Potential of Reduced Fuel Consumption of Diesel-Electric APUs at Variable Speed in Mobile Applications

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ABSTRACT

Auxiliary power units (APUs) are used in mobile applications to provide electrical power until approx. 10 kW. It is state of the art that these generators are driven by a diesel engine at constant speed and are selected according to the expected maximal power needed. These systems have a low efficiency and consequently a high fuel consumption particularly when driven at small loads. The system can yield a higher efficiency for partial load conditions by reducing the rotary speed of the driving diesel engine. The optimum in rotary speed of the diesel engine for different loads is pre-programmed (engine mapping) in the diesel control unit. A frequency converter allows a constant frequency of the electricity output at variable speed of the generator. These higher costs for frequency converter and diesel controller demand especially for mobile applications a proof of efficiency, i.e. a proof of economics, which is shown in this paper.

A diesel electric drive train has been mounted on the test rig consisting of a diesel engine, a permanent magnet synchronous generator, a frequency converter and an electric load. The components were analysed individually in a first step to determine the efficiency characteristics. With the individual efficiencies of the components, the total efficiency of the drive train can be calculated in respect to rotary speed and torque. Relevant load profiles where chosen which represent typical duty cycles in stationary and mobile applications. The consumption of the variable speed generator was tested and the control parameters for the diesel engine were optimized using a simulation model. The final control parameters were implemented into the diesel controller at the test rig. The recorded experimental results were compared to the simulation results. The test results proved the precise prediction of fuel consumption by the simulation model. Tests and simulations resulted in a reduction of fuel consumption of about 30% for all of the relevant load profiles compared to the state of the art power units operating at constant speed of revolution. Further fuel saving potential was achieved with a start/stop-function which stops the diesel engine after a determined time period when no power is needed in order to avoid idle operation periods.

An economic analysis concludes this study. It was proved that the higher investment costs will be amortized within approx. one year.

INTRODUCTION

Diesel electric generators are designed to provide power in stand-alone systems (energy islands) for stationary or mobile applications. Stationary stand alone systems are remote locations which are not grid connected like remote farms, lighthouses or villages. Hybrid solutions - applying also variable speed generators - are subject of today's studies due to their high potential of reduced fuel consumption and better performance [1], [2].

Diesel electric generators are used as auxiliary power units (APU) in mobile applications which provide power additionally to the main diesel engine of the vehicle. Fields of application are military applications [3], ambulances [4], police vehicles, camper vans and long-haul trucks. Especially long-haul trucks are of major interest due to its high market potential particularly in the US [5].

Today, the only reliable way to provide enough onboard electric energy is to generate it by an electric alternator which is connected directly to the main engine. If the main diesel engine is used for auxiliaries in long-haul trucks (power for microwave oven, air conditioning, TV etc.) it runs at a very low efficiency and has therefore high fuel consumption, particularly during off-driving rest periods (idle periods, [6]). With a diesel electric APU scaled to the demand of the auxiliaries, the efficiency of the system can be increased as the main diesel engine does not need to run. These systems are based on a well-established technology and they are offered by a multitude of manufacturers [7]. However, in load profiles with a low load factor, the diesel electric APU has still a very low efficiency when operated at constant speed in order to keep frequency and voltage constant. A useful alternative may be a mechanical solution with a variable transmission between diesel and generator [8] which allows a variable speed of the diesel while the electric frequency keeps constant. For the considered small scaled APUs in a range of 3 to 10 kW, this solution is too costly and thus not a realistic alternative.

Using an electronic converter is an easier way to provide a system at variable engine speed but at constant electric frequency (VSCF). These devices are already available on the market for other purposes but a system with a generator in VSCF technology is still not established in the market as their higher investment costs are not yet proved to be economical by lower fuel consumption.

This paper shows the results of a project where representative load profiles were examined in respect to their fuel consumption potential when used with such a variable speed generator. The project was financed by the German Environmental Foundation (DBU) and was performed by the project partners Chair of Mobile Machines at the Karlsruhe Institute of Technology (KIT), Heinzmann GmbH & Co. KG and Motorenfabrik Hatz GmbH & Co. KG.

