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A new commuter vehicle concept based on a high temperature PEM fuel cell range extender

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Summary

In this paper, a parallel hybrid range extender based on a 6 kW high temperature PEM fuel cell (HT-PEM) for electric vehicles (EV) as a modular standalone exchange kit is presented enlarging the range of an EV up to 35% on NEDC using the 0.5 kg hydrogen stored at 300 bar. The results are obtained for different driving cycles containing a special commuter track on an air conditioned hydrogen certificated dynamometer.

Keywords: fuel cell vehicle, fuel cell, hydrogen, thermal management, demonstration.

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1 Introduction

One strategy to limit worldwide climate increasement below 2K is the reduction of anthropogenic pollution caused by traffic. Local emission free electric propulsion systems will contribute at this ambitious claims at least using regenerative wind or solar energy on charging stations. Unfortunately, even considering the average daily driving distance between 35 and 50 km, an electric driving range below 150 km in pleasant conditions seems not to be sufficient to enable a wider customer market. One solution in addition to increased battery storage capacity is the usage of parallel hybrid drivetrain concepts containing a second energy carrier. To ensure local emission free driving, hydrogen is one solution converted by a fuel cell into electric and thermal energy.

In the Next Generation Car (NGC), a large scale DLR internal project divided in six research and development domains, hydrogen as one solution to increase the range of electric driven propulsion concepts is regarded in the NGC energy management domain. One key result was the proposal of a parallel hybrid vehicle containing a high temperature polymer electrolyte membrane fuel cell (HT-PEM) as a range extender (REX) for mobile road applications [1, 2]. Based on the results, a project containing a special commuter electric vehicle (EV) concept connecting the DLR facilities Stuttgart (ST) and Lampoldshausen (LA) was funded by the ministry of economic affairs of the county Baden Württemberg, Germany. For demonstration, a conventional 950 kg EV (Figure 1) with a 17.6 kWh Li-Ion battery and a 50 kW electric engine was chosen on a special commuter test track presented in Figure 1. In this paper, the interaction between EV and REX is presented focussing on the energy split of the REX hybrid energy storage concept containing electric energy and hydrogen. It is validated in the hydrogen certificated dynamometer of the DLR Institute of vehicle concepts.

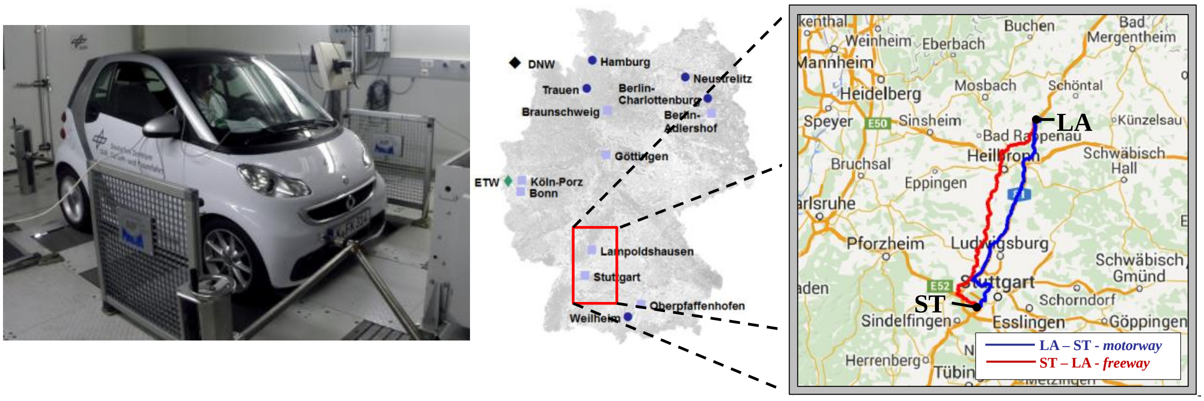

Figure 1: Demonstrator vehicle in the test bench; right: special commuter track between the DLR facilities in Stuttgart (ST) and Lampoldshausen (LA) in Germany, see chapter 3

