



# A technical and financial analysis of two recuperated, reciprocating engine driven power plants. Part 1: Thermodynamic analysis



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## ABSTRACT

This paper is the first of a two part study that analyses the technical and financial performance of particular, recuperated engine systems. This first paper presents a thermodynamic study of two systems. The first system involves the chemical recuperation of a reciprocating, spark ignited, internal combustion engine using only the waste heat of the engine to power a steam–methane reformer. The performance of this system is evaluated for different coolant loads and steam–methane ratios. The second system is a so-called ‘hybrid’ in which not only the waste heat of the engine is used, but also a secondary heat source – the combustion of biomass. The effects of the reformer’s temperature and the steam–methane ratio on the system performance are analysed.

These analyses show that the potential efficiency improvement obtained when using only the engine waste heat to power the recuperation is marginal. However, results for the hybrid show that although the overall efficiency of the plant, defined in terms of the energy from both the methane and biomass, is similar to that of the conventional, methane fuelled engine, the efficiency of the conversion of the biomass fuel energy to work output appears to be higher than for other biomass fuelled technologies currently in use. Further, in the ideal limit of a fully renewable biomass fuel, the burning of biomass does not contribute to the net CO<sub>2</sub> emissions, and the CO<sub>2</sub> emission reduction for this second plant can be considerable. Indeed, its implementation on larger internal combustion engine power plants, which have efficiencies of around 45–50%, could result in CO<sub>2</sub> emissions that are as much as 10–20% lower than typical natural gas combined cycle (NGCC) power stations. This appears to be a significant result, since NGCCs are commonly considered to have the lowest CO<sub>2</sub> emissions of all forms of fossil fuelled, power generation currently in use.

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## 1. Introduction

As the world’s energy demand grows, reducing greenhouse gas emissions to avoid the extreme climate change scenarios poses a significant challenge. While fossil fuel based technologies are relatively cheap and reliable, their higher greenhouse gas emissions are undesirable. On the other hand, baseload generation requirements and cost pose challenges for most renewable technologies. The integration of both fossil fuel and renewable energy sources may therefore be a viable way to reduce greenhouse gas emissions significantly in a cost-effective manner.

Hybrid cycles use both fossil and renewable energy inputs. This combination can reduce the overall carbon intensity of the plant, whilst maintaining the capacity factor and dispatchability of a fossil fuel plant. This approach may also improve the economics of the renewable technology [1–5]. Hybrid systems in the literature in-

clude integrated solar gas turbine combined cycles (natural gas and gasified coal) [2,3,5,6], co-fired coal and biomass [7], biomass assisted combined cycle gas turbines [4,1], amongst others.

Techno-economic evaluations of different power systems are used to evaluate the potential viability of a given technology, e.g. [8–11], throughout the first part of this research the technical performance of two chemically recuperated engine systems is analysed. This is done by undertaking a thermodynamic study of both cycles using the program ASPEN+ [12]. The first system involves the chemical recuperation of a spark ignited internal combustion engine (ICE) using only the waste heat of the engine to power a steam–methane reformer. The second simulation examines a hybrid cycle in which not only the waste heat of the engine is used, but also a secondary heat source is used to boost the steam–methane reforming process.

Steam–methane reforming is a well known process, with around 85% of the world’s hydrogen produced using this method [13–17]. It is achieved by mixing steam and methane in the presence of a catalyst to obtain hydrogen and different products consisting of carbon, hydrogen and oxygen. At equilibrium, the

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extent to which the reactions are shifted towards the products or the reactants depends on the reactant quantities and the temperature and pressure at which the reaction takes place, and also the assistance of a catalyst [18–21]. Industrial applications usually use nickel based catalysts which operate at around 700 °C and above [14,16,22,23].

Chemically recuperating a thermo-mechanical power unit is not a new idea, e.g. [24]. Rostrup-Nielsen [25] analyses the different uses of chemical recuperation, not only in power generation, but also in the industrial production of hydrogen, ammonia, methanol and syngas for gas-to-liquid plants. A relatively large amount of work has been published on chemical recuperation of gas turbines [24–31]. However, no power plants based on this concept appear to have been built.

Integrating steam methane reformers (SMRs) with internal combustion engines (ICEs) has received less attention than gas turbines. However, in the last decade in particular, the concept has gained interest in the research community [32–36]. Work done on the chemical recuperation of natural gas fuelled internal combustion engines shows that while the degree of recuperation is lower than for gas turbines, other benefits are obtained by its implementation. Due to the combination of the combustion properties of methane, carbon monoxide and hydrogen, the synthesis gas resulting from the reforming reaction has several enhanced combustion properties [34,37–44]. These include hydrogen having broad flammability limits, low activation energy and high flame velocity, allowing synthesis gas fuelled engines to run leaner. This can significantly improve the engine efficiency and reduce pollutant emissions if implemented properly.

