal combustion engines, such as industrial devices [80,81], gas turbines and combined cycle power plants [82,83], marine transportation, and CHP configurations [84,85].

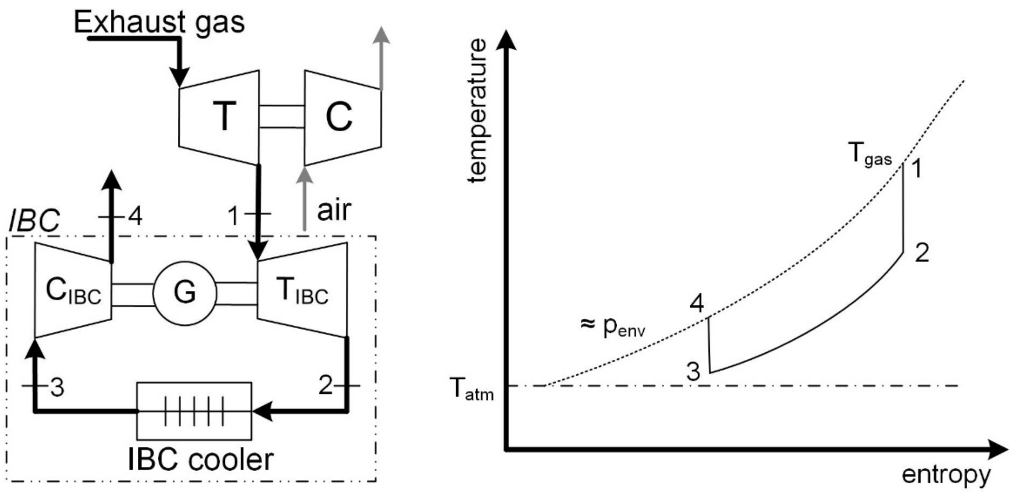


Figure 5. IBC layout and simple T-s diagram. Straight line is the IBC thermodynamic cycle, dotted one is the isobaric curve at environmental pressure, dashed-dot line is the isothermal line at atmospheriric temperature.

2.3. DHR via Thermolectric Generation

The thermoelectric generator (TEG), as one of the WHR systems, can convert part of the wasted thermal power of the exhaust gas directly into electricity thanks to the Seebeck effect. So, it can be categorized as a direct recovery. Its main advantages are related to light-weight, silent operation, and compactness, making it more attractive for light-duty vehicles and passenger cars [86], although applications on larger engines (marine transportation) have also been studied [87]. This direct conversion is very interesting, but the very low efficiency of thermoelectric materials is the major problem, which leads to very low power recoverable [88]. Despite the power producible from each TEG module being only a few Watts, a recovery efficiency equal to 7% of the exhaust gas energy has been demonstrated (so, similar values can be referred to the engine brake power), strongly depending on the material and its so-called figure of merit [89–91].

The shape of the heat exchanger used for TEG can increase the backpressure on the engine exhaust, which raises the pumping mean effective pressure of the ICE, enhances the hot side temperature of the TEG and its maximum output power, and the effects on the brake power, brake torque, engine efficiency, and fuel consumption should be considered in an integrated way [92]. The heat transfer on the cold side should also be improved, in order to increase the TEG efficiency: higher performance can be obtained by using enhanced cooling media, such as nanofluid-based ones [93]. The thermoelectric cells could be arranged according to different shapes in order to make different contributions possible from different exhausted heats. An easy recovery, for instance, could be realized opportunely by shaping the heat exchanger, substituting the ones present on the cooling or lubricating circuits, and also on the exhaust gas [94,95].

Its application in hybrid vehicles is also interesting. In an urban driving cycle, the application of TEG in a series of hybrid vehicles shows better fuel economy than with integration into the conventional vehicle. However, in a highway driving cycle, the fuel-saving effect of the thermoelectric generator integrated into the conventional vehicle is better [96]. The combination with other energy recovery in cascade opportunities is possible since a certain amount of thermal energy is still available [97].

