Exergo-Technological Explicit Selection Methodology for Vapor Cycle Systems Optimization for Series Hybrid Electric Vehicles

Wissam Bou Nader[a,c], Charbel Mansour[b], Clément Dumand[c] and Maroun Nemer[d]

[a] *Ecole des Mines de Paris, Centre Efficacité Energétique des Systèmes CES, Palaiseau, France,* wissam.bou_nader@mines-paristech.fr
[b] *Lebanese American University, Industrial and Mechanical Engineering department, New York, United-States,* charbel.mansour@lau.edu.lb
[c] *Groupe PSA, Centre technique de Vélizy, Vélizy, France,* wissam.bounader@mpsa.com, clement.dumand@mpsa.com
[d] *Ecole des Mines de Paris, Centre Efficacité Energétique des Systèmes CES, Palaiseau, France,* maroun.nemer@mines-paristech.fr

Abstract:

Significant research efforts are considered in the automotive industry on the use of low carbon alternative fuels in order to reduce the carbon dioxide emissions and to improve the fuel economy of future vehicles. Some of these fuels, such as the solid fuels for example, are only compatible with external combustion machines. These machines are only suitable for electrified powertrains relying on electric propulsion, in particular series hybrid electric vehicles (SHEV) where fuel consumption strongly relies on the energy converter performance in terms of efficiency and power density, as well as on the deployed energy management strategy. This paper investigates the potential of fuel savings of a SHEV using a vapor cycle machine (VCM) system as energy converter substitute to the conventional internal combustion engine (ICE). An exergo-technological explicit analysis is conducted to identify the best VCM-system configuration. A Regenerative Reheat Steam Rankine Cycle with condenser reheat and turbine reheat (RReCRTRe-SRC) system is prioritized, offering high efficiency, high power density and low vehicle integration constraints among the investigated systems. A plug-in SHEV model is developed and energy consumption simulations are performed on a worldwide-harmonized light vehicles test cycle (WLTC). Dynamic programing is used as global optimal energy management strategy. A sensitivity analysis is also carried out in order to evaluate the impact of the battery size on the fuel consumption. Fuel consumption simulation results are compared to ICE on same vehicle powertrain. Results show +2% to +3.5% additional fuel consumption, on self-sustaining SHEV, with the RReCRTRe-SRC as auxiliary power unit (APU) compared to ICE. Consequently, the selected VCM-APU presents a potential for implementation on SHEVs with zero carbon alternative fuels.

Keywords:
Exergy analysis, Rankine cycles, series hybrid electric vehicles, vapor cycle machine.

1. Introduction

Automotive manufacturers are investigating the use of alternative fuels in attempt to reduce GHG and pollutant emissions [1, 2]. Internal combustion engines (ICE) are compatible with conventional fuels as well as some alternative fuels such as biogas, ethanol, methanol [3, 4]. However other fuels, such as solid fuels and some other liquid and gas fuels, require the use of external combustion machines, where thermal heat power is generated outside the thermodynamic cycle and added generally through a heat exchanger [5, 6].

Among these external combustion machines, which have been studied largely as waste heat recovery (WHR) systems coupled to ICE [7-11], and/or for cogeneration applications [12-16], the VCM and the Stirling have been largely investigated over years as main energy converter instead of conventional internal combustion engines (ICE) in automotive applications [17-23].

The VCM, main focus of this study, operates according to Rankine cycle (RC), where the thermal heat generated in an external combustion chamber, is added to the working fluid through a heat exchanger (HEX) as illustrated in Figures 1. This thermodynamic system, compared to conventional ICE, offers the benefits of vibration-free operation, low noise and the multi-fuel capability [17-21].

However, the investigation of VCM systems for automotive applications shows three main drawbacks preventing their use in conventional vehicles:

- High fuel consumption compared to ICE caused mainly by low cycle thermal efficiency when operated under vehicle conditions. In fact, when water is the Rankine working fluid, a positive condenser pressure is required to prevent air infiltration and to limit the condenser size. This will limit the turbine expansion work, which limit consequently the efficiency. Also coupling mechanically the turbine to the vehicle-driving load in conventional powertrain, leads to a low efficiency operating range of the system since the optimal machine efficiency cannot be achieved technically in all the operating range.
- High amount of thermal heat rejected through the condenser at relatively low temperature from the Rankine closed loop cycle, requiring a big condenser, a powerful condenser fan and a large vehicle frontal surface.
- The use of a heat exchanger (HEX) evaporator in the VCM adds a thermal inertia upstream of the turbine, which has a negative impact on vehicle acceleration, and makes the VCM system non-compatible for fast response power delivery to follow the variable load applied in conventional power trains.

Nonetheless, VCM revealed interests in specific applications, where the machine operates at quasi-stable load. For instance, in electric energy production, these machines, coupled to gas turbine systems in combined cycle power plants, drive an electric generator at constant speed and deliver a quasi-constant load [24, 25]. In automotive applications, these VCM-systems regained importance today as engine WHR systems where a great deal of attention is focused on methods to reduce air pollution [26-32]. All these works, confirm the virtue of VCM in quasi-stable operation applications.

Moreover, the review of the literature showed also interesting insights on emissions reductions of external combustion machines with continuous combustion systems [33-35].

Therefore, based on the aforementioned findings, VCM-systems present a forthcoming potential for improving emissions of passenger car vehicles, with the benefit of multi fuel-use flexibility; particularly, in series hybrid electric vehicles (SHEV) presented in figure 1. This powertrain combines a thermal and an electric powertrain in a series energy-flow arrangement [36]. The thermal powertrain in this study comprises a VCM-system and an electric generator, and both constituted the Auxiliary Power Unit (APU). The APU operating speed is kinematically decoupled from the vehicle velocity; therefore, the VCM operation is controlled to meet its best efficiency when used to recharge depleted battery. On the other side, the electric powertrain provides the necessary traction power to overcome the driving load and serves to recover the braking energy.