2 Methodical approach

The methodical approach for designing the parallel hybrid vehicle is presented in Figure 2 resulting in a five stage process. For the exemplary chosen demonstrator vehicle the bulk *EV energy demand* was measured integrating 50 sensors to verify the energy consumption on different drive cycles and environmental conditions at the dynamometer [3]. A virtual *vehicle simulation* containing EV physical properties was created in Modelica to gain reasonable system sizes of the REX fuel cell power and the hydrogen storage capacity due to simulation of different parallel hybrid system concepts [1, 2, 6]. To reduce the range influence of heating, ventilation and air conditioning (HVAC) an optimized cooling system containing a waste heat usage and a new metal hydride based cooling concept was developed in NGC energy management [4-8]. In a *virtual design* process the REX was packaged as a standalone modular extension kit to integrate it into the EV trunk leading to the proposed parallel hybrid vehicle concept. A basic parallel hybrid information system to share mandatory user information was developed resulting in a new designed REX control unit. A REX test bench was built to perform different *bulk tests* for model validation and module testing focussing on the REX upheat behaviour [6]. As proof of concept a *combined test* is performed in this paper to evaluate the energy distribution between electrical and chemical energy stored in the parallel hybrid. Several measurement sensors to separate the energy flow out of the battery and to derive the REX hydrogen are used to gain the energy split on different tests containing NEDC, WLTC and the commuter track between ST-LA. The combined test is focussed as a benchmark for further HVAC studies referring on the REX ability to work as a hydrogen based air conditioning unit to enlarge the range of an EV not addicted to environmental conditions.

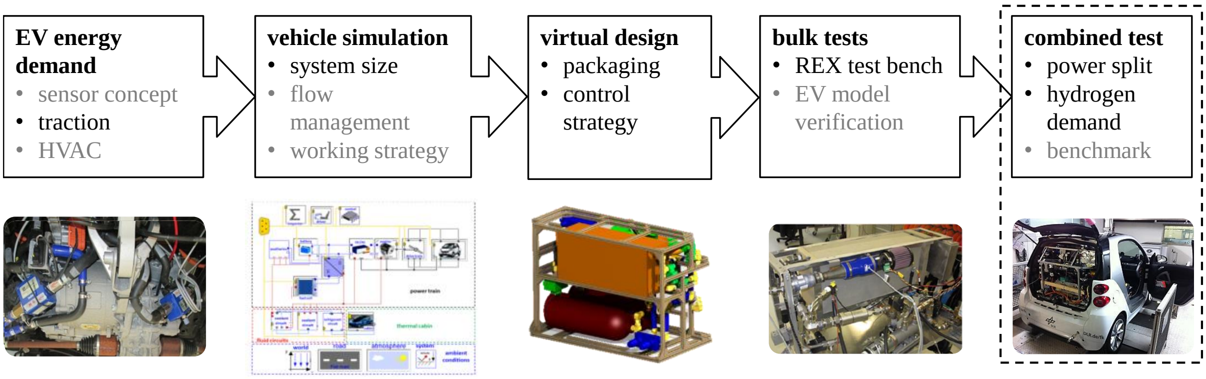

Figure 2: Methodical Approach

3 Exemplary energy demand of an EV urban road demonstrator

To evaluate the range of the EV and the influence of various drivers, cycles and environmental conditions, a base test containing WLTC and NEDC was done to validate the traction energy demand between 13.2 kWh/100 km (NEDC) and 14.7 kWh/100 km (WLTC) without considering HVAC. The 92 km long outward journey ST-LA (freeway) leads to an energy consumption of 9.8 kWh/100 km including a potential recuperation energy gain of 0.55 kWh/100 caused due to an altitude difference of -200m. The average speed was measured around 46 km/h at a maximum speed of 84 km/h resulting in a driving time of two hours. The return track from LA-ST (motorway) shows an average speed of 72 km/h while achieving a top speed of ~125 km/h. An energy consumption of 16.6 kWh/100 km was measured on LA-ST at an average traction demand of 12 kW having an altitude gain of +200m. Referring on the 17.6 kWh Li-Ion battery of the EV, an overall range between 117 km (WLTC) and 132 km (NEDC) on common drive cycles was evaluated while having a range between 102 km (LA-ST) and 168 km (ST-LA) on the commuter track test cycle. This special cycle represents two extreme benchmarks, one lower than NEDC, and one highter than WLTC.

Table 1: Energy demand of the EV measured on a dynamometer using EPA coefficients for smart ED

Cycle	v_{mean} (km/h)	v_{max} (km/h)	dh (m)	Dist (km)	Dur (min)	$P_{traction,dyno}$ (kW)	$E_{nom,tract}$ (kWh/100km)
NEDC	33	120	0	10.8 km	20 min	4.3 kW	13.2 kWh/100km
WLTC	46.5	131	0	23.3 km	30 min	6.8 kW	14.7 kWh/100km
ST-LA(freeway)	46	84	-200	92 km	120 min	4.5 kW	9.8 kWh/100km
LA-ST(highway)	72	126.6	+200	80.7 km	67 min	12 kW	16.6 kWh/100km

Further studies containing the range decrease caused due to HVAC showed an additional energy demand for cabin up to 45% for heating (-10°C) and 28% for cooling (40°C, 40% rh) [3]. To validate the energy demand the EV was used at different commuter tracks from different people in the area of Stuttgart at cold environmental conditions. In total 1257 km were driven at an average speed of 44 km/h on public roads between 0°C and 10°C to evaluate the results. An average energy consumption of 15.3 kWh/100 km was measured while having an average electrical heating demand of 1.2 kW on the road. According to the measurement data additional 17% of heating power was required to ensure passenger comfort at an average environmental temperature of 4°C confirming the results presented in Table 1 [4].

