

Novel Range Extender Concepts for 2025 with Regard to Small Engine Technologies

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ABSTRACT

Energy politics and environmental circumstances demand novel strategies for private transport. Several studies have shown that one of these possibilities can be an electric vehicle with a range extender - REX. Today these REX engines are under way as derivation from modern internal combustion engines. As the need for an optimized usage of energy will further increase in the future, alternative energy converter systems have to be investigated. For DENSO, as supplier of components, it is of strong interest how the basic layout of these concepts could look like. This is necessary in order to be prepared for the specific needs of these concepts in terms of auxiliaries, electric / electronic components as well as for the cabin climate & various control strategies. In these REX-concepts all energies have to be considered. A sophisticated usage of energy inside a REX vehicle is required which leads to the investigation of a combined heat and power usage on-board. Using know-how and experience from small engine research and manufacturing, the range extender solutions can be treated in a very efficient and target-oriented way. Within this study alternative concepts using fossil energy as on-board power plants are being researched for the application in a range extender vehicle after 2025. Based on an analysis and derivation of requirements for upcoming scenarios high potential range extender solutions are investigated. As possible application mechanical energy generation as well as a combined heat-power generation is considered. In the following, a detailed examination of these high potential solutions is performed. This covers simulations and calculations of the necessary and relevant sections in order to generate know-how, identify crucial points, main issues and possible solutions.

INTRODUCTION

Under the influence of the worldwide efforts concerning the reduction of greenhouse gases and therefore the reduction of HC, NO_x and CO₂ emissions (i.e. fuel consumption), the automotive industry is investigating electricity based propulsion systems for passenger cars [1,2]. The increasing environmental consciousness of the civil society, the shortage of resources and the economic competition are further reasons for the development of alternative propulsion technologies. As DENSO wants to be prepared for the

specific needs of these alternative propulsion technologies in terms of auxiliaries, electric / electronic components as well as for the cabin climate & various control strategies, basic knowledge of the layout of these concepts is necessary. In order to optimize the overall system efficiency, these propulsion systems will have to use both heat and power from the energy conversion concept. Within this paper, the knowledge generation of several alternative propulsion solutions and the possible combined usage of heat and power for auxiliaries are discussed.

The electrification of propulsion systems provides additional freedom for the introduction of new technologies and operation modes for future mobility. The technical integration and optimization of the different technologies are the main challenges in the near and far future. It is conceivable that numerous improvements will be possible in different sections (NVH, driveability, fuel consumption, emission...) due to the electrification of vehicles, but the question is how the synergies (e.g. E-motor characteristic in combination with ICE characteristic) can be used. Accompanying, the electrification of the future mobility gives a chance to change the way of thinking in order to overcome the actual issues and problems of the traffic sector. Thus a pure EV (electric vehicle) has a lot of considerable advantages, e.g. the absence of local emissions (HC, CO, NO_x, CO₂, PM), excellent driveability and low NVH. Moreover, low CO₂ emissions can be reached if the electricity production is based on alternative technologies [4]. But the significant disadvantages of the present battery technology are contrary to a pure EV. The low energy density of present batteries and their high costs limit the range of pure EV. Figure 1 shows the comparison of the cost structure of an EV (city vehicle) and a vehicle equipped with an ICE – internal combustion engine (small-sized vehicle class). The EV is more than twice as expensive as the conventional vehicle and the battery is the most expensive part with a fraction of third. The range of the EV can be 150km whereas the range of a conventional vehicle with ICE and a tank volume of 40l is around 650km. Therefore considerable environmental consciousness of the customer is needed in order to decide for an EV which has high costs and a short range. Consequently, the customer will have to either pay a great deal more than he has been used to for his personal mobility or he will have to get used to significantly reduced vehicle range and increased costs.

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due to 'range anxiety' [6]. A solution is needed in order to achieve a high level of customers' acceptance for electric vehicles.