On the other hand, several VCM thermodynamic configurations could be considered for integration in SHEV, combining a simple VCM, to regenerative VCM, to regenerative reheat VCM and others. Plenty of studies have been published over the past decade in the academic literature treating VCM-system configurations and performance analyses [37-39]. The survey of these studies confirms that most VCM-systems are designed based on efficiency optimization. However, there are no recent studies on VCM-systems suitable for automotive applications as main energy converter instead of ICE, due to the lack of competitiveness of VCM compared to ICE in conventional powertrains. Hence, the following main gaps and limitations in the recent literature are underlined:

- There are no studies assessing VCM-systems performance based on a Rankine thermodynamic cycle for automotive applications.
- No specific methodology on selecting the best-suited VCM-systems for automotive application is adopted.
- The overall vehicle consumption under driving conditions is not benchmarked against conventional vehicles and hybrid electric vehicles relying on ICE.

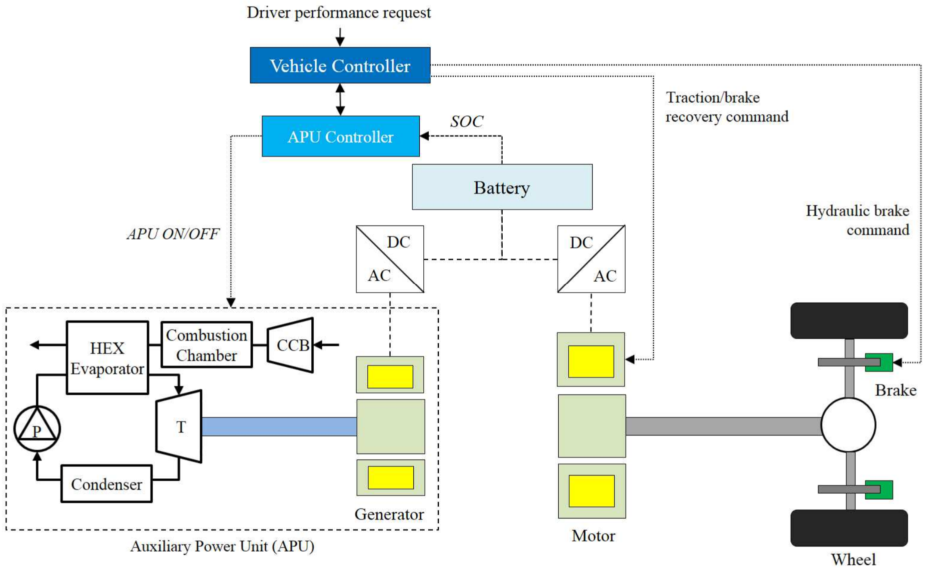

Fig. 1. Configuration of the modelled SHEV with a simple VCM APU.

Therefore, based on the above synthesis of the insights and gaps in the literature for adopting VCM in automotive applications, this study proposes a comprehensive methodology, to identify the potential VCM-system options and to select the optimal system for an SHEV application. An exergo-technological explicit selection (ETES) methodology for the identification and assessment of the different VCM-system options applicable to SHEV and to select the best suited energy converters is carried out in section 2, based on exergy analysis and automotive technological constraints. Observed results are then used for the prioritization and the selection of the optimal VCM-system configuration. The selection criterion are optimizing the system efficiency and increasing the net specific work as well as respecting vehicle constraints, such the thermal power rejected. Thereafter, an SHEV vehicle model is developed in section 3, and powertrain components are designed to ensure vehicle performance requirements. The identified VCM-system is integrated in the developed vehicle model and a comparison between SHEV models with different APU technologies is presented: (1) a VCM-APU and (2) a reference ICE-APU. Energy consumption simulations of these models are compared on the WLTC and a sensitivity analysis illustrating the battery size impact on energy consumption is presented. Note that Dynamic Programing (DP) is adopted as Energy Management Strategy (EMS) in order to provide the global optimal strategy to power ON and OFF the APU.

2. Methodology for the selection of the optimal VCM-system

This section presents the methodology adopted to evaluate the potential of VCM-systems in an SHEV with a series hybrid electric powertrain configuration. The same methodology has been proposed by the authors in [36], for the selection of the optimal gas-turbine systems for SHEV. This approach has been reconsidered in this study and adapted to the VCM-systems.

The methodology consists of two-steps assessment plan. In the first assessment step, energy and exergy analysis are applied to the simple VCM system, and the overall efficiency, specific work, and exergy are calculated. Based on the resulting exergy losses, the simple VCM is modified, and several system options are derived, while considering several measures to reduce exergy losses, such as bottoming WHR cycles, regenerative cycles and reheat cycles among others. Accordingly, the list of potential VCM-system configurations is identified.

The energy and exergy calculations are then carried out in the second assessment step on all identified configurations where components technological constraints and automotive design constraints are considered. The optimal-realistic VCM-system configuration for SHEV application is therefore selected based on efficiency, power density as well as on vehicle constraints, among them the thermal heat rejected from condenser located in the front of the vehicle.

2.1. Energy and exergy analysis of the simple VCM

This section presents the modeling of the simple VCM-system. The system presents two loops: (1) a Rankine cycle loop (RC) and a combustion chamber loop (CC), as illustrated in figure 1. The RC-loop consists of a pump, a heat exchanger (HEX) evaporator, a turbine and a condenser, whereas the CC-loop includes a combustion chamber blower (CCB) and a combustion chamber. Both loops exchange heat in the common HEX evaporator component, which serves at the same time as heater, boiler and super-heater.

As all thermodynamic energy converters, VCM-systems are more efficient when operating at high source temperature and water is among best-suited and compatible Rankine working fluids for high temperature [40, 41]. Therefore, the simple VCM-system is referred as Steam Rankine Cycle (SRC). Note that air is considered as the working fluid in the CC loop.

First law of thermodynamics is applied in order to deduce the cycle thermal efficiency and power density. The system efficiency is computed according to equation (1).

$$\eta_{system} = \frac{W_{turbine} - W_{pump} - W_{CCB}}{Q_{cc}} \tag{1}$$

With
η_{system} : Overall efficiency of the SRC
$W_{turbine}$: Turbine work in the RC loop (kJ/kg)
W_{pump} : Compressor work in the RC loop (kJ/kg)
W_{CCB} : Combustion chamber blower work in the CC loop (kJ/kg)
Q_{cc} : Heat added in the combustion chamber

Exergy analysis is then carried out as expressed in equation (2) in order to trace the work losses in the system and their quantities, informing on the possible options to reduce the inefficiencies.

$$E_{in} = [W_{CV}]_{in}^{out} + \left(E_{out}^{Q} - E_{in}^{Q}\right) + E_d + E_{out} \tag{2}$$

With
E_{in} : Exergy of the entering flow
E_{out} : Exergy of the leaving flow
$[W_{CV}]_{in}^{out}$: Net Work output
E_{out}^{Q} : Exergy of the heat rejected
E_{in}^{Q} : Exergy of the heat added
E_d : Exergy destruction in the system

Exergy destruction results of the investigated simple VCM-system are illustrated in figure 2. This figure points out the three highest shares of exergy losses, occurring in the combustion chamber (52%), in the HEV evaporator (23%) and in the heat rejected from the condenser (17%).