4 Fuel Cell Range Extender Design

A driving range of 182 km on the freeway is required while only having 162 km to drive on the motorway (Table 2). A combined track using both, freeway outward and motorway return from ST-LA-ST will lead to a range demand of 173 km. Based on the parallel hybrid configuration of EV+REX an additional range demand out of the hydrogen storage varying between 3 km (freeway) and 56 km (motorway) is required to ensure a full round trip on the commuter test cycle. This leads to a parallel hybrid hydrogen demand between 0.5 kWh and 9.2 kWh converted out of the hydrogen referring to the EV battery capacity of 17.6 kWh.

Table 2: Range demand to make a full track on ST-LA-ST for EV+REX parallel hybrid split based on dynamometer measurement results

	x_{track} [km]	x_{EV} [km]	x_{hyd} [km]	E_{EV+REX} [kWh]
ST-LA-ST (freeway)	182 km	179 km	3 km	18.0 kWh
ST-LA-ST (motorway)	162 km	106 km	56 km	26.9 kWh
ST-LA-ST(combined)	173 km	144 km	29 km	22.4 kWh

Several simulations were performed leading to a fuel cell stack power of 6 kW and a hydrogen storage capacity of 0.5 kg hydrogen [1, 2, 5, 6]. Different cooling circuits were developed and compared using Modelica leading to a EV thermal management system containing a new HVAC approach for driver cabin conditioning containing stack waste heat usage on winter and a new metal hydride based cooling concept using the pressure drop in the REX hydrogen supply on summer. As conclusion, the REX is able to work as a combined hydrogen powered charging/HVAC unit at different environmental conditions to ensure passenger comfort [4,5,7,8]. The constant fuel cell output power points used for concept validation in chapter 5 were calculated and compared in [6] and led to a fuel cell output power between 2.0 kW (NEDC) and 3.4 kW (LA-ST motorway). The individual power points P_{FC} for combined REX and EV testing are summarized in (Table 4).

Table 3: Power points (P_{FC}) in dependence of the driving cycle [6]

	NEDC	WLTC	ST-LA (freeway)	LA-ST (motorway)
REX fuel cell power	2.0 kW	2.5 kW	2.4 kW	3.4 kW

4.1 Fuel cell PEM technology comparison

A comparison between low temperature (LT) and high temperature (HT) polymer electrolyte membrane (PEM) fuel cell technologies showed a good suitability for the HT-PEM as an alternative stack technology. Referring on the proton exchange mechanism the hydrogen proton exchange on a conventional LT-PEM membrane is a function of the humidity of the wet NAFION membrane doped with sulfuric acid, an optimized membrane water management is mandatory to gain good hydrogen conversion efficiency. Due to the water management and the chemical structure of the membrane, LT-PEM is restricted to temperatures below 100°C while having good start abilities in less than one minute up to its nominal power stack output even on temperatures below 0°C. In difference, a HT-PEM membrane containing a phosphoric acid doped polybenzimidazole (PBI) working at ~170°C has to be preheated up to >100°C before hydrogen conversion can be started. This is because of the weak binding mechanism between PBI and the phosphoric acid, where wet water has to be avoided in the stack leading to an increased degradation due to washing out the phosphoric acid. The high stack working temperature leads to a high acceptance of carbon monoxide up to 1%, enabling the usage of reformatted hydrogen. Another advantage caused due to higher core temperature are good heat exchange abilities. The stack waste heat dissipation at ~140°C coolant temperature will lead at hot environmental conditions to smaller heat exchange surfaces compared to LT-PEM technology. To avoid high pressure stack cooling system geometries a coolant with a high boiling point and a low electric conductivity has to be used. Possible coolants for HT-PEM are thermal oil and alcohols e.g. Triethyleneglykol (TEG) with a boiling point of 295°C. Referring to the REX HT-PEM stack, a 120 cell stack at a maximum output current of 100A leading to an output power of 6 kW. The key stack values are summarized in Table 4. Due to the uncritical water management, a fixed stoichiometry between hydrogen and air of $\lambda = 2$ is used while having a maximum anode hydrogen pressure of 50 mbar within the stack. To reduce thermal stress, the maximum allowed stack temperature gradient between coolant inlet and outlet is limited to 12 K at a pressure drop of 0.2 bar. This restricts the maximum heating power to 1.3 kW considering the physical properties of TEG and the flow channel stack geometry.