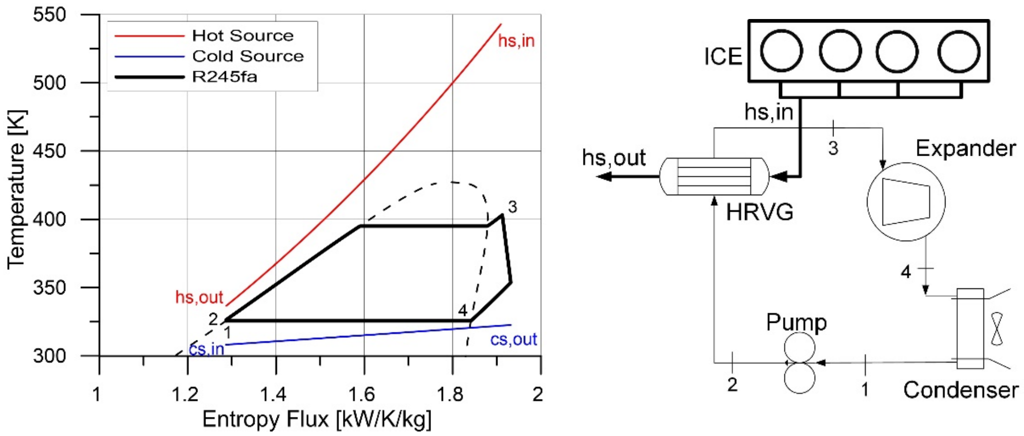
2.4. IHR via Thermodynamic Cycles

As already presented, when the energy recovery is realized with a different fluid, and not acting directly with the exhaust gases, it can be categorized as indirect heat recovery. This principally referred to recovery options that use the thermal power of the exhausts to feed a bottomed thermodynamic cycle whose net output is the production of work and residual heat to be discharged at low temperatures. On the gas side, the heat exchanger used to capture the exhaust energy is the crucial component. It should be small, and light, with high exchange coefficients, low thermal inertia, and very low pressure drops [98,99]. This latter is the main limitation, since the pressure drop produced on the exhaust side causes a backpressure increase on the engine, with higher fuel consumption as a consequence [100,101]. The reduced weight avoids the increase in the propulsion power of a vehicle and a suitable design can reduce the incumbrance which is a problem on vehicles of reduced dimensions. Definitively, hot and cold sources are represented by exhaust gases and the environment, so requiring optimized heat exchangers.

Few cycles can be used for this purpose: Rankine cycles are the most studied, in particular with organic fluid as working fluid (ORC) due to the low boiling temperature which corresponds to low pressure values which makes easier and cheaper the construction of the recovery unit. Additionally, the Brayton cycle can be used when the thermodynamic working fluid is a gas, but it is not so studied in the transportation sector. Other innovative cycles try to improve the overall efficiency of the recovery, introducing cascade cycles, internal heat exchangers and multiple evaporation pressures, zeotropic mixtures as working fluids and wet expansion in Trilateral flash cycles (TFC). The Stirling cycle has also been proposed for its quite simple implementation.

2.4.1. IHR via Organic Rankine Cycles

The Organic Rankine Cycle (ORC) is by far the most studied opportunity in waste heat recovery: it is very similar to the steam Rankine cycle but uses a working fluid of an organic nature (Figure 6a,b). This consents to the recovery from low-grade thermal sources [102]. An ORC-based recovery unit is composed of a heat exchanger acting as an evaporator (or Heat Recovery Vapor Generator, HRVG, from section 2 to 3), an expander or turbine (state points 3–4), a condenser (4–1) and a pump (1–2). Some other components can be introduced for efficiency optimization or plant operability (such as a tank/reservoir, a bypass branch for the turbine, an internal heat exchanger for the regeneration stage, etc.) [103].



(a) (b)

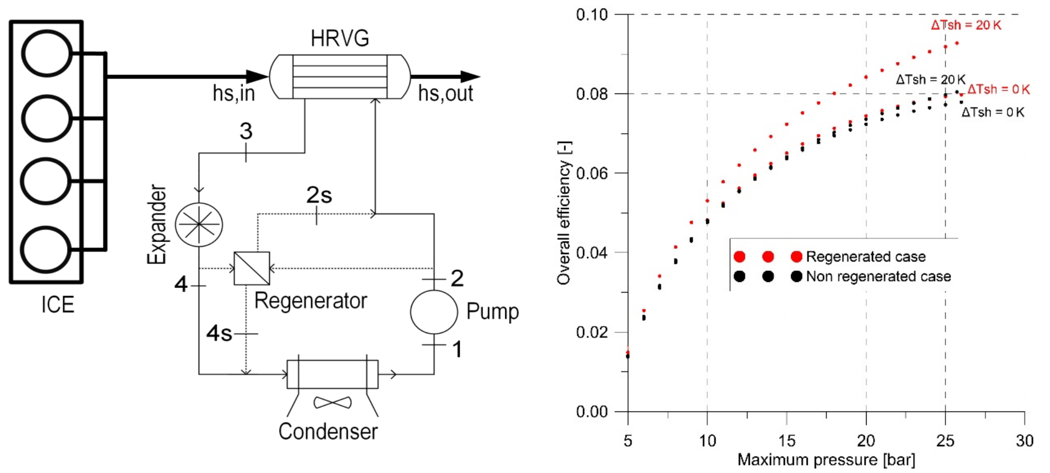
Figure 6. (a) base T-s diagram of an Organic Rankine Cycle bottomed to exhaust gas and using R245fa as working fluid (dashed line is the saturation curve of the fluid)); (b) base layout of ORC unit.

It is quite commercial for different applications (industrial, geothermal) but it has been studied only in recent years for the transportation sector, in particular for heavy-duty applications. For light-duty and passenger cars, the higher variability of the waste heat temperature and amount (for instance, exhaust mass flow rate) makes it difficult to implement a high-efficiency recovery plant in operating conditions [104].

Several adjustments on the base cycle have been proposed, which are promising solutions from a thermodynamic point of view [13]; real experimental data for low-temperature heat recovery also on scaled-down pilot plants are scarce. Every experimental testing agreed with a potential which is around 5–6% of overall net efficiency [105,106], although thermodynamic efficiencies of the ORC can overcome 20% also in experimental and numerical activities in design conditions [107]. Indeed, the final efficiency of a recovery plant is strongly determined also by the conversion efficiency of the machinery and the components needed for the production of a kind of energy really usable, as well as the often off-design conditions achieved in real operation [108,109].