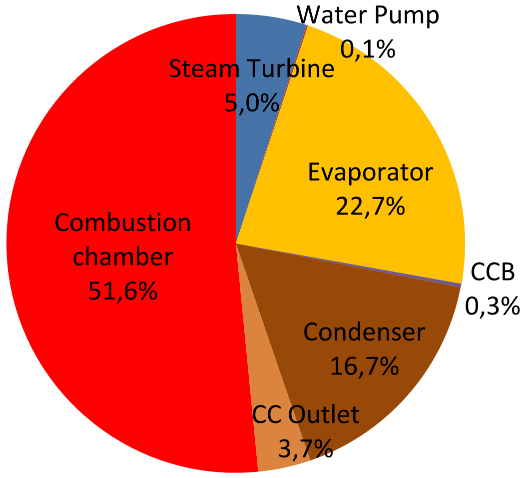

Fig. 2. Distribution of exergy destruction in the SRC system with maximum combustion chamber temperature of 1250°C and maximum cycle pressure of 10 MPa.

The exergy destruction in the combustion chamber decreases as the average temperature increases [42-44]. Accordingly, three ways can be considered to decrease these exergy losses in this component: (1) increasing the combustion chamber outlet temperature while respecting metallurgic constraints. (2) Increasing the average combustion temperature using a regenerator which recovers waste heat downstream the HEX and increases the temperature upstream the combustion chamber. (3) Performing a combustion chamber reheat cycle where a second combustion took place in the exhaust gas at the outlet of the first HEX and a second identical RC is performed, where heat is added through a second HEX downstream the second combustion chamber.

Exergy destruction in the HEX evaporator, can be reduced by reducing the temperature difference and the pinch between hot and cold stream inside this component. However small pinch implies larger heat exchange surface and bigger HEX. Another option can be envisaged to reduce exergy destruction in the HEX, consists of performing a supercritical Rankine thermodynamic cycle, where water is pumped to a pressure higher than its critical point [45, 46]. However, this option was not considered for technological constraints reasons.

As for the third major source of exergy destruction, losses from the steam condenser to the ambient air, these exergy losses can be reduced in three ways: (1) The first option relies on the adoption of external waste heat recovery systems or bottoming cycles, among them, Organic Rankine Cycle (ORC) recovering heat at low temperature is considered. (2) The second option considers an internal heat exchanger to serve as an internal regenerator that recover heat at the steam turbine outlet to heat the water at pump outlet [47]. This configuration, discussed in more details later, has the benefit of reducing the amount of heat rejected through the condenser, limiting therefore, the condenser surface. (3) The third option consists of recovering condenser thermal losses through an external heat exchanger to serve as regenerator that heat the air at the combustion chamber inlet. In this study, only the first option is considered for the following reasons: (1) The additional ORC system add complexity and cost and (2) it was proven by calculations, that heat rejected at the outlet of the HEX remains at higher temperature than the condenser inlet temperature. Therefore, it is more advantageous to recover this heat since it allows reducing more the exergy destruction in the CC.

Regarding the exergy losses at HEX outlet to the ambient air, it can be recovered in two ways: (1) internally using a regenerator upstream the combustion chamber and (2) through a bottoming ORC cycle which was not considered in this study, for the same reasons discussed before.

The exergy destruction shares of the combustion chamber blower, the pump and the turbine are negligible compared to the rest. They can be further reduced by improving the efficiency of these components. Note also that turbine reheat systems were also considered. These systems known in the literature [40, 48], allow increasing Rankine cycle efficiency by approaching isothermal expansion through multi-stages turbine expansions with reheat.

Based on these findings, the different VCM-system options showing a significant potential for exergy loss reduction compared to the simple VCM system are listed below. These systems are classified according to the combination of the suggested techniques for exergy loss reduction such as the use of regenerators upstream the combustion chamber, turbine reheat cycle, condenser re-heater as well as post combustion cycles. These systems, are considered in the rest of the study for further assessment in order to determine the most suitable VCM-system configuration for an SHEV application:

1- SRC: Simple Steam Rankine Cycle
2- R-SRC: Regenerative Steam Rankine Cycle
3- CR-SRC: Condenser Reheat Steam Rankine Cycle
4- RCR-SRC: Regenerative Condenser Reheat Steam Rankine Cycle
5- Re-SRC: Reheat Steam Rankine Cycle
6- RRe-SRC: Regenerative Reheat Steam Rankine Cycle
7- RReCR-SRC: Regenerative Reheat and Condenser Reheat Steam Rankine Cycle
8- TRe-SRC: Turbine Reheat Steam Rankine Cycle
9- RTRe-SRC: Regenerative Turbine Reheat Steam Rankine Cycle
10- RReTRe-SRC: Regenerative Reheat and Turbine Reheat Steam Rankine Cycle
11- RReCRTRe-SRC: Regenerative Reheat Condenser Reheat and Turbine Reheat Steam Rankine Cycle

2.1. Energy and exergy analysis of the identified VCM-system

The identified VCM-system options are assessed now in order to prioritize these options based on their respective efficiency and net specific work, and to select the most suitable configurations. The assessment methodology for each option was presented in [36]. Systems are modelled using both Dymola software and Refprop software, using the set of physical parameters such as combustion chamber maximum temperature, machines efficiency, steam maximum pressure, pinches, among others; as summarized in table 1. These parameters correspond to the state-of-the-art specifications and limitations of VCM component technologies and to automotive design constraints.