Table 4: 6 kW HT-PEM stack values

P_{stack}	T_{FC}	$T_{Coolant}$	$T_{FC,Start}$	U_{Stack}	I_{Stack}	λ_{air}	n_{cell}	ΔT_{Stack}	dp_{FC}	p_{H2}
6 kW	160°C	140°C	>100°C	84…54 V	100 A	~2	120 cells	12 K	0.2 bar	50 mbar

4.2 Parallel hybrid vehicle interaction

Due to the modular construction the REX is created as a standalone application extension kit for the trunk of the EV shown in Figure 3. It contains the designed fuel cell control unit and a 0.5 kg hydrogen storage at 300 bar in combination with an integrated hydrogen and air conditioning unit to ensure the working conditions presented in Table 4.

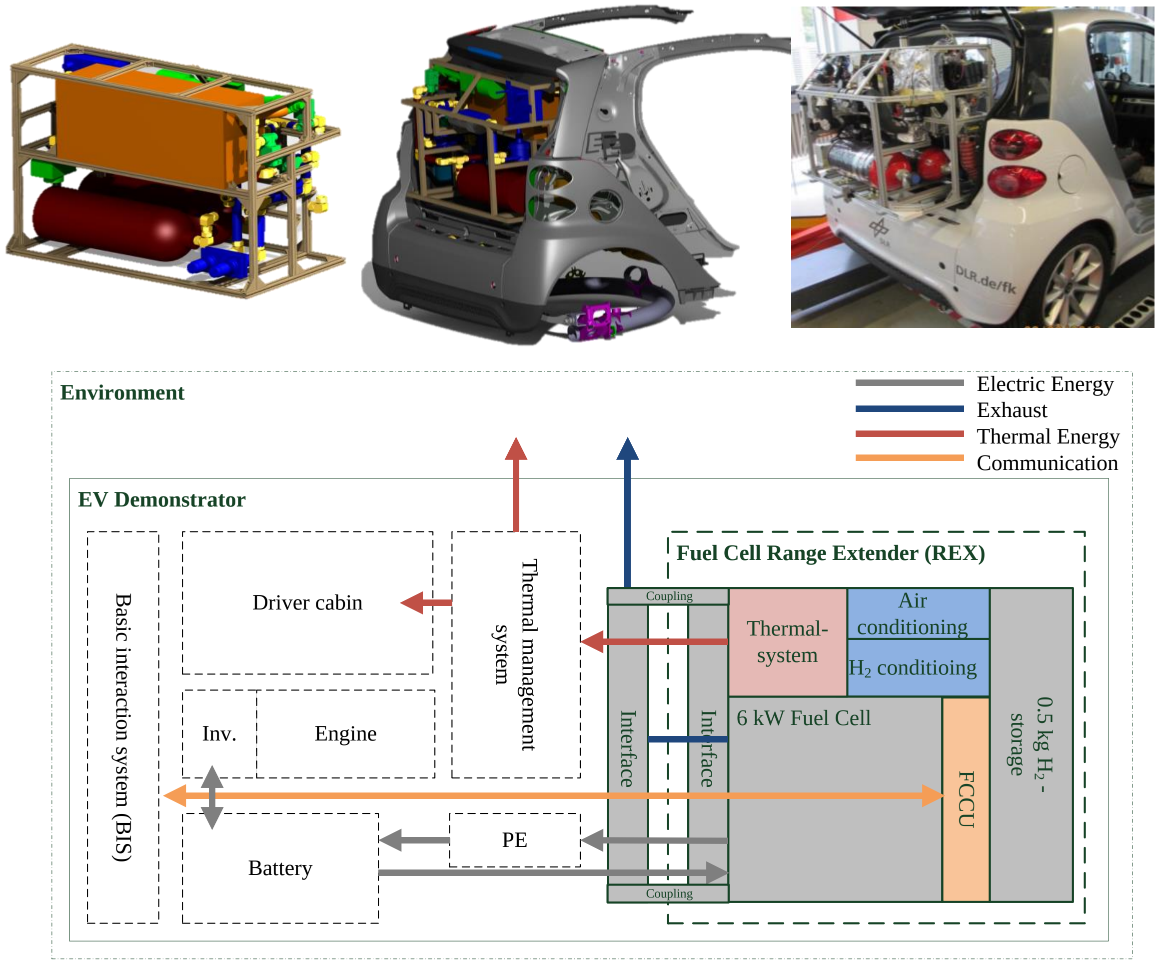

Figure 3: top: REX module for the trunk of the EV; bottom: Interface Diagram of the parallel hybrid EV+REX