From a thermodynamic point of view, the superheating degree (ΔTsh) can be important, but it is limited by the degradation of the fluid and the operability of the components (i.e., high pressure and temperature management) [100]. The need for always higher efficiency, in order to increase the potential power production, opens to systematic optimization towards supercritical and transcritical cycles, but high pressures and unconventional working fluids limit this kind of application [110].

The need to improve the efficiency of the recovery unit, which is usually so low to be on the borderline of having an energetic advantage, opens the possibility of a regeneration stage, mainly realized through an internal heat recovery (Figure 7a, section 2-2s to 4-4s). This is suggested also by the thermodynamics of the cycle, where the expansion phase ends in superheated vapor due to the dry nature of the fluid, and is useful for an internal recovery towards the heating phase of the liquid before evaporation [111,112]. The improvement in the thermal efficiency can be significant (a few percentage points, Figure 7b) but with the increased complexity of the circuit, which reflects in higher weight and encumbrances, it is not suitable for low space required applications, and higher investment costs [113]. However, the regenerated cycle reduces the recoverable thermal power at the upper source, introducing a trade-off with the increased cycle efficiency. So, the design of the unit should be conducted considering the whole power produced and not only the efficiency itself. The mechanical power producible is the product between the mass flow rate of the working fluid and the mechanical work, related to the efficiency. Following the different criteria, the effect on the sizing of the component can be evaluated, paying particular attention to the heat exchangers (evaporator, condenser, and regenerator) [114].



(**a**) (**b**)

Figure 7. (**a**) layout of a regenerated ORC; (**b**) comparison with base cycle in terms of thermodynamic efficiency as a function of cycle top pressure and superheating degree [112].

A double pressure evaporator can also be proposed in order to fully exploit the thermal energy of the upper source [115,116]; the net power output can be increased up to 15% thanks to the double-pressure layout [117]. Expander selection and design is an open issue and a relevant number of studies are devoted to its design, implementation, optimization and operating conditions evaluation, both in numerical and experimental ways [118–120]. In general, expanders can be categorized as dynamic and volumetric ones [121]. Dynamic expanders also called turbomachines are limited by constraints in small ORC units, such as high rotational speeds, with the need for gear and specific lubrication [122,123]. In addition, the development of turbomachines is usually more expensive, making them more suitable for larger-scale plants [124]. Concerning volumetric machines, they are characterized by lower shaft speeds and a pressure ratio dependent on the built-in volume ratio, so constrained by the design geometry. This includes the production of different losses: under- or over-expansion, leakages, friction, and heat losses. However, they are more flexible and capable to work in off-design conditions, especially if a non-completely dry expansion is realized [125].

Therefore, the optimization of the expander is under investigation, in particular considering volumetric ones, where the mismatch between the discharge pressure and the condenser one (which produces high losses in off-design conditions) is an open issue, and it can be mitigated by introducing more complex opportunities: variable geometry expanders [126], variable expansion ratio [127] or variable speed [128] and parallel machines [129]. In addition, a kind of supercharging technique for the expander has been tested, in order to increase the flexibility of the machine and its field of operation [130,131].

The optimization of the recovery requires a control strategy, which contemplates different regulation parameters, such as the mass flow rate and the inlet pressure of the expander [132,133], related together by the permeability of the circuit [134], the revolution speed of the expander [135], or acting on the upper thermal source and, as well as possible, on the cold sink to keep the ORC closer to the design conditions. Machine learning techniques and neural networks have also been proposed to optimize the control of the ORC recovery unit [136,137].

One of the disadvantages is related to ORC thermal inertia, which makes it difficult to follow the dynamics of the engine in light-duty road applications. Therefore, applications, where the engine is run in a steadier way, are more suitable, such as marine engines [138,139], railway locomotives [140], truck and long-hauling transportation vehicles [141,142], and hybrid ones [143,144]. This aspect is usually neglected in the literature, but the dynamics of the ORC are significantly slow, and the final efficiency of the recovery can result in strongly reduced with respect to expectations based on steady or quasi-steady analysis [145].

2.4.2. IHR via Trilateral Flash cycle (TFC)

Trilateral Flash Cycle (TFC), or Organic Flash Cycle (OFC), is a bottoming thermodynamic cycle particularly suitable for low-temperature waste heat recovery, around 80–100 °C [146,147]. The name "Trilateral" highlights the shape of the cycle, which is almost triangular (Figure 8) and it is particularly suitable for that kind of upper thermal sources that do not match with a Rankine or Hirn cycle. So, it can be interesting for very low temperature sources and limited flows of fluid cooling, or for cascade cycle, bottoming to a main recovery unit to further increase the final energy produced. The shape of the T-s diagram at the saturated liquid side can add some additional interest to the exploitation of this technology. It is based on a Rankine cycle in which the vaporization is not realized, but a saturated liquid is expanded. Hence, it is composed of a pump, a simple heat exchanger used to heat up the high pressure working fluid to the saturated liquid state and so, a wet expansion within the two-phase region and a final condensation [148].