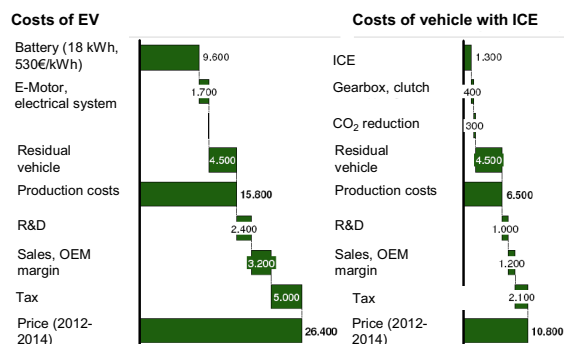


Figure 1: Cost structure of EV vs. vehicle with ICE (city vehicle / small-sized vehicle) [3]

In order to address these shortcomings - while still reaping most of the benefits of full electrification - the concept of a range-extended electric vehicle is suggested [6,13]. Different concepts have been presented by the industry [5,6,12] but most of them have a serial hybrid powertrain, an electrical storage capability sufficient for most daily drives and a combustion engine which starts when the battery state-of-charge (SOC) is below a certain level and therefore the engine acts as a 'range extender'. Range-extended electric vehicles are plug-in hybrids and some can switch between a serial or parallel hybrid powertrain depending on driving condition. The REX solution allows producing a vehicle where most of the daily drives can be done electrically which leads to zero emissions (local) and low running costs (with actual electricity price - will be low until EV take-up becomes significant). The price of the vehicle will only be little increased compared to conventional powertrains as less battery capacity is installed and small low cost engines are used. The small engine technology is of great importance for range extender applications. The REX concept is the bridge technology towards the pure EV and will be investigated and applied as long as the battery has that low energy density and high cost. It is foreseeable that the automotive standard of battery technology will likely not be available before 2020 [comp. 8,9,10]. The first generation of range extended vehicles is based on conventional ICE [6,7] and for the second generation engines (reciprocating and Wankel), optimized to the special requirements, are investigated [5]. Presumably conventional combustion engine concepts will not be the single technology for driving the generator of a range extender. Also alternative propulsion technologies and alternative engine concepts come into consideration for the third REX generation although these technologies neither had the development time nor the manufacturing investment the internal combustion engine had enjoyed.

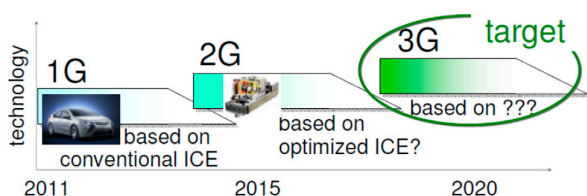


Figure 2: Evolution of REX technology
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This publication covers basic research work for the third generation passenger car range extender applications considering the whole power system and powertrain which consists of a power source similar to internal combustion engines as well as a mechanical / electrical power conversion (motor/generator). As the effort for the investigation of all possible technology concepts would be too high for this study, a selection of promising novel concepts was done using an evaluation process. In order to cover all possible technologies in the following, the word on-board power plant is used meaning the auxiliary mobile electric energy production source for the propulsion energy of the vehicle.

As evaluation basis the present requirements on engines used as range extenders are analyzed followed by a discussion of their possible changes in the future. The pros and cons of alternative technologies and engine concepts are evaluated and assessed for the application as on-board power plant. Two alternative technologies are investigated in more detail and the reason for their choice is presented. The focus is put on the on-board power plant technology which is judged on the basis of the range extender requirements (fuel consumption, power, weight, NVH...). The influence of different REX technologies on the hybrid control strategy (charging of battery) is not processed within this paper. Due to its lead in case of research, industrialization and manufacturing, the most likely future on-board power plant technology will be a conventional combustion engine optimized and adapted to range extender requirements. However, the consideration that several alternative technologies might fit better for some requirements and their chance for application as onboard power plant in a REX vehicle is content of this publication.