The energy and exergy calculations are made as function of parametric design criteria: the steam maximum pressure ($P_{max,SRC}$), the steam maximum temperature ($T_{max,SRC}$), the reheat steam maximum temperature ($T_{max,TRe-SRC}$) and the HP steam turbine expansion ratio ($\beta_{HP\text{-}SRC}$). Therefore, the second calculation step uses the multi-objective non-dominated sorting genetic algorithm (NSGA), to determine the Pareto optimal efficiency and net specific work solutions for the optimal ($P_{max,SRC}$), ($T_{max,SRC}$), ($T_{max,TRe-SRC}$) and ($\beta_{HP\text{-}SRC}$) [49]. It is worth to note that NSGA optimizations were performed with a set of constraints such as a minimal vapor quality of 0.92 at turbine outlet, and a minimum exhaust gases temperature of 85°C at the outlet of the CC loop. These technological constraints were set to avoid turbine blades corrosion caused by low vapor quality releasing from turbine [50] and to avoid HEX corrosion due to water condensing in the exhaust gases [51].

The Pareto curves of figure 3 illustrated the net specific work versus the efficiency for the investigated VCM-systems. The VCM-systems using the combustion chamber regenerator, the combustion chamber reheat, the condenser reheat and the turbine reheat systems have higher efficiency than basic configurations. Also, the combustion chamber reheat systems present higher net specific work compared to non-combustion chamber reheat cycles. This can be explained by the post combustion that occurs in the same air flow, downstream the first combustion chamber, which approximately, doubles the power for the same mass flow. This is very benefic for vehicle applications, because it offers the possibility of reducing the components size, mainly the HEXs, for the same pressure drop.

Table 1. Simulation parameters based on state-of-the-art component specifications and automotive design constraints.

Parameter	Unit	Value	Parameter	Unit	Value
Reference temperature	°C	25	Steam max pressure	MPa	10
Reference pressure	MPa	0.1	Steam max temperature	°C	650
CC blower efficiency	%	75	Steam reheat max temperature	°C	650
Combustion chambers max T°	°C	1250	Regenerator efficiency	%	85
Combustion chambers pressure drop	hPa	50	Condenser Re-heater efficiency	%	60
Turbine isentropic efficiency	%	85	HEX pinches	K	100
Pump isentropic efficiency	%	65	HEXs pressure drop	hPa	50
Steam Condensing temperature	°C	100	Steam quality at turbine outlet	-	> 0.92
Steam condenser sub-cooling	K	3	Exhaust gas outlet	°C	> 85

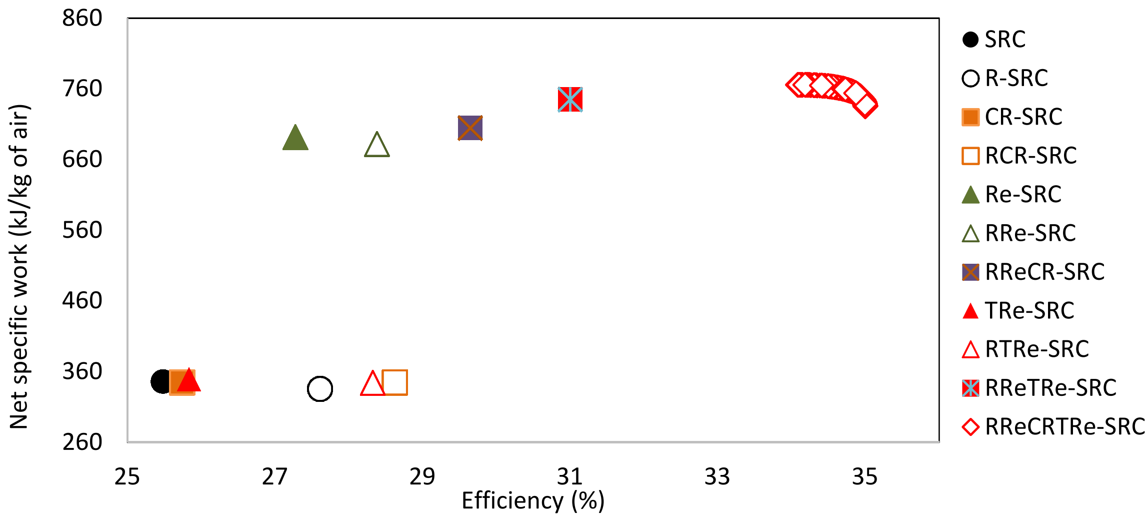

Fig. 3. Pareto optimal efficiencies and net specific work solutions of the different VCM-systems.

Among no complex realistic systems, the RReCRTRe-SRC presents the highest efficiency (35%) and high net specific work, followed by the RReTRe-SRC with a maximum efficiency of 31%, the RReCR-SRC with maximum efficiency of 30% and the RRe-SRC with maximum efficiency of around 28%. As seen, the common points of these configurations are the combustion chamber reheat configuration and the combustion chamber regenerator. It is worthy to mention, that for all studied configurations, the optimal efficiency and net specific work were achieved for a maximum pressure of 10 Mpa and maximum temperature of 650°C. For turbine reheat cycles, the optimal high pressure (HP) turbine expansion ratio are presented in figure 4. Where the HP turbine optimal expansion ratio is close to 4 for TRe-SRC, RTRe-SRC and RReTRe-SRC, when adding a condenser re-heater, the optimal HP expansion ratio increases to 15. This is explained by the fact that optimal efficiency occurs for a lower low pressure (LP) turbine expansion, enabling higher LP turbine outlet temperature, which is more beneficial for recovering turbine outlet thermal heat through the condenser re-heater.

Finally, the potential high net specific work VCM-systems are compared regarding one of the main vehicle constraints: the thermal power rejected from the condenser to the ambient air. Figure 5 presents the steam condenser thermal power function of net mechanical power for the different pre-selected VCM-machines. Two main conclusions can be drawn from this figure:

1- Steam condenser thermal power increases as the VCM-system net power increases.

2- Adding an internal regenerator recovering heat from the turbine outlet, upstream the condenser, reduce the thermal power rejected from the vehicle condenser.

The RReCRTRe-SRC rejects the smallest amount of heat among the other selected VCM-systems, since the condenser heater recover a valuable fraction of thermal power from the steam turbine outlet before entering the steam condenser. Also the RReCR-SRC rejects low amount of heat compared to RRe-SRC and RTRe-SRC, the internal condenser heater isn't efficient since the steam turbine outlet temperature is low.