The difficulties to recover energy in the two-phase region of the fluid (wet expansion) suggest using volumetric machines as expanders and, preferably, with a variable volume ratio [149]. As shown in Figure 8, the possibility to increase the exergy recovered is great (i.e., the closer the value of the TFC to the upper and lower thermal source/sink), but only if the expander efficiency is close to the one of a conventional turbine; TFC can compete with ORC in terms of final energetic efficiency [150]. More recently, the use of fluid mixtures has also been proposed to increase the efficiency of the OFC [151].

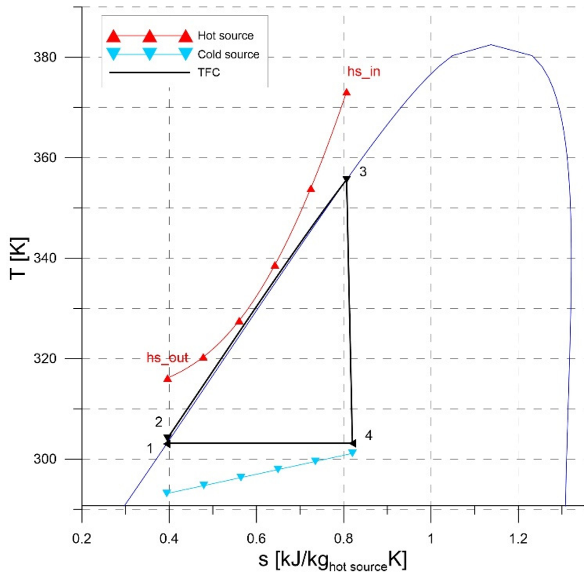


Figure 8. TFC T-S diagram [152]: transformation 1–2 is a pressurization in the liquid phase, 2–3 heating of the liquid, 3–4 is the wet expansion, 4–1 the condensation. Dark blue line is the saturation curve of the working fluid (R1234ze(E)).

2.4.3. IHR via Cycles with Zeotropic Mixtures as Working Fluids

The selection of working fluids is one of the most investigated issues. It should respect several constraints and parameters: low flammability, no toxicity, low ozone depletion potential and global warming potentials, as well as other low environmental impacts. At the same time, the working fluid should have high thermodynamic performances in relation to the upper and the lower thermal sources available. Dry and isentropic fluids are suitable for ORC-based units [153]. The opportunity to be mixed with lubricating oil is an additional positive issue because volumetric expanders which are very suitable for small-size recovery units need to be lubricated to improve mechanical and volumetric efficiencies.

In this regard, the opportunity to use zeotropic mixtures (i.e., mixtures of fluids, which can vary their temperature during phase change) can have the opportunity to better approach the thermal sources and sinks during evaporation and condensation of the working fluid, thanks to the temperature glide during phase transition (Figure 9) [154].

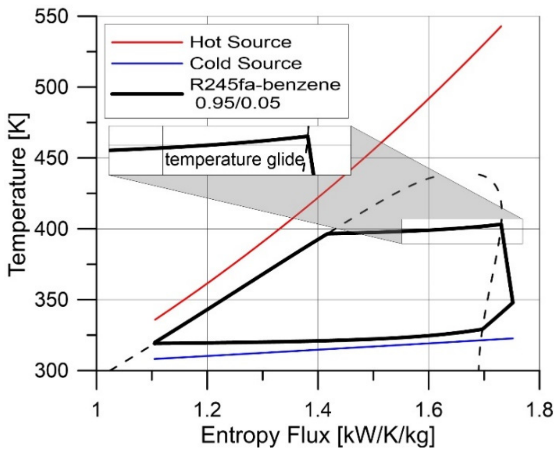


Figure 9. T-s diagram of an ORC with mixtures of working fluids [155]. Inset zoom on the temperature glide in the evaporation phase. Similar to the condensation one. Dashed line is the saturation curve of the fluid mixture (R245fa/benzene 0.95/0.05).

Several feasibility studies have been proposed, also in small units (1 kW) experimentally tested [156]. The results obtained are strictly dependent on the fluids used in mixtures: siloxanes and other hydrocarbons are very promising, but with some concerns about flammability [157]; other mixtures of fluids can involve fluorinated gases and also CO_2 (R744) [158].