PRESENT AND FUTURE REX REQUIREMENTS

The removal of the mechanical link between the engine and wheels changes the requirements on the engine layout and creates more freedom in the design. The first consideration during engine layout is the maximum engine power. In a REX vehicle the main power source is the electric motor, not the combustion engine. The required amount of wheel power to drive a vehicle is depending on the driving cycle, vehicle mass, drag coefficient and rolling resistance. This can be calculated by longitudinal dynamics simulation. Figure 3 shows the average required wheel power for different driving cycles vs. the vehicle weight using a typical drag coefficient and rolling resistance. It can be seen that the driving cycle has a strong impact on the averaged required power as well as the vehicle mass on the required wheel power. A typical vehicle with a weight of approximately 1200kg needs 2.6kW average wheel power to drive the NEDC. For a constant vehicle speed of 120km/h a wheel power of about 20kW is required.

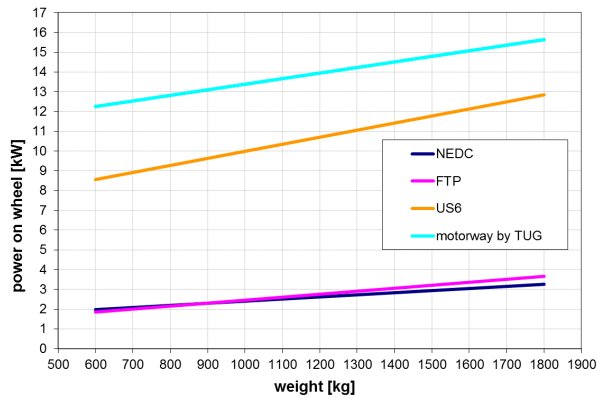


Figure 3: Required average wheel power vs. weight

The power of the on-board power plant should be high enough to permit driving in different cycles and to reach a maximum vehicle speed of 120km/h also with an empty battery. Some concepts consider a mechanical fixed drive for motorway driving [14,16]. These results and considerations lead to a maximum required power of 20kW of the on-board power plant for the A/B vehicle classes. Figure 4 shows the power and displacement of present and forthcoming on-board power plants in REX vehicles (all are internal combustion engines) which have been presented by industry and research [6,7,12,13,14,15,16]. The power varies between 10 and 53kW and is influenced by the vehicle class (mass) and the operating strategy. The 4-stroke principle is the most used concept with a cylinder number from 1-4 in-line and V, the Wankel engine is used for the lower power range and some 2-stroke concepts with 1-2 cylinders are also considered.

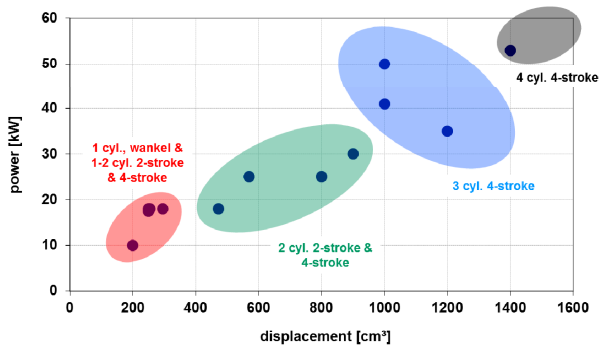


Figure 4: Maximum power of present and forthcoming on-board power plants used in REX vehicles

A reduction of vehicle mass by improved materials and lightweight design, a reduced drag coefficient and a reduced rolling resistance is the aim of several research projects. It is conceivable that a future A or B vehicle will require lower wheel power than today due to these improvements. For this research project a maximum **power** of the on-board power plant of 20kW is used.

One reason for the REX concept is the high cost of batteries of a pure EV. In order to be competitive the **cost** of the range extender should be significantly lower than the cost of the battery pack the engine is effectively replacing. This leads to a high pressure on costs for the design and layout. The combustion engine or rather the on-board power plant should be as cheap as possible.

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Weight is a special research topic for a range extender, because the on-board power plant is always carried with the vehicle, even though it should operate infrequently only when the battery is low. Most of the distances should ideally be driven by electric energy coming from the plug.

Efficiency becomes more and more important for transportation systems. Nevertheless, the on-board power plant in a REX vehicle should ideally operate infrequently and therefore it is not necessary to attain highest reachable efficiency. The on-board power plant should only be efficient enough for this purpose.