DUTY CYCLES AND CONTROL STRATEGIES

The idea of the VSCF-principle is based on a generator which is able to manage spontaneous power changes by an adjustment of rotary speed in order to keep the engine running in operational points of best efficiency at the actual load demand. The proof of efficiency needs to be done on typical duty cycles for APUs in mobile and stationary applications. It is not easy to find typical duty cycles for APUs as they are used in many different applications under various operation conditions. The application with the highest market potential is its use for long-haul trucks.

Long distance truck drivers keep their main diesel engine running after driving to supply the cabin with power for auxiliaries, especially in the US. The engine is, therefore, kept idling over night and generates high air pollution. This led the Californian government to ban idling of any truck over 10,000 pounds (ca. 4.5 t) for more than 5 min [9]. A duty cycle for this application is known ([10] and [11]) and considered in this project (duty cycle A).

More general but still well accepted cycles (in Germany) were selected for other applications though with lower market potential. The German Association of Electricity Business (VDEW, today's BDEW) generated a variety of different duty cycles of different types of consumers. The objective is to give grid operators an idea over typical load cycles of end consumers with less than 50 kW power demand. As the daily power demand of a particular consumer may vary from day to day, the problem is presented in the same way as for the analysis of load cycles of APUs. The generated VDEW-profiles are based on measured values and represent an approximation of the real demand but are still sufficiently exact to be accepted by suppliers and operators [12]. From this variety of profiles, there were some profiles chosen which seemed to be the most relevant for an application of a diesel electric APU with VSCF.

The load profile "Household" (duty cycle B) was chosen as an example for a stand alone (energy island) system. This profile covers the daily demand of a typical household. This profile is applicable to mobile APU applications where typical "hotel" loads occur like leisure yachts, caravans, recreational vehicles and long-haul trucks (as alternative to the truck profile described above).

Further duty cycles where chosen out of the VDEW-cycles in order to cover professional applications as law enforcement, rescue or specialty vehicles. The third one is the most general and describes the power demand of businesses in general (duty cycle C), the 4th one the power demand of businesses weekdays from 8-18h (duty cycle D) and the 5th one shows businesses with the highest demand in the evening (duty cycle E).

The 6th and last one represents the power demand of a farm (duty cycle F) which makes this cycle covering the stationary application of a diesel electric generator for a remote farm.

These load profiles where scaled to a peak power of 3 kW which corresponds to the maximum electric output power of the system on the test rig. The base load of the original

VDEW cycles was set to 0 kW which allowed checking the benefit of a start/stop-function of the system. For good results and good repeatability of the results, the profile duration was scaled to 20 minutes. Therefore, all cycles could be well compared as shown Table 1. All profiles have in common that no power peaks occur as they are all averaged which makes them more representative and provide a good idea of a fuel reduction of a VSCF-APU.

Four different control strategies where chosen for the tests:

1. constant speed of revolution
2. constant speed with start/stop-function
3. variable speeds of revolution
4. variable speeds with start/stop-function

The constant speed mode represents a conventional generator. As the profiles where scaled to the peak power, the system needed to be run in this mode at maximum speed of 3600 rpm in order to be able to meet the power demand by the small diesel engine of this test campaign. The start/stop-function allows to switch off the engine when no power is needed which increases the efficiency of the system. A rotary speed range of 1500-3600 rpm was chosen for the variable speed mode.

SIMULATION

A simulation model was created to analyse two different issues:

1. to calculate the consumption of the motor for the given profiles
2. to determine the optimum efficiency of the system for different load cases

The first one is used for verification of the model. Comparing the simulation results with the test results can quickly identify errors in measurements or simulations when large deviations occur. Moreover, it can be used for further load profiles of other applications to prove fuel consumption reduction potential.

The latter one was of high importance for this project. It allowed to determine the rotary speeds of the diesel for highest system efficiencies. The objective was to interpolate these points and to provide a characteristic curve of the system which was stored in the control device of the diesel engine. This ensures that the system always operates at best efficiency for any power demand. In a first step, the components creating the VSCF-system needed to be considered in the simulation. Fig.1 shows the system with all relevant components such as it was mounted on the test bench. For the simulation, only the drivetrain was examined, consisting of diesel engine, generator and motor inverter.