2.4.4. IHR via Cascade Cycles

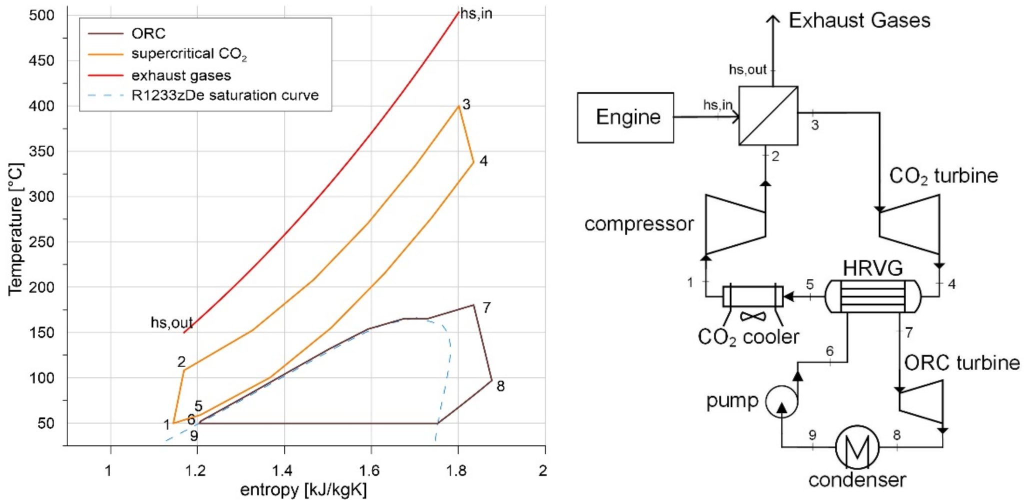
When the temperature of the upper thermal source is enough high (>300 °C, for instance), only ORC is not suitable, since it introduces a high exergy destruction rate in the heat recovery vapor generator [159]. Indeed, the influence of the pinch point temperature on the energy recovered is significant and the differentiation of the layout can be proposed to increase the recovery efficiency [160]. In particular, the combination of more than one thermodynamic cycle can be used, in a cascade form [161], in order to match the upper thermal level with one recovery section, and the cold sink with a bottomed one, increasing the exergy efficiency of the overall recovery unit [162].

The use of the CO_2 Brayton cycle is very popular, where the CO_2 is performed in the supercritical phase ($p_{c,CO2}$ = 74 bar). In particular, the CO_2 is in a dense phase when it is close to the critical point, with a thermodynamic advantage in terms of fluid density (it has a density close to the one of a liquid and it has low viscosity like a gas, increasing the mass per unit volume without increasing pressure drops across ducts) and reduced viscosity with respect to a gas. Moreover, CO_2 is a natural compound, stable, non-toxic and non-flammable, with a reduced environmental impact with respect to fluorinated gases. Thus, the supercritical CO_2 (sCO_2) topping cycle is bottomed by an ORC one, aimed to partially recover the thermal energy to be disposed of in the lower CO_2 pressure side (Figure 10a, [162]), and a trade-off between the cycle efficiency and the heat recovery must be analyzed, [163]. Only a few sCO_2 recovery plants have been manufactured and actually operated since this technology has not yet reached technical and commercial maturity [164]. Several configurations have been proposed in this regard (parallel, cascade [165], regenerative [166,167], re-heated and intercooled [168,169], recompression [170], dual expansion [171,172], etc.) in order to increase the net power output. The complexity of the recovery plant is shown in Figure 10b, where the two cascade sections are sketched. State points from 1 to 5 refer to sCO2 Brayton cycle, while 7 to 9 are referred to ORC one. The need for an additional heat exchanger (CO_2 cooler after HRVG, from state points 5 to 1) is highlighted. The management of supercritical values of CO_2 pressures can also represent a limiting factor, in particular for small-scale units, where the amount of recovery does not justify high-pressure components, piping, seals, etc., which in turn brings higher costs. In fact, the introduction of ORC as the bottoming cycle in combined recovery plants has been proposed also for medium-low temperature sources, to increase the overall energy recovered [173].

The aim to maximize energy recovery has been pursued also in combination with other thermodynamic cycles, such as IBC [174] and turbocompounds [175]. Higher performance can be achieved using also a proper mixture of fluids: the target of 40% energy efficiency has been demonstrated with a combined cycle and fluid mixture in the bottomed ORC [161].

2.4.5. IHR via Stirling Cycle

Even though the Stirling engine was discovered in the early 1800s, only recently it has been applied in several applications, especially in combination with renewable sources and as a waste heat recovery option in industry [176,177]. The Stirling cycle is a gas engine cycle composed of two isotherms and two isochore lines as an indicator diagram. A regenerator is interposed in between. Its main advantage is that the Stirling cycle does not replace the working fluid for every cycle. The working gas can be air or other gases. The overall amount of thermal energy is supplied externally from the engine, making possible the use of any kind of source. Stirling engines can achieve high thermal efficiencies, ideally the one of the Carnot cycle, since the heat exchange takes place at a constant temperature. In reality, the transformations are usually far from the ideal ones, and the real efficiency does not overcome 20–25% during operation [178].



(**a**) (**b**)

Figure 10. (**a**) example of T-s diagram of a combined energy recovery unit composed by supercritical CO_2 and ORC [162]; (**b**) simple layout of sCO_2+ ORC unit.

Stirling engines could be an interesting solution for ICE thanks to their compact design, easiness of management, application flexibility and the possibility to be adopted for different energy sources [179,180]. The power recoverable can range from hundreds of watts to kW. Different solutions of Stirling engines can be found, such as alpha, beta, and gamma configurations [181], single or double-acting cylinders [182], or free-piston operational mechanism [183].