A special topic for a REX vehicle is **NVH** – noise vibration harshness. The electric motor operates very quiet and has nearly no vibrations. Therefore the customer will be used to a quiet smooth operation behavior. When the on-board power plant starts and is in operation the customer should not be bothered by the noise and vibration of the REX. Especially during driving in the city or waiting at a red light the on-board power plant should have a very low noise level. NVH has a higher priority for an engine used in a REX vehicle than in a conventional vehicle. Most of the present REX concepts have adjustments of intake and exhaust parts in order to reduce the noise level.

Packaging and **volume** are treated in a similar way as weight. The volume of the on-board power plant is always required although operation is only infrequent. Therefore high demands are made on the packaging and smallest size.

The requirements on **reliability** are very high for an on-board power plant as it might have long shutdown periods but should start within seconds when needed. This can be improved by a special starting strategy where the electric motor drags up the combustion engine.

Regarding limited **emissions** (NO_x, HC, CO, PM, etc.) EU, CARB and EPA have defined special emission measurement procedures for a PHEV including REX vehicles. In the EU REX vehicles are also tested in NEDC. Two tests are performed, the first NEDC with full state of charge and the second NEDC with minimum state of charge. The emissions of both tests are weighted. Only the weighted value has to fulfill the emission standard. The calculation of the weighted emissions includes the electric range of the vehicle. The higher the electric range, the higher emissions are allowed. E.g. a vehicle with an electric range of 100km is allowed to emit 5 times higher emissions than the EURO6 limit [see 17,18]. Thus, the emission level of a REX engine in the EU can be worse than the emission level of an engine applied in a conventional vehicle. From today's point of view this emission legislation will be intensified after 2015. The procedure in US is similar but more stringent. However, the emission target for this research project is EURO6. Figure 5 shows the emission limits for SI and CI in the EU. The emission limits after 2014 are still in discussion but a further reduction is conceivable, the dotted lines show a scenario which is derived from actual trends.

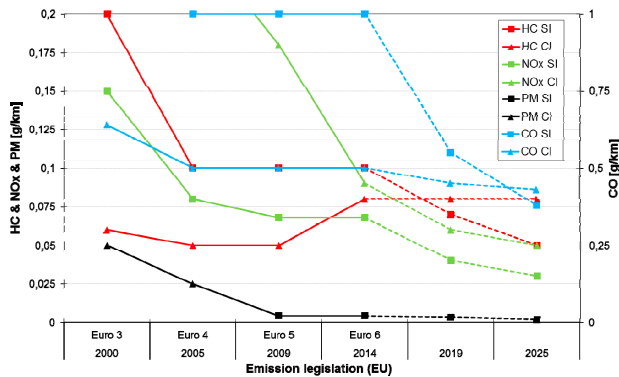


Figure 5: Emission limits for SI and CI in the EU

The *operation strategy* is a key topic for a REX application and in any case is influenced by the type of battery and powertrain of the vehicle. From today's point of view 2-3 operational points of the on-board power plant are necessary. The first one is used for charging during idle or city driving conditions and therefore low engine power is required as the battery cannot be charged with a higher current and noise emission of the engine should be low. The second point is charging of the battery at higher speed (70-100 km/h) with a power of approximately 20kW. In this operational point fuel efficiency is more important. The third operational point is at high speed of the vehicle ($v > 100$ km/h) where higher power is required and a mechanically fixed drive can be additionally realized.

Operation strategy:

2 or 3 operational points

Ranking of criteria:

1. Costs
2. NVH
3. Packaging & Weight
4. Reliability
5. Fuel consumption (Efficiency)

Emission level has to fulfil legislative.

	Power	Criteria	Driving situation	Remark
Op. point	kW			
1.	~2-5	NVH Power	Idle speed, city driving	Only at very low SOC
2.	Min. 20	NVH Efficiency	Vehicle speed > 70 km/h	Optimal op. point
3.	>30	NVH, Durability Power	Highway, $v > 100$ km/h	Optional op. point

Figure 6: Ranking of criteria and operational points of REX on-board power plant

The requirements on the on-board power plant are:

Table 1: REX requirements

Engine requirements	
Maximum Power	20 kW
Fuel consumption at optimum operational point	~ 260 g/kWh
Emission target	EURO6
Noise level	65 dBA

Furthermore a possible usage of biofuels and multi fuel ability is considered.