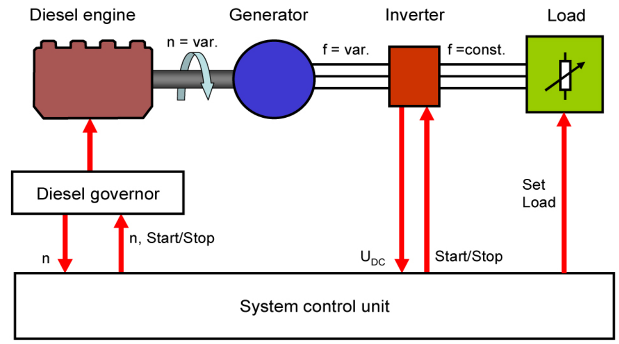


Fig. 1. Set up of the analysed system

As shown in Fig. 1, a buffer battery was not part of the system, in contrast to real APU systems. The battery is essential if spontaneous load peaks occur and the engine operates in a low rotary speed. In this project, the focus was mainly on the reduction of fuel consumption of the system so the profile was "known" by the control unit and a battery was therefore not needed.

The characteristic maps of the relevant parts of the drive train as engine, generator and converter and the efficiency optimization of the system were needed for the simulation.

The characteristic map of the diesel engine was provided by the Diesel manufacturer Hatz and directly integrated in the simulation model. The characteristic maps of the converter and the generator were measured on a test bench as shown in Fig. 2.

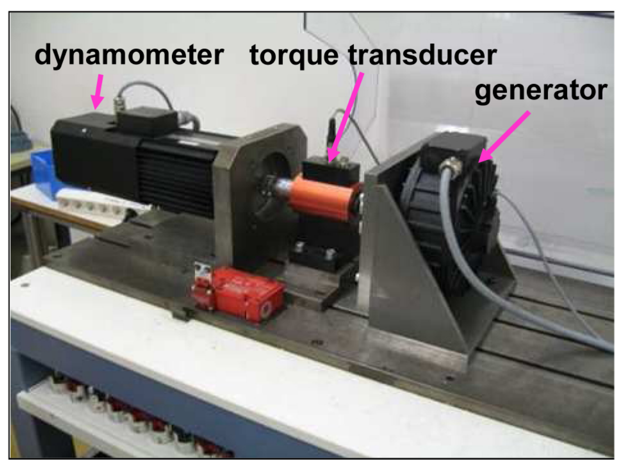
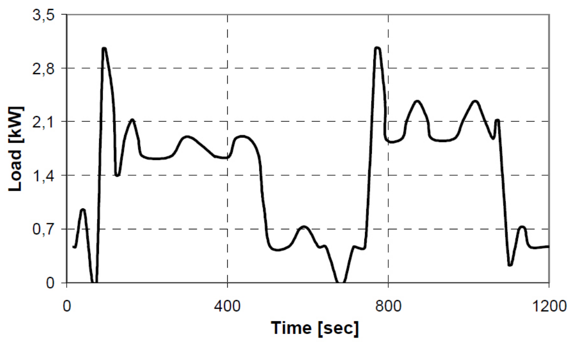


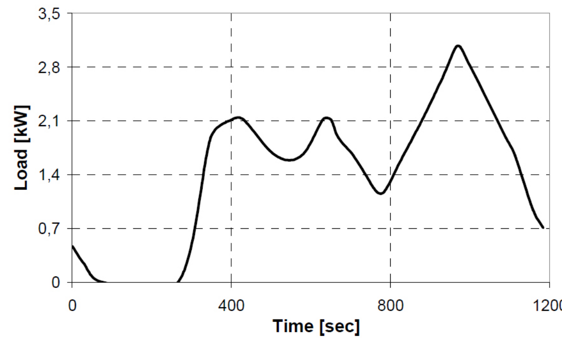
Fig. 2. Test bench for determination of characteristic maps