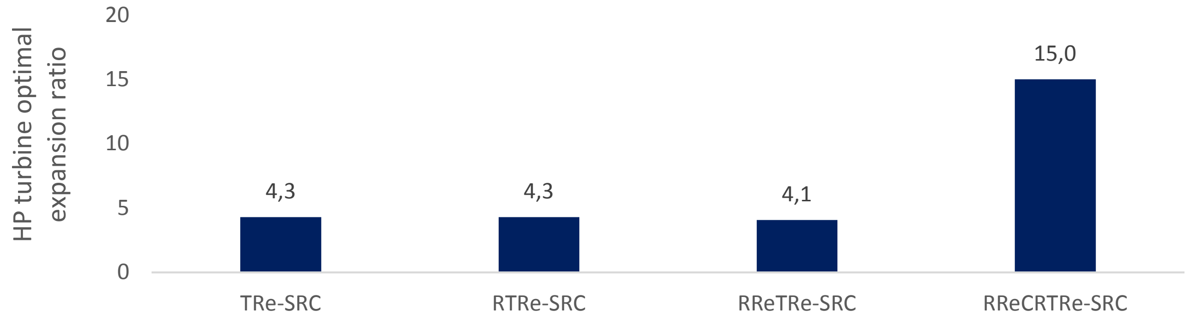

Fig. 4. High pressure turbine optimal expansion ratio for the different turbine reheat systems.

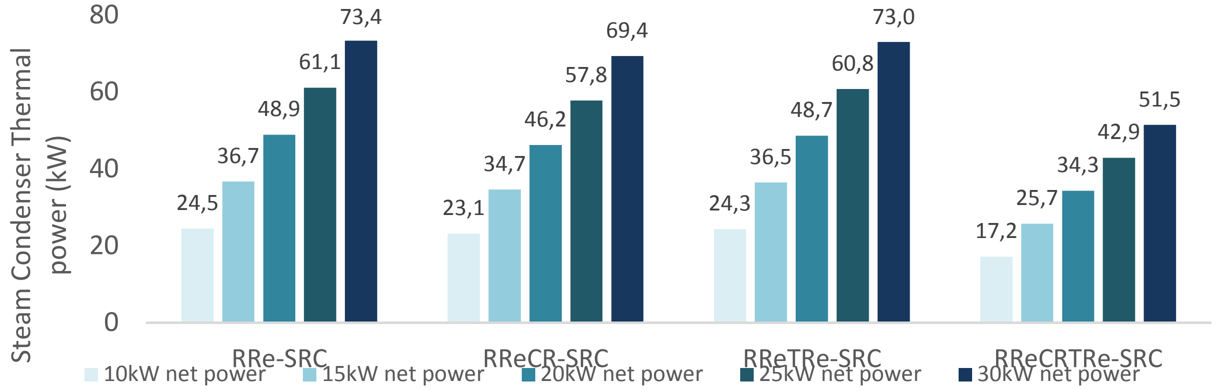

Fig. 5. Steam condenser thermal power function of net mechanical power for the different selected VCM-machines.

These results yield to conclude that the most suited cycle for vehicle applications is the RReCRTRe-SRC, since it represents the lowest constraints in term of vehicle frontal area, a high efficiency and a high net specific power. Therefore, this VCM-system will be selected for the rest of this study and will be implemented in SHEV where fuel consumption will be compared with ICE-SHEV configuration.

3. Powertrain setup and energy management strategy

In order to evaluate the benefit of the selected VCM-system in terms of fuel savings compared to ICE, a medium-class SHEV with series hybrid powertrain, consisting of a VCM-APU and an electric traction system (as illustrated in figure 1) is modelled and presented in this section.

Series hybrid powertrain configuration presents the advantage of tackling two of the main deficiencies of VCM systems in automotive applications as discussed in the literature: the poor efficiency, and the acceleration lag. On one hand, the VCM operates in this SHEV at steady power corresponding to the optimum efficiency. On the other hand, the vehicle is propelled by an electric motor powered by a battery and/or the APU, and properly sized to ensure the vehicle performance without deficiency.

The vehicle parameters considered in this study are summarized in table 2 below. The series hybrid powertrain model was developed in details in paper [36]. Four different battery capacities (2, 5, 10 and 20 kWh) are considered in order to assess the impact of the battery size on improving fuel consumption. The additional mass of the increased battery capacity is also taken into account [36].

An energy converter based on RReCRTRe-SRC, with net power of 20 kW is selected. It presents a good compromise between the thermal heat rejected through the condenser according to figure 5, the traveling distance and the battery recharging time. The selected powertrains will be simulated with different battery capacities and results will be compared to ICE-SHEV powertrains in terms of energy consumption. Note that it was proven by simulations not presented in this work, that 23kW is required to propel the vehicle at a constant speed of 130 km/h, emulating highway driving. Therefore, a powertrain with 20kW net power VCM and 20 kWh battery allows travelling a distance of about 160 km at 130km/h while maintaining a final battery state of charge (SOC) of 30%.

Table 2: Vehicle and components specifications.

Vehicle specifications	**Symbol**	**Unit**	**Value**
Vehicle mass	M_v	kg	1210
Frontal area	S	m²	2.17
Drag coefficient	C_x	-	0.29
Wheel friction coefficient	f_r	-	0.0106
Wheel radius	R_w	m	0.307
Auxiliaries consumption	P_{aux}	W	750
Battery max power	$P_{b\ max}$	kW	80
VCM-system power	P_{VCM}	kW	20
VCM-system efficiency	η_{VCM}	%	35
Generator max power	P_g	kW	25
Generator max efficiency	η_g	%	95
Motor max power	P_m	kW	80
Motor max efficiency	η_m	%	93
Transmission ratio	i	-	5.4
Transmission efficiency	η_t	%	97
Vehicle total mass	M_t	kg	$M_v + M_b$
Fuel heating value	H_v	MJ/kg	42.5

Note that dynamic programming (DP) is considered in this study in order to provide the global optimal strategy to control the APU operations [52-54]. It decides on the optimal strategy for the scheduled route at each instant t while minimizing the fuel consumption. Consequently, DP computes backward in time from the final desired battery state of charge SOC_f to the initial state SOC_i the optimal fuel mass flow rate in the discretized state time space. Note also that the resulting optimal APU on/off strategy must not cause the components to violate their relevant physical boundary constraints included in the DP model in terms of speed, power or battery state of charge, in order to ensure their proper functioning within the normal operation range. It is also noteworthy to mention that DP excludes the impact on the consumption of rule-based energy management strategies currently used on hybrid vehicles and the obtained fuel consumption results are only dependant on the investigated energy converter and its efficiency.