NOVEL SOLUTIONS AND EVALUATION PROCEDURE

The basis of the evaluation procedure is a comprehensive investigation of possible on-board power plants for future range extender (REX) applications. Therefore many different prospective technologies are analyzed. They all ground on the principle of transforming available energy (e.g. chemical energy, thermal energy, etc.) into mechanical work and afterwards into electrical work. The investigation is based on literature research and basic calculations. The results of the study are summarized in a "Possible Novel Technology Matrix". The matrix contains following main concepts and technologies of energy conversion:

Table 2: Possible Novel Technology Matrix

Conventional internal combustion engines (ICE)	Turbo Engines
Alternative ICE	Thermoelectric Engines
Rankine Concepts	Fuel Cells
Expander Concepts	Shape Memory Alloy Concepts
Stirling Engines	

These main concepts are subdivided and classified into topics which cover the operating principal, the design and the used working fluid. For all concepts the general working principle, reachable efficiencies, emissions, design properties, cost estimations, etc. are investigated and listed. These results are summarized in pros and cons of each main concept.

PRESENT AND NOVEL SOLUTIONS

Conventional internal combustion engines

The conventional ICE technologies are generally split up in two groups – SI (spark ignition) engines and CI (compression ignition) engines.

SI engines are the most used propulsion systems in automotive applications. They have a wide range of products and different operating principles. Following, the most important technologies (operating principles) will be discussed and the pros and cons regarding the REX-requirements will be presented. The principle drawbacks of the reciprocating piston engines are the moderate NVH behavior concerning the combustion noise, gas exchange and mechanical noise. Further the unbalanced forces depend on the engine layout.

- 4-Stroke SI Port Injection Engine ($\lambda=1$)

With respect to the diverse applications this engine technology is well-engineered and a low-cost system except for its engine control unit and auxiliaries like VVT. Due to stoichiometric operation no soot emissions occur and an exhaust gas aftertreatment with a three-way catalyst is possible. Furthermore, the reliability is also an advantage and starts in operation.

are easily possible in almost any condition. The disadvantage is the moderate efficiency due to the throttling loss (quantity control).

- 4-Stroke Gasoline DI Engine ($\lambda > 1$)

This engine technology has been in series production since approximately 2000 and mainly operates in two different modes depending on engine load and speed [30,31,32]: the homogenous operation mode with $\lambda = 1$ (WOT) and stratified operation mode with $\lambda > 1$ (part-load). The lower fuel consumption at part-load is the main advantage in comparison to conventional SI engines. However, drawbacks are the higher system costs (injector, fuel pump, variability of GE, etc.), the missing TWC and the worse NVH (combustion noise).

- 4-Stroke Gasoline DI engine ($\lambda = 1$, homogenous)

This well-established engine technology is a common application for downsizing. Higher specific power is reachable in comparison to conventional SI engines and used components like solenoid injectors, fuel pump are well-engineered. Furthermore, the knocking behavior is improved and a TWC can be used. The disadvantages are the moderate efficiency due to the throttling loss (quantity control) and the higher system costs in comparison to conventional MPFI engines.

- 4-Stroke Gasoline SI Crankcase charged engine

This 4-stroke engine concept was developed by IVT, the Institute for Internal Combustion Engines and Thermodynamics, at Graz University of Technology and is designed for engine units up to 50cm³ [33,34]. The aim is to provide a power output like a 2-stroke engine with the emission level of a 4-stroke engine. The major advantages are the high specific power, small packaging, possible usage of TWC, lesser engine out emissions than 2-stroke and lower costs than conventional charged 4-stroke engines. Nevertheless this concept is more expensive than conventional 2-stroke engines, it is only suitable for 1-cylinder units and due to the prototype-status the reliability is not proven.