Table 1. Considered representative duty cycles

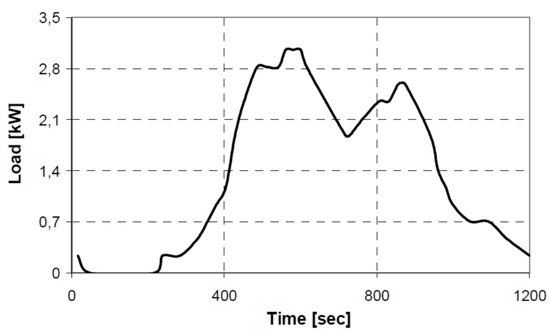
Profile "Long-haul truck"
Duty cycle A



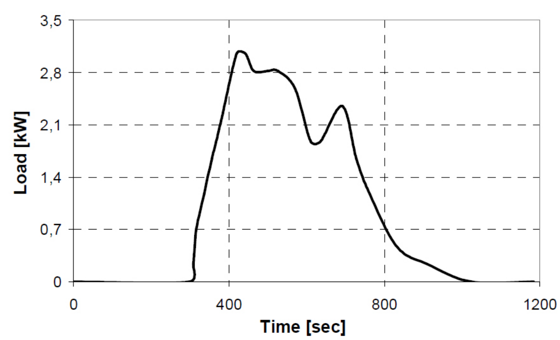
"Household"
Duty cycle B



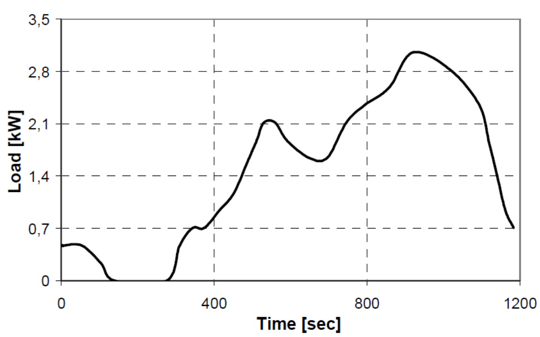
"General businesses"
Duty cycle C



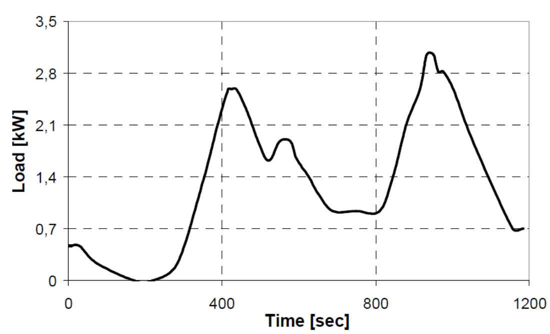
"Businesses workdays from 8-18h"
Duty cycle D



"Business with high demand in the evening"
Duty cycle E



Profile "Farm"
Duty cycle F



The simulation model was designed with Matlab ® - it is easy to handle and it seemed to be the best choice to determine the optimum operation points of the system.

The measured characteristic maps of generator and converter were included in the simulation model and a total characteristic map of the system was generated. Then an algorithm was programmed which calculates the points of best efficiency for each (electric) power demand. This resulted in a characteristic curve of optimum efficiency which is represented in Fig. 3. It can be seen that the lines of constant electric power provided to the consumer are deformed due to the different efficiencies of converter and generator. The area of highest system efficiency is at the top of the characteristic diesel engine field and located at the curve of maximum engine torque. This resulting curve was used for the control unit which adapts the rotary speed of the diesel engine to the present load.

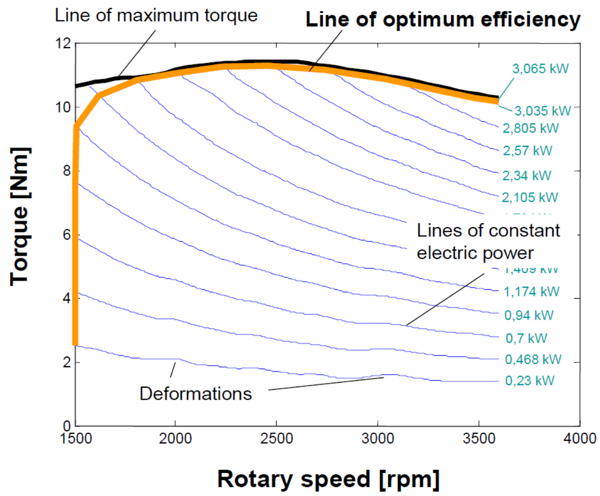


Fig. 3. Determined characteristic curve of optimum fuel consumption of the system

TEST BENCH AND RESULTS

The set up as presented in Fig. 1 shows a system without a battery, so that sudden power peaks could not be buffered. This function was not relevant for the proof of the fuel saving potential of the investigated VSCF so the duty cycle needed to be stored in the control unit of the system. The system managed that the diesel had enough time to change the rotary speed when the power increased. The system control unit had the following tasks:

• Control of the load: the control unit governs the electrical load in order to create the chosen load profiles

• Control of the rotary speed of the diesel engine and monitoring of the actual speed. The control unit communicates with the integrated diesel governor which is mounted on the diesel engine. The current rotary speed of the diesel is determined by the current load and the calculated curve of best efficiency

• Start and stop of the engine: when the profile was operated with start/stop function, the control unit stops the motor when no power is need and restarts it

• Control of the inverter with status check and error handling

The used diesel engine was a four stroke air cooled motor with one piston. The diesel has a nominal power of 3.5 kW @ 3500 rpm and its rotary speed can mechanically be changed which makes it well adapted for the digital diesel governor DG3005.10 of Heinzmann (Fig. 4)

Fig. 4. Diesel governor DG3005.10

The generator is a brushless permanent magnet synchronous generator (manufacturer: Heinzmann) and provides electric power of 4.5 kVA @ 3500 rpm. The winding is dimensioned in a way that it can provide under load a voltage of 150 VAC at 1500 rpm. This was necessary to ensure that the converter generates a stable voltage of 100 VAC at 50 Hz.

The frequency converter was connected directly to the generator. The alternating current was rectified by a passive rectifier into a direct current at variable voltage. This direct voltage was transformed into a 3-phase alternating current at a constant frequency of 50 Hz. A transformer changed this voltage to 400 VAC which corresponds to the common voltage in European low voltage grids.

The electric load was generated by four parallel connected resistances which allow 16 different linear increasing load levels. The continuous profiles were transformed by the control software into a discrete load profile according to the 16 power levels which could be created by the resistances. During a test run the software switched the resistances in order to approximate the entered load profile (see Fig. 5).

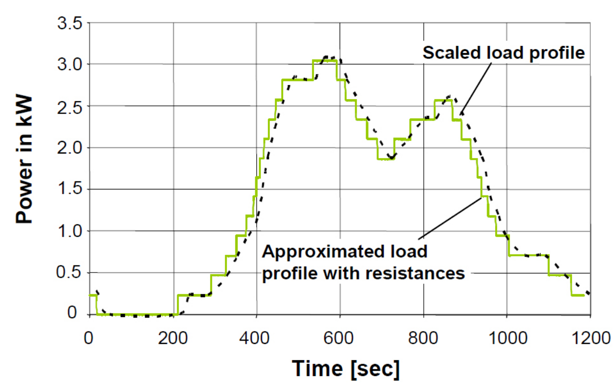


Fig. 5. Approximation of load profile with resistances

In order to measure the whole power chain, the driving torque and the rotary speed were measured directly at the drive train connecting the generator with the diesel engine (Fig. 6).