The REX is mounted in the EV via mechanical interface on a drawer runner inside of the luggage compartment using a specially designed mechanical clasp. For stack heating, a 1.3 kW electrical heater is required in combination with a double pump concept integrated in the REX thermal system as a two circuit system separated by a coolant valve and a leakfree coupling mechanism. The required stack heating energy is taken out of the EV battery using an electrical power plug. To run the REX and to interact with the EV demonstrator a basic interaction system (BIS) is integrated in the demonstrator communicating with the fuel cell control unit (FCCU) programmed according to IEC611313 standards [6]. Hydrogen and feed air demand of the stack are conditioned inside of the REX and controlled by a watchdog implemented in FCCU. A hydrogen connector according to SAE J2600:2002 is mounted on the outside to ensure fast hydrogen refilling. The electrical output power is transferred via power electrics (PE) mounted in the EV to merge fuel cell output voltage and HV system. The produced hot vaporized product water of the chemical hydrogen reaction is transferred together with the HT-PEM stack purge losses via exhaust out of the EV.

5 Parallel power split configuration EV+REX

To investigate the hydrogen contribution of the parallel hybrid EV+REX combination in chapter 5.3, the test bench lineup is presented in chapter 5.1. A bulk test to derive fuel cell stack starting conditions was done at the laboratory (chapter 5.2).

5.1 Parallel hybrid combined test bench lineup

The combined test was performed in the fully air conditioned hydrogen certificated dynamometer of the German Aerospace Center Institute of Vehicle Concepts. The dynamometer contains an external gas conditioning unit for hydrogen. The REX was mounted in the EV. A concept picture of the test bench including the sensor/actor concept is presented in Figure 4.