4. Results and discussion

Two different SHEV configurations are compared in this section:

1- A VCM-APU with the RReCRTRe-SRC as energy converter delivering 20 kW of mechanical power and operating at it optimal efficiency point of 35%.
2- An ICE-APU with a reference 1.2 liters spark ignition engine, with 97kW of maximum power and achieving a thermal efficiency of 36%. During APU operation, the ICE is allowed to operate at any point of its torque-speed map. For both models, gasoline is the fuel used.

The simulations conducted emulate the behaviour of self-sustaining hybrids with a zero use of electric energy from the battery at the end of the cycle. Thus, the initial and final battery SOCs are set at 60%. Simulations are performed on a one to ten WLTP driving cycle, covering a total distance around 230 km. APU operation and battery SOC results for three repeated WLTC are illustrated in figure 6. Note that for this study, the mass of the selected VCM powertrain is considered equal to the mass of the ICE powertrain and its accessories.

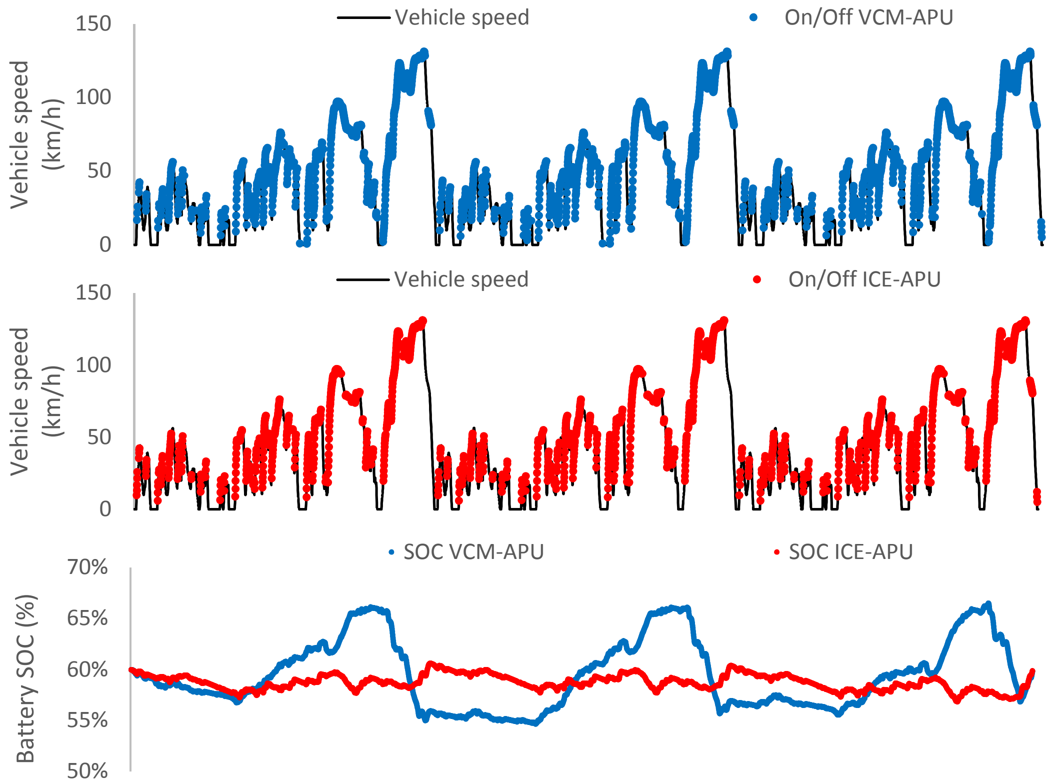

Fig. 6. Results emulating SHEV with 5 kWh battery on 3 WLTC ($SOC_i = SOC_f$ = *60%).*

Comparing the fuel consumption results between the VCM-APU and the ICE-APU in figure 7. Two conclusions can be drawn out from this figure:

1- An additional consumption of 2 to 3.5% is observed with VCM-APU under the sets of simulations. These extra consumptions are explained by the higher operating efficiency of the ICE. Note that unlike the VCM-APU which was constrained to operate at one operating point, results showed that the ICE operation was at the optimal operating line (OOL) where the efficiency remains close to 36%.
2- Comparing the fuel consumption of the two considered models for the four battery capacities investigated, shows that 8% more fuel is consumed as battery capacity increased from 2 kWh to 20 kWh. The additional consumption is explained by the unnecessary additional carried weight of the 20 kWh battery.

Note that in self-sustaining SHEV, battery is used as energy buffers. Therefore, the fuel consumption is the same on one to ten repeated WLTC and depends only on the APU efficiency. It is worthy to mention that the VCM-APU operates around 50% of time compared to around 32% for the ICE-APU. This has an advantage when considering vehicle thermal energetic needs. For instance, the VCM-system can offer the thermal heat power required for cabin heating from the condenser, for longer period compared to ICE. This reduces the additional energy consumption on hybrid electric vehicles (HEV) where cabin thermal need relies on electric resistances when the ICE is off.

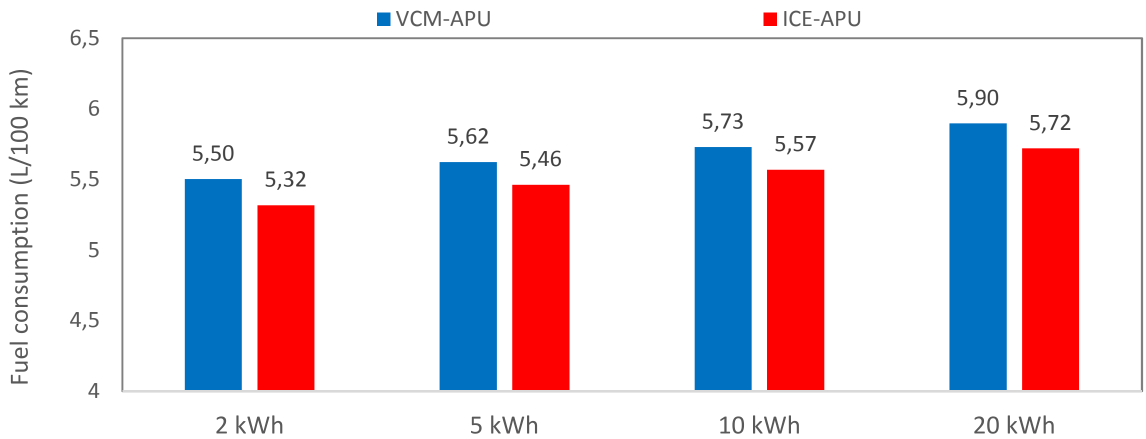

Fig. 7. Fuel consumption of VCM-APU and ICE-APU for the different battery capacities