However, the relatively low exhaust temperature of internal combustion engines nonetheless remains as a significant issue, prompting this work's proposed use of a secondary renewable energy source to raise the reforming temperature. The relative performance of these cycles is demonstrated by first examining the basic, chemically recuperated cycle, and then examining an equivalent, hybrid cycle with the secondary, renewable energy source included. The second part of this two part study then considers the financial performance of hybrids only, since the thermodynamic benefit of the basic cycle is found to be marginal.

## 2. Cycle layout and description

Fig. 1 shows the layouts of the chemically recuperated cycles. The basic system is shown in Fig. 1a and is composed of 4 main streams. Stream 1 is the inlet air to the engine. Streams 2, 3, 4 and 5 are the engine exhaust gases after going through the engine, the SMR, the steam generator/methane super-heater and the condenser respectively. Stream C is the coolant flow of the engine; part of its heat is used to pre-heat the fuel and the water. The rest of the heat is dumped into the atmosphere through a radiator in order to achieve the cooling stream inlet temperature. Stream F is the fuel line and W is the water flow that goes into the SMR. Both lines are pre-heated with the coolant flow and then super-heated with the exhaust gases and consequently mixed before entering the reformer.

Fig. 1b shows the proposed layout for the hybrid. In this case, the heat from the exhaust gases and the cooling system are used to preheat the steam and methane, which is then reformed in a biomass fired SMR. Stream 1 is the inlet air to the engine, 2, 3 and 4 are the different paths of the exhaust gases as they go through the different heat exchangers. Stream C is the cooling flow of the ICE. Part of its heat is used to pre-heat the methane and the water; the rest is dumped into the atmosphere through a radiator in order to achieve the cooling stream inlet temperature. Line F carries the fuel and W is the water flow that goes into the reformer.

Both lines are mixed and pre-heated with the cooling flow, and then super-heated with the engine exhaust gases in the steam generator and methane super-heater before entering the reformer. Line BM carries the air which passes through the biomass burner. Stream BIOMASS is the biomass intake of the combustor. The LHV of different biomass fuels ranges approximately between 15 and 25 MJ/kg [45–47], therefore it is reasonable to assume that the biomass used in this process has a LHV of 20 MJ/kg, although this dose not affect the cycle analysis. The heat from this process is used to maintain the temperature of the SMR output stream at a pre-set value.

Table 2 shows the pressure and temperature of the input streams of both cycles.

### 2.1. Steam-methane reformer (SMR)

In both Fig. 1a and b the steam-methane reformer is represented as block SMR. It is modelled as an adiabatic, equilibrium reactor. In the case of the chemically recuperated cycle, heat is extracted from the exhaust gases and dumped into the reformer to feed the endothermic steam-methane reforming reaction. In the case of the hybrid cycle the SMR is kept at a constant temperature using the heat of the biomass combustion.

Non-equilibrium effects are likely to make the process too slow at temperatures below 700 K [18–21]. Thus, 700 K is defined as the minimum catalyst activation temperature (MCAT). The MCAT is the temperature below which the catalyst is unlikely to be active and therefore chemical recuperation is not feasible. It is also relevant to define an industrial catalyst activation temperature (ICAT), which is the temperature at which most industrial catalyst start to work. This will be set at 1000 K [14,16,22,23]. Non-equilibrium membrane reformers would be ideal for this application, because of their high methane conversion factor (90%) at lower temperatures [48–52]. However, because such devices are still not commonly used and are in development, they will not be modelled in this research. The heat transfer effectiveness of the SMR is set at 80%.

Since lower pressure favours the reaction, the pressure in the reformer is set to the lowest at which proper injection of the fuel can be achieved. According to previous work done with a natural gas powered ICE [53,54], this is around 0.5 MPa, which will be the pressure used in the entire fuel line F.

### 2.2. Heat exchangers

Blocks H<sub>2</sub>O-PH and CH<sub>4</sub>-PH are counter current heat exchangers that use the hot water from the engine's coolant circuit to pre-heat the water and methane coming out of the pump and compressor respectively. The steam generator and methane super-heater, blocks STEAM-GN and CH<sub>4</sub>-SH, are also counter current heat exchangers. It is during this stage where the water and methane are super-heated with the exhaust gases before entering the SMR. The effectiveness of the low and high temperature heat exchangers is 80% and 90% respectively.

Blocks RAD and COND work are a radiator and a condenser, respectively. They dump the excess heat of streams C and F into the atmosphere. In the case of the condenser, it is during this stage where the injected water and some of the water generated during the combustion can be recovered.

The Biomass burner consists of two parts. The BM-PH is the biomass burner air pre-heater. It recirculates the hot biomass exhaust gases coming out of the biomass combustor to pre-heat the biomass inlet air stream. Block BM-BURN is modelled as a combustor in which the biomass is burnt and the heat of the combustion is transferred to the SMR. The efficiency of the process, defined as

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