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Technology competition in the internal combustion engine waste heat recovery: a patent landscape analysis

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ABSTRACT

Fuel prices and tightening emission standards have challenged the dominance of internal combustion engines. As a response to this changed business context, the automotive industry has shown active interest in waste heat recovery technologies, which have seen rapid development in recent years. This paper uses a literature review and patent landscape analysis to study key emerging technologies in the field, namely, thermoelectric generators, and Rankine cycle and organic Rankine cycle systems. The state-of-the-art review highlights the challenges, advantages and future prospects of the selected technologies. The patent analysis reveals the leading countries, principal technological development indicators and most important actors active in the field. The results indicate a growing trend of patenting in all selected technologies. The United States and Japan are by far the most dominant countries in the waste heat recovery area, although their relative share of patent applications is declining. By applying a patent landscape approach, the study offers a quantitative perspective on current developments in waste heat recovery technology, provides indicators of future trends, and contributes to debate about technological competition in the automotive industry. Based on the conducted analyses, thermoelectric generators seems to be the most developed of the alternatives and closest to commercial application. Rankine cycle-based technologies, although less well developed, potentially offer greater environmental gains and better efficiency than thermoelectric generators. The study provides valuable information for stakeholders interested in waste heat recovery technologies and gives policymakers perspectives regarding different technological options in development of cleaner engine solutions.

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1. Introduction

Growing awareness of environmental issues together with concerns about competitiveness have created considerable interest in research of advanced technologies for highly efficient internal combustion engines (ICE). Studies have identified that there is great potential for energy savings through the use of waste heat recovery (WHR) technologies. Thus, such technologies can potentially play a major role in responding to increasingly strict emission standards and in maintaining the dominance of internal combustion engines.

Although competing technologies are being developed, such as electric vehicles, fuel cell vehicles and hybrid vehicles, [Oltra and Saint Jean \(2009\)](#) found in their study that more than 50% of

firms' patent portfolios are still dedicated to the dominant design, i.e. ICE and diesel vehicles. Technological development of the dominant design is driven by a need to be competitive in the environmental function, in addition to the primary transport function, and the share of advanced diesel vehicles is expected to increase in the next 30 years ([Oltra and Saint Jean, 2009](#); [Berggren and Magnusson, 2012](#)). From the point of view of its primary function, ICEs are very competitive: an ICE can be produced at low cost and liquid fuel is an easily available and powerful energy reserve ([Thiel et al., 2010](#)). Currently, about 80 million cars are sold worldwide each year, and 95% of transportation is provided by petrol or diesel powered vehicles.

Rising fuel prices, stricter regulations for fuel economy and more stringent emission requirements have prompted manufacturers and researchers to work on the development of cleaner engine solutions. Consequently, the automotive industry finds itself in a position where multiple alternative fuel and powertrain technologies are challenging the dominant internal combustion engine

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vehicle design (Orsato and Wells, 2007; Zapata and Niewwenhuis, 2010). Technology competition in the motor vehicle industry has been intensively studied; from the technological perspective (Hoed, 2007; Bakker et al., 2012), the policy perspective (Browne et al., 2012; Sushandoyo and Magnusson, 2014), the economic and environmental impact perspective (Dhingra and Das, 2014; Taghavi and Chinnam, 2014) and a combination of these viewpoints (Oltra and Saint Jean, 2009). Patent based studies have noted strong interest in radical innovation paths (Rizzi et al., 2014; Golembiewski et al., 2015) and the potential for a new dominant design (Thiel et al., 2010; Bakker et al., 2012). However, as a countermove, there appears to be a strong sailing-ship effect promoting innovation in ICE vehicles (Taylor, 2008; Dijk and Yarine, 2010).

Irrespective of its precise motivation – legislative changes, competitiveness concerns or sailing-ship effect – there have been many improvements in engine efficiency in recent years. Technological advancements include direct fuel injection, variable valve timing, turbochargers, brake energy regeneration, and auto start-stop functions. Despite the improvements, a great proportion of the waste heat from internal combustion engines is still lost, and finding ways to recover this lost heat energy has become a major goal of ICE development.

In the literature, waste heat recovery technologies are recognized as a future technology potentially relevant to reaching the fuel economy goals (e.g. Berggren and Magnusson, 2012). In spite of the vast existing academic and practical research on WHR technologies and their applications, there remains a need for analysis of the factors and actors affecting the development directions of emerging WHR technologies. To address this gap, this paper presents a patent landscape analysis of waste heat recovery technologies for ICE. The patent landscape contains patents that are related to waste heat recovery in mobile application, such as automotive applications and heavy duty trucks, and patents that are related to waste heat recovery in larger scale applications, e.g. marine and stationary engine applications.