- 2-Stroke Gasoline DI engine

Due to the light and compact design 2-stroke engines provide high specific power and therefore this engine concept is often used when weight has to be very low. Disadvantageous are the high scavenging losses which result in lower specific fuel consumption and poor HC emissions. A direct injection system instead of a carburetor can reduce the scavenging losses. Beside the very high power to weight ratio and the compact design, this technology is one of the cheapest of all conventional internal combustion engines. If the engine is designed for a very high trapping efficiency of oxygen and fuel and is operated stoichiometrically, it is possible to use a TWC. This seems suitable for a REX application as the operation area is limited compared to a conventional engine. Normally, the design of the exhaust silencer for 2-stroke engines is very difficult due to the wide speed range. But for a nearly stationary operation as in REX (cf. REX requirements) it is easily possible.

- Rotary engine (Wankel)

For automotive applications only Mazda has an applied concept. The compactness, the small number of parts, the running smoothness and pure rotational motion are decisive advantages. But, despite the long development, Wankel engines do not reach the efficiency of reciprocating engines. Also HC emissions, oil consumption and costs are higher compared to conventional 4-stroke engines. Furthermore, the piston sealing is still challenging and influences the durability.

CI engines are the most efficient combustion engines. Due to higher compression- and A/F-ratio and the quality control higher overall efficiencies are obtained. Based on their working process the use of a TWC is not possible and they have high NO_x and smoke emissions. Due to the higher cylinder pressure gradient the combustion noise of a CI is high compared to an SI. In general CI engines are more expensive than SI engines.

- 4-Stroke Diesel engine

Beside the general CI properties, the HC and CO engine-out emissions are lower than in comparable 4S gasoline engines. The lean mixture of the diesel engine prevents the effective use of a controlled TWC and sophisticated exhaust gas aftertreatment systems are necessary to fulfill the legislation. Considering future emission limits this issue will be even more challenging.

- 2-Stroke Diesel engine

Depending on the load and the engine size 2-stroke Diesel engines are the most efficient thermal machines and therefore widely used as large engines in ships or for stationary power plant applications. In the power range up to 25kW a standard application is not known. The disadvantages are similar to 4-stroke Diesel engines.

Alternative internal combustion engines

The alternative ICE technologies include alternative combustion systems (HCCI diesel and HCCI gasoline), hydrogen engines and the Stelzer engine.

- Alternative combustion systems

Alternative combustion processes combine the advantages of both CI and SI [38]. The characteristic of the alternative CI process allows the combustion of very lean or diluted mixtures with low combustion temperatures leading to low NO_x and smoke emissions [35]. An HCCI gasoline engine has good part load fuel consumption due to de-throttling. The challenge of all these systems is the controlled start of combustion [36]. Various control strategies to control the start of combustion and the combustion process are investigated [37]. Beside other alternative combustion systems (e.g. CAI, DCCS, etc.), HCCI diesel and HCCI gasoline, with respect to higher degree of development, come into consideration for the evaluation procedure.

HCCI Diesel Engines have low NO_x and smoke emissions and therefore an additional exhaust gas aftertreatment system is not required. A sophisticated control of the residual gas is necessary which results in

a variable valve train leading to higher system complexity & costs. Further, only a limited operation area can be operated in HCCI mode [cf. 37]. In comparison to conventional Diesel engines, HCCI Diesel engines are larger, have a lower efficiency and higher system costs.

To fulfill the requirements of operation mode control ($\lambda > 1$ at part load and $\lambda = 1$ at WOT) HCCI gasoline SI engines need a high charge dilution, high EGR rate and therefore variability in the GE. The benefits are low NO_x engine out emissions and in comparison to conventional SI engine a higher efficiency is reached at part load. The operation area of HCCI is limited by a too low thermal energy in low load area and by a too high combustion pressure gradient at higher load. Disadvantageous are the reliability, the complex control strategy, the higher system costs, the limited HCCI operation area and the worse NVH behavior due to the higher cylinder pressure gradient.