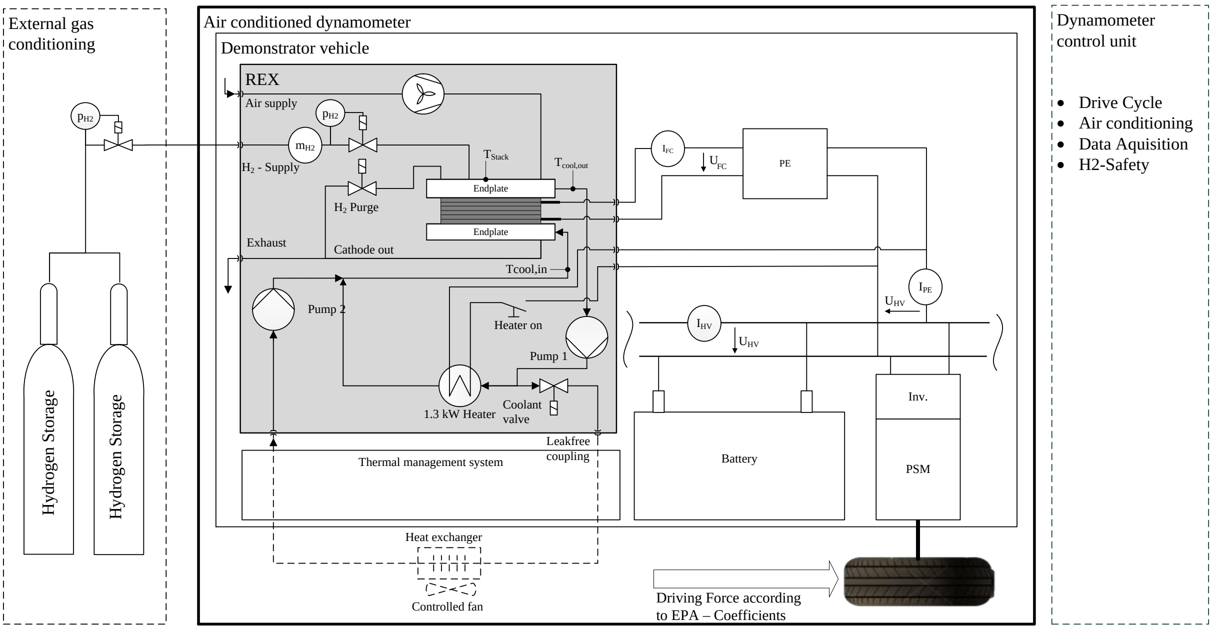

Figure 4: REX demonstrator car test bench lineup

For calculating the parallel hybrid hydrogen consumption a Coriolis mass flow sensor was integrated at the external hydrogen conditioning unit due to the space requirement. The REX conversion efficiency (1) is calculated using the power ratio of the HT-PEM output power P_{el} and the chemical power consumption P_{fuel} referring on the measured hydrogen mass flow $\dot{m}_{H2}$ and a hydrogen heating value of $\Delta h = 120\ kJ/kg$. Numerical integration will lead to overall REX hydrogen consumption $\mathrm{m_{Cycle}}$ (2).

$$\eta_{\mathrm{el,FC}} = \frac{\mathrm{U_{FC} \cdot I_{FC}}}{\mathrm{\dot{m}_{H2} \cdot \Delta h}}; \tag{1}$$

$$m_{Cycle} = \int_0^{t_{Cycle}} \dot{m}_{H2}\, dt \tag{2}$$

For completing the parallel hybrid energy split the electrical EV power on batteries HV system is measured integrating voltage U_{HV} and current I_{HV}. Neglecting secondary conversion between HV and 12V at disabled HVAC, only traction power is measured at HV. Using law of Kirchhoff (3) considering the electric current from PE and the measured HV current I_{HV}, the battery current I_{Bat} is calculated.

$$\sum_{k=1}^{n} I_k = 0; \qquad I_{HV} - I_{PE} - I_{Bat} = 0; \qquad I_{Bat} = I_{HV} - I_{PE} \tag{3}$$

The energy balance to derive the hydrogen contribution of the parallel hybrid power split between EV and REX is calculated according to driving time t_{Cycle} in equation (4).

$$\sum_{k=1}^{n} [E_k] = 0; \qquad E_{HV} - E_{PE} - E_{Bat} = 0; \qquad E_k = \int_0^{t_{Cycle}} [U_{HV} \cdot I_k]\, dt \tag{4}$$

5.2 REX Startup conditioning

For preheating the REX a start ping from BIS is send to FCCU (Figure 3) while closing the coolant valve and starting Pump 1 shown in Figure 4 to bypass the EV thermal management system. Closing the load contactor “Heater on” will start the 1.3 kW heater integrated in REX thermal system. The preheating power request is calculated using the EV battery voltage U_{HV} and current I_{PE} measured behind PE. A first bulk test of the designed REX was performed in [6]. The laboratory test showed a maximum stack heating gradient of 2 K/min consuming 10 Wh/K of electric energy starting at ambient conditions of 20°C up to a measured fuel cell end plate temperature of 120°C. After achieving the startup conditions, chemical fuel cell reaction is started by opening valve p_{H2} (on a hydrogen pressure of 50 mbar at purged anode dead end mode). FCCU controls the air fan according to $\lambda = 2$. HT-PEM waste heat is released in the EV thermal management system by opening the coolant valve forcing the outside heat exchanger by the usage of Pump 2. A mixing process between the hot coolant stored in the REX and the cold coolant in the thermal management system of the EV is done on a FCCU reheat procedure. A combined electrical heating and stepwise fuel cell load increase of P_{FC} will reduce the thermal stress caused due to TEG temperature drop. After stationary conditions in the cooling system are achieved REX is ready to deliver its maximum output power. A basic fuel cell testing procedure at a constant stack output current between 10A and 50A showed a maximum efficiency of around 52% having an average hydrogen purge loss of around 2% [6].

Table 5: Key results of REX testing [6]

$P_{heat,instat}$	$E_{heat,instat}$	$T_{Stack,Start}$	grad(TStack)	η_{max}	Purgeloss
1.3 kW	10Wh/K	120°C	2.0 K/min	0.52	~2%

5.3 Parallel hybrid energy split

The REX text experiment shown in Figure 4 was installed in the dynamometer at ~22°C ambient temperature. The parallel hybrid energy split evaluation includes NEDC, WLTC and the commuter track between ST and LA. For all results the vehicle HVAC system was disabled while REX module was ready for load at a measured end plate temperature of 120°C. An exemplary result including the FCCU reheat mode is shown in Figure 5 at the motorway track of the commuter LA-ST.