5. Conclusions and perspectives

An exergo-technological explicit selection (ETES) method considering both component and automotive technological constraints is applied in this study to identify the most suitable VCM-system for series hybrid electric vehicles (SHEV). The Regenerative Reheat Steam Rankine Cycle with condenser reheat and turbine reheat (RReCRTRe-SRC), offering high efficiency and power density, was selected among several VCM system configurations. It represents also low vehicle constraints since it requires smaller vehicle condenser, compared to other investigated VCM-systems.

An SHEV with a series hybrid powertrain is modelled and the RReCRTRe-SRC and ICE auxiliary power units (APU) are simulated and compared in terms of fuel consumption using the dynamic programming optimal control as APU management strategy. A parametric study was also conducted in order to evaluate the impact of battery capacity on fuel consumption.

Simulation results showed that the RReCRTRe-SRC-system increases by 2% to 3.5% the fuel consumption compared to similar ICE on self-sustaining SHEV.

Results also highlighted the interest of considering small battery capacities for maximizing fuel savings on self-sustaining SHEV. Up to 8% of fuel savings were observed on one to ten-repeated WLTC respectively between 2 kWh and 20 kWh battery models.

The methodology presented in this study will be further elaborated in order to evaluate the fuel consumption saving for VCM-systems on different vehicle applications ranging from small to large and SUV extended range electric vehicles. Simulations will include Real Driving Cycles (RDE) and other vehicle energetic criteria such as the cabin thermal needs.

References

[1] Cracknell R., Kramer G., Vos E., Designing Fuels Compatible with Reformers and Internal Combustion Engines. SAE Technical Paper 2004-01-1926, 2004.
[2] Murr F., Winklhofer E., Friedl H., Reducing Emissions and Improving Fuel Economy by Optimized Combustion of Alternative Fuels. SAE Technical Paper 2011-28-0050, 2011.
[3] Ashton, P., McCurdy, G., and Osier, C., "Methanol as an Alternative Automotive Fuel: CMC's Approach and Experience," SAE Technical Paper 831176, 1983.
[4] Jonas Holmborn, “Alternative fuels for internal combustion engines”, Institutionen för Maskinkonstruktion, March 2015.
[5] Heywood J. B., Automotive engines and fuels: A review of future options. Progress in Energy and Combustion Science, 1981.

[6] Grandin A., Ernst W., Alternative Fuel Capabilities of the Mod II Stirling Vehicle. SAE Technical Paper 880543, 1988, https://doi.org/10.4271/880543.
[7] Saxena S., Ahmed M., Automobile Exhaust Gas Heat Energy Recovery Using Stirling Engine: Thermodynamic Model. SAE Technical Paper 2017-26-0029, 2017.
[8] Domingues A., Santos H., Costaa M., Analysis of vehicle exhaust waste heat recovery potential using a Rankine cycle. Energy, 2013.
[9] Sahoo, D., Kotrba, A., Steiner, T., and Swift, G., "Waste Heat Recovery for Light-Duty Truck Application Using ThermoAcoustic Converter Technology," SAE Int. J. Engines 10(2):196-202, 2017, https://doi.org/10.4271/2017-01-0153.
[10] Orr B., Akbarzadeh A., Mochizuki M., Singh R., A review of car waste heat recovery systems utilizing thermoelectric generators and heat pipes. Applied Thermal Engineering, 2015.
[11] Song B., Zhuge W., Zhao R., Zheng X., Zhang Y., Yin Y., Zhao Y., An investigation on the performance of a Brayton cycle waste heat recovery system for turbocharged diesel engines. Journal of Mechanical Science and Technology, June 2013.
[12] Eidensten L., Yan J., Svedberg G., Biomass Externally Fired Gas Turbine Cogeneration. *J. Eng. Gas Turbines Power* 118(3), 604-609 (Jul 01, 1996), doi:10.1115/1.2816691
[13] Aliabadi A. A., Thomson M. J., Wallace J. S., Tzanetakis T., Lamont W., Di Carlo J., Efficiency and Emissions Measurement of a Stirling-Engine-Based Residential Microcogeneration System Run on Diesel and Biodiesel. *Energy Fuels*, 2009.
[14] Bonnet S., Alaphilippe M., Stouffs P., Energy, exergy and cost analysis of a micro-cogeneration system based on an Ericsson engine. International Journal of Thermal Sciences, 2005.
[15] Qiu K., Hayden A.C.S., Integrated thermoelectric and organic Rankine cycles for micro-CHP systems. Applied Energy, September 2012.
[16] Thiers S., Aoun B., Peuportier B., Experimental characterization, modeling and simulation of a wood pellet micro-combined heat and power unit used as a heat source for a residential building. Energy and Buildings, 2010.
[17] Strack C. W., Condensers and boilers for steam-powered cars: A parametric analysis of their size, weight, and required fan power. NASA Technical note, TN D-5813, 1970
[18] Renner R., Wenstrom M., Experience with Steam Cars in California. SAE Technical Paper 750069, 1975, https://doi.org/10.4271/750069.
[19] Norton D., The Design of a Steam Powered Paratransit Vehicle. SAE Technical Paper 750736, 1975, https://doi.org/10.4271/750736.
[20] Carter J., The Carter System-A New Approach for a Steam Powered Automobile. SAE Technical Paper 750071, 1975, https://doi.org/10.4271/750071.
[21] Miner S., Developments in Automotive Steam Powerplants. SAE Technical Paper 690043, 1969, https://doi.org/10.4271/690043.
[22] Gardiner A., Automotive Steam Power – 1973. SAE Technical Paper 730617, 1973, https://doi.org/10.4271/730617.
[23] Nightingale N., Automotive Stirling Engine: Mod II Design Report. National Aeronautics and Space Administration, Lewis Research Center, DOE/NASA/0032-28, October 1986.
[24] Xiang W., Chen Y., Performance improvement of combined cycle power plan based on the optimization of the bottom cycle and heat recuperation. Journal of Thermal Science, 2007.
[25] HORLOCK J. H., Advanced Gas Turbine Cycles. ISBN 0-08-044273-0, Pergamon, 2003.
[26] Sprouse C., Depcik C., Review of organic Rankine cycle for internal combustion engine exhaust waste heat recovery. Applied Thermal Engineering, vol 51, pp 711-722, 2013.
[27] Abbe Horst T., Tegethoff W., Eilts P., Koehler J., Prediction of Dynamic Rankine Cycle waste heat recovery performance and fuel saving potential in passenger car applications considering interactions with vehicles energy management. Energy Conversion and Management, 2014.
[28] Endo T., Kawarjiri S., Kojima Y., Takahashi K., Baba T., Ibaraki S., Takahashi T., Shinohara M., Study on Maximizing Exergy in Automotive Engines. SAE Technical Paper 2007-01-0257
[29] Ibaraki S., Endo T., Kojima Y., Takahashi K., Baba T., Kawajiri S., Study of efficiency onboard waste heat recovery system using Rankine cycle. Review of Automotive Engineers, 28, 307-313, 2007.
[30] Freymann R., Ringler J., Seifert M., Horst T., The second generation Turbosteamer. MTZ Worlidwide 2012;73:18-23.
[31] Freymann R., Strobl W., Obieglo A., The Turbosteamer: a system introducing the principle of cogeneration in automotive applications. MTZ, 69, 20-27, 2008.