In the ICEs, the Stirling engine can be used to exploit the thermal energy of the exhaust gases, as well as from EGR or coolant circuits. The possibility to optimize the geometry of the heater side can add an important degree of freedom to the design, in order to be integrated into the exhaust line or the other thermal sources in ICEs [184]. A very interesting application has been recently proposed in integration with ORC and latent heat thermal storage, which consents to maximize the thermal energy recovery by the exhaust gases also at different enthalpy levels, dump the temperature oscillations of the ICE exhaust and extend the application also to micro CHP configurations [185,186].

3. Technologies Comparison and Energy Valorization

All the technologies here presented can be used for effective waste heat recovery from engines in the transportation sector. Table 3 summarizes the most important figures of recovery and a comparison among the technologies reviewed. In particular, two specific parameters have been considered. Specific final power recoverable (P/P_{ICE}) is the ratio between the mechanical or electrical power producible by the recovery unit and the engine brake power: it represents the possible fuel consumption reduction in the engine and is related to the size of the engine itself. On the other hand, the efficiency of the WHR unit can be defined as the ratio between final useful power and thermal power usable and entering the recovery unit. It depends strictly on the physical mechanism of energy conversion (mainly thermodynamic). In other words, the efficiency of the recovery system is the ratio between the output power (mainly in mechanical form) and the inlet one (thermal power usable). However, according to the recovery unit optimization (which can pursue maximum specific work or efficiency or power), the components of the recovery unit are sized, and thermal power recovered (entering the recovery system) can be lower than the one entirely available and owned by the exhaust gases. This is mainly due to technological and environmental constraints. Hence, in Table 3, the efficiency evaluates the performance of the unit as it is, decoupled by the waste heat source, while P/P_{ICE} considers a relation to the engine when the WHR unit is applied.

Table 3. Summary of the technologies reviewed.

Technology	*P/P_{ICE}*	*Efficiency*	*TRL*
Turbocompound	3–20%	55–70%	9
Thermoelectric	1–7%	1–7%	8
IBC	1–5%	2–8%	4
ORC	1–6%	4–12%	7
Stirling	2–6%	10–25%	7
TFC	1–2%	5–14%	4
Combined cycles	3–7%	8–40%	3

Technology Readiness Level (TRL) is the maturity of the technology and its capability to be ready for the market in the transportation sector: it ranges from 1 to 9, where 9 is a commercial product and 1 is a system at a very early concept. Turbocompound is the most mature technology, and it is present in some vehicles. Thermoelectric devices are technologically ready, but still not economically convenient. ORC and Stirling have been proven with prototypes in operating environments, while IBC and TFC have been tested only at a laboratory scale. Combined cycles with sCO2 and ORC lack experimental demonstration applied to the transportation sector.

Hence, all the technologies presented have advantages and drawbacks for their use as waste heat recovery options from internal combustion engines in the transportation sector. Its suitability depends strictly on the thermal conditions of the streams to be used for recovery. The choice of technology should consider also the constraints related to encumbrances, weight, cost and sizing, which depend on the very specific application. Table 4 tries to summarize the positive and the negative aspects of each technology reviewed at the moment. The size of the engine and its specific application (usual duty cycle operation) as well as the expectations in terms of fuel saving can orient a choice with respect to another.

Finally, once the suitable technology is chosen, according to technological and energetic constraints and opportunities, the final energy recovery is valorized for the goals of the specific application. The thermal power recovered, indeed, can be directly used as it is for heating purposes, or converted into mechanical power and, eventually, in electrical form.

Table 4. Advantages and drawbacks of the technologies considered.

Technology	*Advantages*	*Drawbacks*
Turbocompound	Maturity Reliability Direct conversion	Backpressure effect High rotational speed for an electrical energy conversion Simultaneous turbocharging adjustment
Thermoelectric	Small size and weight Direct thermal-to-electric conversion Different sources (exhaust gas, oil, cooling fluid)	High specific cost Low specific power Materials
IBC	Very limited effect on the engine High rate of waste heat exploitation	Sub-atmospheric pressure management Needs of high efficiency machines Turbine-compressor management

Table 4. *Cont.*

Technology	*Advantages*	*Drawbacks*
ORC	Maturity Wider applicability	Low dynamic response Long energy conversion chain (efficiency) Encumbrance and weight
Stirling	Technological simplicity	Low overall efficiency Encumbrance and weight
TFC	Suitable for low grade enthalpy streams	Wet expansion Low efficiency
Combined cycles	High energetic and exergetic efficiency	Weight and space requirements System complexity and inertia Whole system management

3.1. Direct Heat Utilization

The thermal power recovered can be directly used for heating purposes, in particular for steady state applications in CHP mode. The first example usually considered, is cabin heating in automotive applications [187]: the heat removed from the engine by the coolant is partially used in a heat exchanger placed in the dashboard of the vehicle. This exchanger is crossed on one side by the hot coolant, exiting from the engine jackets, and by air on the second side, thanks to the controlled fan, which regulates the thermal power to be sent to the cabin interior. Often, the cabin heater lays in a branch of the cooling circuit in parallel with the radiator and the bypass branches, without undergoing thermostat control [188]. Additionally exhaust heat or lubricating heat can be used for this purpose, in order to optimize the thermal level [189,190]. Its integration with other thermal needs improves the overall efficiency of the system [191], for instance, accelerating the warming up of the lubricant oil, reducing frictions, and improving engine thermal management: the use of the exhaust to warm up the engine oil during cold phase demonstrated a fuel consumption reduction over 3% [192,193].