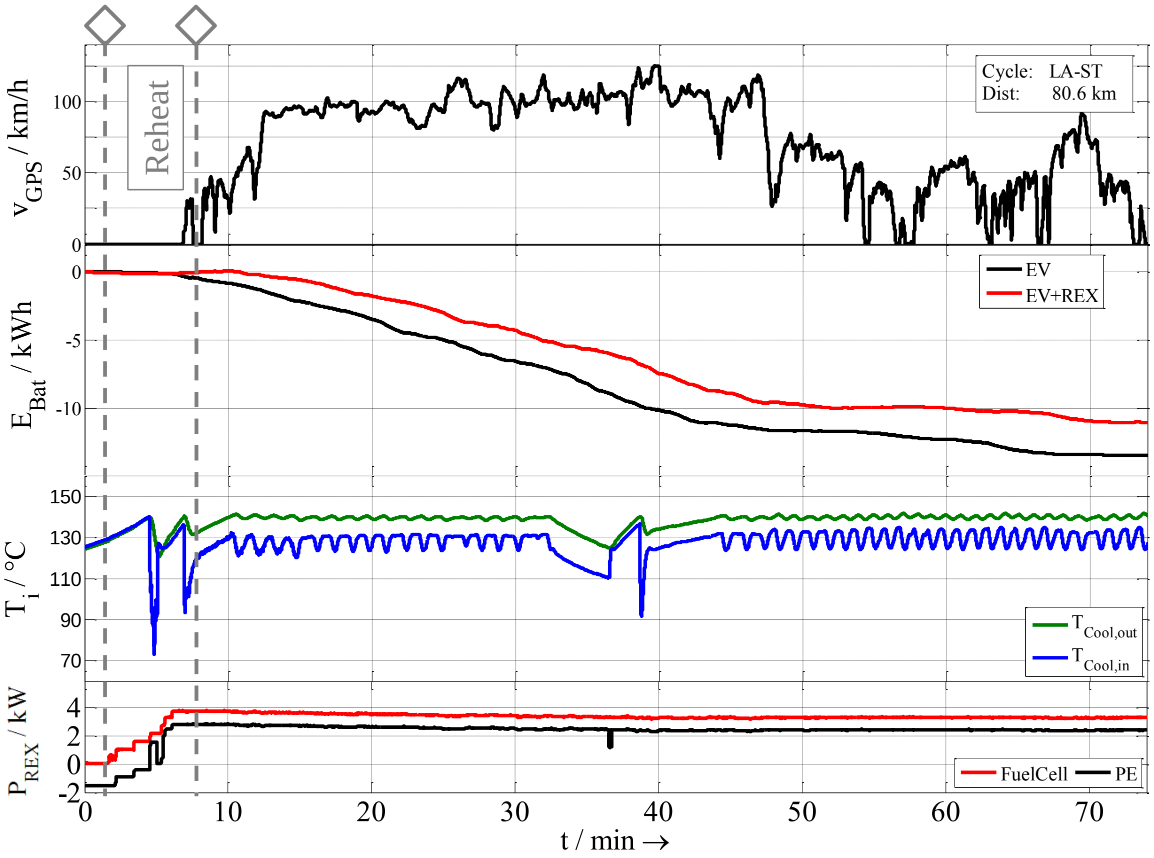

Figure 5: driving profile (1/4), energy demand out of the Li ION Battery (2/4), TEG coolant temperatures (3/4) and REX power state (4/4) on the track LA-ST (motorway)

In the first 7 minutes, the reheat process of FCCU is shown containing an electrical heating represented by a negative PE power (red line in the diagram) and an increasing stack output power P_{FC} (black line in the diagram) is shown. After 7 minutes the reheat procedure is finished starting the REX at its output power P_{FC} . Due to the voltage drop while discharging the demonstrator Li-Ion battery and setting a constant current regulation at the HV output of PE, the electrical fuel cell power dropped down from 3.9 kW to 3.3 kW. Referring on the measurements only 2.8 kW of the converted fuel cell electric power is transferred via PE to the HV system leading to an average conversion efficiency of ~72%. A calculation of the parallel hybrid energy distribution between Li-ION battery and REX showed an energy split of 80% (battery) while having a 20% contribution out of the hydrogen storage. This leads to an electrical battery energy demand of 11 kWh with an additional consumption of 3.4 kWh converted out of 0.28 kg hydrogen on the 80.7 km long test track at a fuel cell efficiency of 0.52 and additional 0.72% ratio of the prototypically integrated PE. The testing results for all tracks are summarized in Table 6.