[32] Smague P., Leduc P., Integrated Waste Heat Recovery System with Rankine Cycle. 22nd Aachen Colloquium Automobile and Engine Technology 2013.
[33] Schneider P., Steam Power Systems' California Clean Car Project. SAE Technical Paper 750070, 1975, https://doi.org/10.4271/750070.
[34] Ernst W., Stirling Engines for Hybrid Electric Vehicle Applications. SAE Technical Paper 929137, 1992, https://doi.org/10.4271/929137.
[35] Lienesch J., Wade W., Stirling Engine Progress Report: Smoke, Odor, Noise and Exhaust Emissions. SAE Technical Paper 680081, 1968, https://doi.org/10.4271/680081.
[36] Bou Nader W., Mansour C., Nemer M., Guezet, O., Exergo-technological explicit methodology for gas-turbine system optimization for series hybrid electric vehicles. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2017.
[37] Zhou L., Xu G., Zhao S., Xu C., Yang Y., Parametric analysis and process optimization of steam cycle in double reheat ultra-supercritical power plants. Applied Thermal Engineering, 2016.
[38] Mohammadi K., McGowan G. J., Thermodynamic analysis of hybrid cycles based on a regenerative steam Rankine cycle for cogeneration and trigeneration. Energy Conversion and Management, 2017.
[39] Jiang L., Lin R., Jin H., Cai R., Liu Z., Study on thermodynamic characteristic and optimization of steam cycle system in IGCC. Energy Conversion and Management, 2002.
[40] Sonntag R., Borgnakke R., Fundamentals of Thermodynamics, Sixth Edition, 2003, p.411-423.
[41] Cha W., Kim K., Choi K., Optimum Working Fluid Selection for Automotive Cogeneration System. World Academy of Science, Engineering and Technology, 2010.
[42] Datta A., Som S., Energy and exergy balance in a gas turbine combustor. J Power Energy - Proc Inst Mech Eng, 213:23–32, 1999.
[43] Dunbar R. W., Lior N., Sources of combustion irreversibility. Combustion Science and Technology, Volume 103, 1994 – Issue 1-6.
[44] Som K. S., Datta A., Thermodynamic irreversibilities and exergy balance in combustion processes. Progress in Energy and Combustion Science, Volume 34, Issue 3, June 2008.
[45] Hasti S., Arronwilas A., Veawab A., Energy Analysis of Ultra Super-Critical Power Plant, Energy Procedia, 2013.
[46] Kumar R., A critical review on energy, exergy, exergoeconomic an economic (4-E) analysis of thermal power plant. Engineering Science and Technology, an International Journal, 2017.
[47] Deethayat T., Kiatsiririat T., Thawonngamyingsakul C., Performance analysis of an organic Rankine cycle with internel heat exchanger having zeotropic working fluid. Case Studies in Thermal Engineering, 2015.
[48] Zhou L., Xu G., Zhao S., Xu C., Yang Y., Parametric analysis and process optimization of steam cycle in double reheat ultra-supercritical power plants. Applied Thermal Engineering, 2016.
[49] Deb K., Pratap A., Agarwal S., A fast and elitist multiobjective Genetic Algorithm: NSGA-II. In: IEEE Transactions on evolutionary computation, Vol. 6, No. 2, APRIL 2002.
[50] Ganjehkaviri A., Mohd Jaafar N. M., Hosseini E. S., Optimization and the effect of steam turbine outlet quality on the output power of a combined cycle power plant. Energy Conversion and Management, January 2015.
[51] Trojanowski R., Butcher T., Worek M., Wei G., Polymer heat exchanger design for condensing boiler applications. Applied Thermal Engineering, June 2016.
[52] Mansour C., Trip-based optimization methodology for a rule-based energy management strategy using a global optimization routine: the case of the Prius plug-in hybrid electric vehicle. In: Proceedings of the Institution of Mechanical Engineers. Part D: Journal of Automobile Engineering, Vol 230, Issue 11, pp. 1529 – 1545, 2015.
[53] Mansour C., Optimized energy management control for the Toyota Hybrid system using dynamic programming on a predicted route with short computation time. In: International Journal of Automotive Technology. Paper N° 220100321, vol.13, No. 2, 2012.
[54] Sundstrom O., Guzzella L., A generic dynamic programming Matlab function. 2009 IEEE Control Applications, (CCA) & Intelligent Control, (ISIC). St. Petersburg, 2009, pp. 1625-1630. doi: 10.1109/CCA.2009.5281131