The most common technologies in waste heat recovery from engines comprise mechanical or electrical turbo-compounding, Rankine cycle (RC) based systems with steam or organic working fluids, and thermoelectric generators (TEGs) (Knecht, 2008; Saidur et al., 2012; Armstead and Miers, 2014; Sprouse and Depcik, 2013). Diesel engines with mechanical turbo-compounding have been available for some years, but it has been argued that considerably greater reductions in engine fuel consumption can be achieved by the use of a Rankine cycle (Knecht, 2008). Thus, thermoelectric generators and Rankine cycles are selected for detailed study because they exhibit greatest potential for advances in cleaner energy production (Armstead and Miers, 2014).

The paper aims to address the following research questions: 1) What are the most important technologies in the WHR area? 2) Who are the top actors and leading countries in the selected WHR technologies? And 3) based on patent indicators, which of the studied technologies is the most mature?

The rest of the paper is structured as follows: Section 2 provides a short description of the working principles of waste heat recovery as well as an overview of the development and current applications of the studied waste heat recovery technologies. Section 3 describes the research method, and Section 4 reports on the results of the study. Section 5 contains discussion of the results and closes the paper with conclusions.

2. Waste heat recovery technologies for internal combustion engines

This section provides a short description of the working principles as well as an overview of the development and current

applications of the studied waste heat recovery technologies. In the literature (e.g. Saidur et al., 2012; Armstead and Miers, 2013; Sprouse and Depcik, 2013) several technologies are identified that are common in waste heat recovery: (i) the Rankine cycle, (ii) the organic Rankine cycle, (iii) thermoelectric generators, (iv) turbo-compounding, (v) the Kalina cycle, and (vi) the Stirling cycle. Based on the available literature, preliminary patent searches, and Web of Science searches Rankine cycle, organic Rankine cycle and thermoelectric generators were shortlisted as the most active WHR technologies from a research perspective.

2.1. Thermoelectric generators

Thermoelectric generators (TEGs), which convert waste heat directly into electricity, are a promising WHR technology for internal combustion engines (Zhang et al., 2008). Such generators can be used both to convert heat power into electricity and to convert electrical power into cooling or heating power. The working principle of TEGs is based on the Seebeck effect, which converts the temperature difference between the hot side and cold side directly into electricity. General technical aspects and the most common applications of thermoelectric generators are presented and discussed in, e.g., (Rowe, 1999; Riffat and Ma, 2003; Bell, 2008).

The advantages of using TEG technology in waste heat recovery are its silent operation and high reliability (Rowe, 1999; Riffat and Ma, 2003). In addition, TEGs have no moving or mechanically complex components, unlike systems based on Rankine cycle technology (Rowe, 1999; Zhang et al., 2008). Thus, thermoelectric generators can have very long technical lifetimes, and it has been shown that thermoelectric devices can exceed 100 000 h of steady state operation (Riffat and Ma, 2003). The primary challenge facing TEGs is their relatively low thermal efficiency at the present technology level (Saidur et al., 2012). However, advanced thermoelectric materials such quantum-well (QW) materials have been shown to have the potential to reach significantly higher efficiency values than commercially available bismuth telluride (Bi_2Te_3) (Karri et al., 2011), thus improving the feasibility of TEG systems. An interesting future development could be the combination of thermoelectric and photovoltaic systems to increase the obtainable power output (Zhang and Chau, 2011). Currently, one of the challenges facing current TEG systems is the large size of the radiator and the extended piping to the exhaust. A possible solution to this problem could be use of a nanofluid in the radiator system, which would reduce the size and weight of the radiator without affecting its heat transfer performance (Saidur et al., 2012). Alongside technological developments, another significant consideration is reduction in the cost-per-watt of TEG devices, which is important to ensure that TEGs are commercially feasible in a wide variety of WHR applications (Riffat and Ma, 2003).

Zorbas et al. (2007) estimated that use of TEG technology could achieve a 5% reduction in the fuel consumption of a passenger car at the current technology level and that a 20% reduction could be achievable with the use of more advanced thermoelectric materials. Similarly, Haidar and Ghojel (2001) concluded that fuel consumption could be reduced by 2%–5% if the alternator were replaced with a TEG system as the main electrical power source.

2.2. Rankine cycle WHR

Systems based on the Rankine cycle (RC) have been identified as a suitable approach for the conversion of waste heat into usable power (Sprouse and Depcik, 2013). RC is a thermodynamic process

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