A different use of the thermal power to be disposed on board is represented by absorption chillers, which can improve the integration concept of thermal needs [194,195], feeding refrigeration, and cooling needs. Waste heat driven heat pumps can also allow low-temperature heating purposes [196,197]. The integration of absorption chillers on board can also be used for increasing the propulsion system efficiency, cooling the engine charge air [198], or optimizing the thermal management of electric devices [199,200]. In industrial applications, the integration of Rankine cycles with multiple-level refrigeration systems can meet the requirements of air-conditioning, refrigeration, and also cryogenic cooling, aiming at a full energy recovery of lost heat [201].

When applied to exhaust gases, the heat exchanger performance plays a crucial role: it should have high thermal efficiency to maximize the thermal exchange towards the working fluid of the recovery unit [202], and also in terms of backpressure increase on the engine, which should be significantly limited in order to avoid excessive overconsumption on the engine itself and tailpipe emissions [203]. The impacts of extra weight, additional cooling fan power consumption, transient control, effects on engine intake air management as well as exhaust after-treatment thermal inertia should be also considered in mobile applications [204].

3.2. Mechanical Power Production

The waste heat recovered energy is usually converted into a mechanical form in the most kind of technology here reviewed; in particular, in direct heat recovery ones or thanks to a thermodynamic cycle. Mechanical work, indeed, is the useful energy of a thermodynamic transformation or a sequence of transformations. In this way, the mechanical power is collected on a shaft, which should be coupled to the engine crankshaft. Hence, a gear could be needed to adjust the revolution speed of the expander/turbine to one of the crankshaft [205]. Other mechanical needs can take benefits from mechanical energy recovery, in particular in vehicles where the auxiliaries are so important and account also more than 10% of the average propulsive power of a vehicle, depending on mission speed profiles [206,207]: air conditioning, an air compressor for braking in heavy duty vehicles, or for doors opening and closing in buses, oleodynamic compression in off-road vehicle for lifting arms [208], but also power steering, cooling fans and pumps or other devices for fluid circulation in hybrid or CHP applications [209]. The simultaneity of the loads is the more stringent requirement for this kind of recovery: the devices coupled with the recovery unit should require mechanical power at the same time at which the mechanical power is available from the recovery unit. A mechanical storage device can be represented by flywheels, with high power outputs, but low overall energy accumulation [210].

3.3. Electrical Conversion

The most investigated opportunity is related to an electrical conversion section to be placed on board, which can convert the mechanical power produced by the recovery unit into an electrical form. In this way, the possibility to match it with electrical energy storage (i.e., battery) is very useful and consents to decouple the energy recovery/production with the energy utilization during the time. Several auxiliaries on board are actually driven by electrical energy and can benefit from electrical energy storage, releasing the propulsion system from this duty, and consenting to its downsizing and simpler overall control [211]. Hence, the energy efficiency of the propulsive system can be higher, in particular, if the electrical energy comes from a recovery section. The possibility to recover energy in an electrical form in vehicles can also push the electrification of other auxiliaries on board, with further benefits in overall efficiency and degrees of freedom in the control strategy [212,213].

Moreover, the recent increased interest in hybridization can boost the research activity in this perspective, making the onboard recovery more feasible and giving the right utilization to the recovered energy. The electrical form can be of different ways: DC at 12, 24, or 48 V seems the most usable on board, to drive auxiliaries, depending on the level of hybridization of the vehicle and the power needed by the auxiliaries [214], but also a muti-voltage level net can optimize the power distribution and reduce energy consumption [215]. Hence, electric motors and generators, in particular, if operating in AC mode, should be equipped with electric devices to rectify the current produced and transform it into the desired voltage (inverters and power converters): although the conversion efficiencies are high enough, each conversion step has intrinsic losses and reduced the final recovery efficiency [216].

Finally, the flexibility of the electric drive of devices is undoubtedly the main advance of an electrical energy recovery, but the efficiency chain should be clearly evaluated to assess the real final benefits of the recovery itself, also considering the life cycle perspective [217,218].

4. Conclusions

Internal combustion engines represent the most important system for propulsion in the transportation sector. They will still assume great importance in the future, particularly for commercial and heavy-duty vehicles, despite the increasing electric propulsion for passenger cars. The current international discussions on the use of e-fuels or bio-fuels are expected to delay the end of production of combustion engines by 2035, opening a new technological perspective of improvement. In this regard, to meet international awareness of reducing fuel consumption and harmful emissions, waste heat recovery opportunities should be strongly considered. In this work, a review of the different technological options presently developed for waste heat recovery has been performed, categorizing them into direct and indirect ones.