- Hydrogen engines

In this study internal and external mixture preparation systems were considered. Today all forthcoming concepts are SI hydrogen engines. The reason is the possible usage of similar engine components as in gas engines. CI hydrogen engines only have prototype status [39]. The main problem is the durability [40]. SI hydrogen engines have similar efficiency compared to conventional gasoline engines whereas the efficiency of CI hydrogen engines is higher. In general, the pros are good cold start emission behavior, no carbonic and particular emissions and high development potential. The cons of hydrogen technologies are the mobile H_2 -storage, high costs, missing infrastructure for H_2 -fuelling and the high NO_x -emissions (two times higher than conventional gasoline engines) which require an NO_x -aftertreatment system.

- Stelzer engine

The Stelzer engine is a 2-stroke SI free piston engine which was developed by Frank Stelzer in 1964 [28]. The engine has no valves and no rotary parts and consists of only a few main components. Due to the pure linear oscillating motion and the few parts the engine has low friction losses. Despite the 2-stroke working principle a TWC can be used as long as the engine is operated stoichiometrically and the uniflow scavenging process leads to high trapping efficiency of fuel and oxygen. Generally, the engine is simple, small, of low weight and has low costs. Disadvantages are the higher HC emissions and the worse efficiency in comparison to conventional SI gasoline engines. Also the electric energy conversion by a linear generator is not well-developed.

Rankine concepts

The Rankine concepts are based on the Rankine cycle with an external heat supply and a phase-transformation of the working fluid (e.g. steam, ionic fluids or organic fluids). For the conversion of thermal energy into mechanical energy a large number of possible expander types can be considered (e.g. axial/radial turbine, reciprocating piston-, Roots-, screw-, scroll-expander,

etc.). Rankine-based applications are usually used for stationary power generation or CHP generation. They have high mass flows in order to achieve high power and are large of size. Nevertheless, some concepts for automotive applications already exist [41,42,43]. The advantages of Rankine concepts are the possible usage of a non-hazardous working fluid like water, a high reliability, low emissions by external continuous combustion (no aftertreatment is required) and the multi-fuel ability. The disadvantages are the heavy weight, the large required space, the bad start-ability (needs a long warm-up time), the noise emission (scavenging process) and the higher costs in comparison to a conventional SI gasoline engine.

Expander concepts

In contrast to the Rankine concepts the expander concepts use a single phase of the working fluid. The working fluid, stored in a high pressure reservoir, is expanded in an expander. No automotive applications can be found in literature research and therefore this concept is based on theoretical approaches. Different fluids (e.g. air, helium, etc.) and various expander types (e.g. axial/radial turbine, reciprocating piston-, Roots-, screw-, scroll-expander, etc.) are considered. The pros are: high variability concerning fluid and expander type, low emissions and multi-fuel ability due to external combustion and avoidance of an aftertreatment system. However, most concepts will be just prototypes without empirical values and a long cost-intensive development phase is necessary in order to reach the required standard. Moreover, packaging, weight, storage, noise and warm-up time (pressure generation of working fluid) are disadvantageous.

Stirling engines

The Stirling engine is traditionally classified as an external combustion engine. The general cycle consists of compressing cool gas, heating the gas, expanding the hot gas and finally cooling the gas before repeating the cycle. Today the engine is used for stationary CHP generation, solar-dish applications and propulsion in submarines. The engine power ranges from 0.2 to 200kW. According to the working space there are basically three different kinds of Stirling types – the α -engine, the β -engine and the γ -engine [24]. The concepts are further divided into crank mechanism and free piston engines. The benefits are a long life cycle, low maintenance efforts, a high BMEP, a very high theoretical efficiency, an almost constant efficiency in a wide load range and very low noise emissions. In addition, aftertreatment systems can be avoided due to external combustion and multi-fuel operation is possible. The drawbacks are high component costs, the concept driven warm-up time, limited engine speed area, packaging, weight and transient engine control.

Turbo engines

The concepts are based on the Brayton-cycle considering two possible heat supply systems – internal or external. Gas turbines for automotive applications are not new. Chrysler and Rover built turbine cars, but only