Table 6: Testing Results of the demonstrator with the mounted REX according to Figure 4 measured at the dynamometer with EPA coefficients for smart eD

	NEDC	WLTC	ST-LA (freeway)	LA-ST (motorway)
hydrogen	4.4 kWh/100km	3.8 kWh/100km	3.0 kWh/100km	3.5 kWh/100km
battery	8.9 kWh/100km	11.3 kWh/100km	7.5 kWh/100km	13.7 kWh/100km
$E_{tract,demonstrator}$	13.3 kWh/100km	15.1 kWh/100km	10.5 kWh/100km	17.2 kWh/100km
energy split	33% H_2	25% H_2	29% H_2	20% H_2
η_{FC}	0.52	0.50	0.45	0.42
η_{PE}	0.72	0.73	0.72	0.74
m_{H2}	356 g/100km	320 g/100km	359 g/100km	350 g/100km
overall range increase	35%	34%	30%	30%

The results showed a measured energy split between 20% (LA-ST) and 33% (NEDC) on overall demonstrator traction energy demand. The fuel cell consumed between 320…360 gH_2/100km of hydrogen enlarging the EV+REX overall driving range up to 35% on NEDC using 0.5 kg hydrogen. The overall vehicle driving range measured on the dynamometer varies between 133 km on LA-ST (motorway) up to 219 km on ST-LA (freeway) consuming 0.5 kg hydrogen (Figure 6).

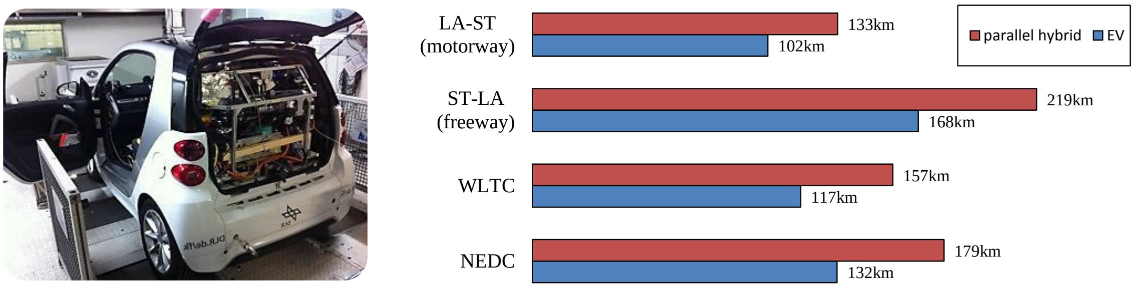

Figure 6: left: parallel hybrid vehicle at the dynamometer; right: calculated driving ranges based on the REX hydrogen storage capacity

A calculation based on the measurement results showed a validated overall parallel hybrid storage capacity of 22.8 kWh usable for traction. Referring on the ST-LA-ST (combined) cycle an energy demand of 22.4 kWh is required for a full trip. With the proposed system a freeway outward and a motorway return trip on the commuter cycle is possible without recharging the battery or the hydrogen storage.

6 Summary and Conclusion

The presented parallel hybrid vehicle with a modular 6 kW HT-PEM Range Extender containing 0.5 kg hydrogen storage showed a validated range increase up to 35% depending on the drive cycles. The conversion efficiency is limited by a measured fuel cell stack efficiency of ~50% and additional ~70% of the integrated power electronics PE. Using an optimized PE with an efficiency of 90% would increase the vehicle range up to 37% on the special commuter track and 42% on NEDC. Further restrictions are given by available hydrogen storage concepts limiting the overall parallel hybrid range. The integration of e.g. a high pressure storage with a pressure of >700 bar or the usage of metal hydride storages with optimized packaging will contribute to an increased hydrogen capacity. Furthermore, the usage of the fuel cell waste heat at 140°C shows the ability to minimize the driver cabin heating demand at cold environmental conditions [1, 2, 6]. First tests in the climate chamber showed the ability to heat the driver cabin at -10°C on stationary conditions without additional electrical heating. To reduce the cooling demand, a new metal hydride cooling concept using the cathode hydrogen pressure drop between storage and anode showed a HVAC cooling demand reduction of around ~10% [7, 8]. This enables the HT-PEM range extender to work as a hydrogen based thermal management unit to compensate additional range reduction caused due to HVAC. Additional simulations referring an optimized hydrogen conversion for HVAC at different ambient conditions are currently done on NGC energy management project. To validate the results, the proposed parallel hybrid vehicle test bench lineup can be used to reveal the influence of different fuel cell power points in combination with HVAC on overall vehicle range. This leads to the conclusion of a vehicle concept containing hydrogen as an alternative energy carrier for air conditioning to encouple the EV range from the influence of different ambient conditions. Based on overall project results the usage of a HT-PEM range extender showed some more research to reduce the thermal stress caused due to temperature drop in the stack and to lower the fuel cell starting temperature.

Acknowledgments

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