The direct Heat Recovery option considers turbocompounds, an inverted Brayton Cycle unit, and thermoelectric generation. The first two options can be applied to the exhaust gases, while TEG can also be applied to other thermal streams, such as engine coolant and oil. They are more suitable for heavy duty engines when the sequence of the loads-speeds is not characterized by significant variations during a typical operation. TEG could find a wide application in passenger cars due to its simplicity but higher efficiencies are expected and significant cost reduction. In fact, costs, low efficiency and powers limit the broad application of TEG, while turbocompound is mature and affordable, and IBC units should be considered with more attention to meet the right overall efficiency to be convenient. All these technologies, part of which are close to technological maturity, will improve the performances of internal combustion engines reducing fuel consumption and CO_2 emissions if fossil fuels are used. They will improve only the conversion efficiency in the case of e-fuels or bio-fuels which by definition are really close to zero carbon. Important efficiency increases of these recovery technologies are foreseeable, being referable to high speed compressors and turbines (IBC and turbocompound) improvements or to thermoelectric materials with enhanced Seebeck effects via innovative materials doping.

Among Indirect Heat Recovery options, ORC-based units, Stirling cycles, Brayton cycles, Trilateral Flash cycles and a combination of them have been analyzed. Recovery units based on Organic Rankine Cycles seem the most mature ones, but they are characterized by limits on the final energy recoverable, despite acceptable recovery efficiency. Additionally, their dynamics should be more investigated and better managed in the transportation sector, considering the variations of the cold and hot sources during vehicle operation. TFCs have very limited applications and should be referred to as low enthalpy sources even though the management of wet expansion calls for higher efficiency machines. Stirling units have been widely studied for several applications but do not seem appropriate for transportation using ICEs. Brayton cycles require a gaseous working fluid and considering the typical hot and cold source temperatures they could require the management of transcritical thermodynamic conditions (for example CO_2) whose technology is not yet mature at a small scale level. Definitely, Rankine, Brayton, or Stirling cycles can be certainly improved in terms of efficiency increasing the interest for a wide diffusion but some technological gaps must be solved. Rankine transcritical cycles could be considered together with new working fluid formulations based also on mixtures with synthetic hydrocarbons; this will increase the maximum temperature with benefits on the efficiency and the full exploitation of the wasted heat. Brayton cycles which consider CO_2 as a working fluid operating in a transcritical state, allow, with respect to ORC, an increase in the maximum temperature with positive effects on the efficiency but more efficient machines (compressors and expanders) are needed. New components integrating more functions are the right answer to decrease weight and costs, making the use of these recovery units more profitable regardless of the thermodynamic cycle considered. It does not appear of secondary importance to use these indirect heat recovery systems fed by thermal sources which derive from the thermal management of batteries or electric motors or fuel cells in a medium-long term. In heavy-duty engines, these perspectives are more realistic than in passenger cars, with fuel saving being the most important parameter, regardless of its nature or type.

Heavy duty engines in the transportation sectors, genset and marine applications could receive significant additional benefits also when combined solutions are applied for WHR. For these applications, up to 20–25% of the original engine power could be recovered, representing a very interesting figure. Among most mature technologies, ORC-based power units have undoubtedly some advantages but only 4–6% of fuel savings are expectable for light duty engines. For heavy duty engines, 7–8% as fuel efficiency is the most correct estimate. Turbocompounding only can ensure 15–20% of fuel reduction. In this sector, the introduction of WHR technologies appears to be mandatory for heavy duty vehicles for long distance transportation, where full electrification is hard to achieve. When it is transformed into electrical energy (which allows easier storage), is really suitable also for hybrid powertrains supporting the electrification of the auxiliaries, improving engine efficiency and environmental performances. Finally, WHR, in particular in an indirect way, can be applied also to unconventional powertrains, such as H_2-based ones (both in ICE and with fuel cells), and also in battery electric vehicles which need to be cooled or generally thermal managed.

A final remark concerns the direct utilization of the heat recovered directly as heat, finalizing it to engine and vehicle thermal management. Thermal storage easily manageable on board can support the reduction in engine warm up time, with benefits on engine transient behavior particularly suitable in light duty engines for CO_2 and harmful emissions reduction.

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Nomenclature

acronyms	
AC	Alternate Current
CAC	Charge Air Cooler
CHP	Combined Heat and Power
CI	Compressed Ignition
CVT	Continuous Variable Transmission
DC	Direct Current
DHR	Direct Heat Recovery
EGR	Exhaust Gas Recirculation
G	Generator
HRVG	Heat Recovery Vapour Generator
IBC	Inverted Brayton cycle
ICE	Internal Combustion Engine
IHR	Indirect Heat Recpvery
M	Motor
OFC	Organic Flash Cycle
ORC	Organic Rankine Cycle
RPM	Revolution per minute
sCO2	superctritical CO_2 cycle
SI	Spark Ignition
TEG	Thermo Electric Generator
TFC	Trilateral Flash Cycle
TRL	Technology Readiness Level
VGT	Variable Geometry Turbine
WHR	Waste Heat Recovery
symbols	
P	power
c_p	specific heat
cs	cold source
hs	hot source
m	mass flow rate
p	pressure
T	temperature
Tsh	superheating temperature

subscripts	
atm	atmospheric
aux	auxiliary
eng	engine
env	environment
exh	exhaust
th	thermal

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