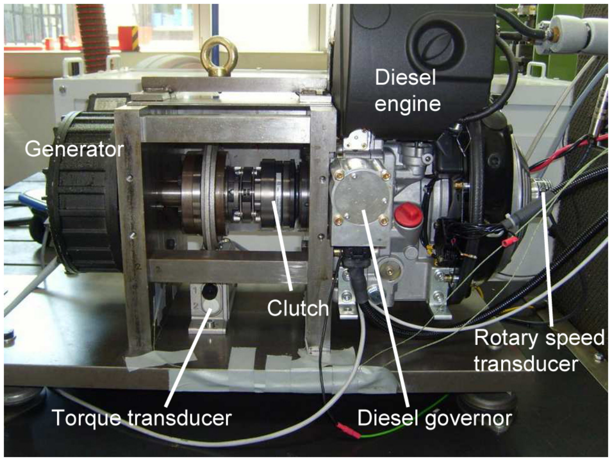


Fig. 6. Test bench with mounted diesel engine and generator

Table 2. Determined reduction of fuel consumption

Control Strategy		Duty Cycles A	B	C	D	E	F
Constant Speed	**E**	**0.28 L**	**0.28**	**0.27**	**0.24**	**0.29**	**0.27**
	S	0.26 L	0.26	0.26	0.22	0.27	0.25
Constant Speed S/St*	**E**	**0.28 L** ***1.3%***	**0.25 L** ***9.0%***	**0.25 L** ***8.5%***	**0.18 L** ***25.5%***	**0.27 L** ***6.8%***	**0.25 L** ***5.5%***
	S	0.26 L *1.5%*	0.24 L *9.2%*	0.24 L *8.5%*	0.16 L *26.7%*	0.25 L *7.0%*	0.24 L *5.6%*
Variable Speed	**E**	**0.19 L** ***30.3%***	**0.2 L** ***29.2%***	**0.12 L** ***28.5%***	**0.15 L** ***34.5%***	**0.21 L** ***27.1%***	**0.18 L** ***31.1%***
	S	0.18 L *30.8%*	0.19 L *28.7%*	0.19 L *28.6%*	0.14 L *34.8%*	0.20 L *26.9%*	0.17 L *31.3%*
Variable Speed S/St*	**E**	**0.19 L** ***30.8%***	**0.19 L** ***32.0%***	**0.19 L** ***30.5%***	**0.13 L** ***43.2%***	**0.20 L** ***29.0%***	**0.18 L** ***32.9%***
	S	0.18 L *31.2%*	0.18 L *31.8%*	0.18 L *31.3%*	0.12 L *44.3%*	0.19 L *29.2%*	0.17 L *32.5%*

E = Experiment, S = Simulations; *S/St = control mode with start/stop function

The test results with the total fuel consumption in litres for the considered load profile with different control strategies are shown in Table 2. The table shows in normal letters the simulation results, and the experimental results are presented in **bold** letters. The fuel consumption reduction with the given control strategy is written in *italic.* It can be seen that the fuel consumption of the diesel is lower for each profile when operated at VSCF. The start/stop-function has a stronger effect at longer periods of zero power demand, as expected. Generally, the rotary speed adaptation has a much stronger fuel saving effect than the start/stop function. Furthermore, it can be seen that the simulation model predicts very precisely the fuel consumption of the system. The deviation to the measured results is within low percentages.

The simulation model is also well suitable for predicting dynamic values like torque and current fuel consumption as shown in Fig. 7 and Fig. 8. In Fig. 8, a peak in fuel consumption can be observed which occurs when the diesel is accelerating to reach the next power level. These peaks are not modelled in the simulation model as it is quasi static.

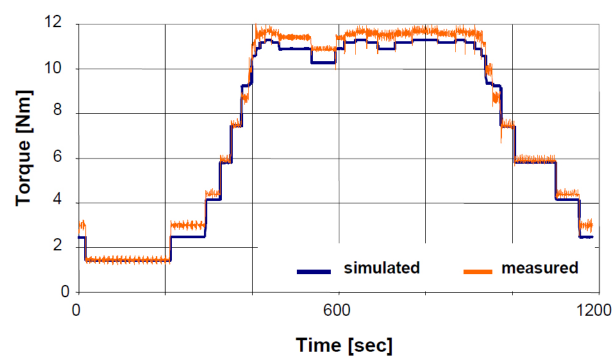


Fig. 7. Time dependent diesel torque, simulation and test results

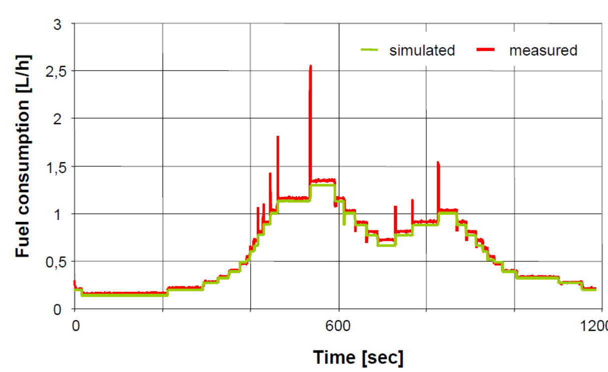


Fig. 8. Time dependent fuel consumption, simulation and test results

Table 3. Net present value analysis for a VSCF generator (according to [15])

	(unit)	Parameter (VSCF generator) Low	Middle	High	Payback periods for varied parameters (years) Low	Middle	High
Annual vehicle idling	(hours)	1818	2121	2424	1.3	1.1	1.0
Diesel							
Idling diesel consumption	(L per hour)	2.27	3.79	8.52	2.5	1.1	0.4
Diesel fuel cost	(€ per L)	0.80	1.00	1.20	1.4	1.1	0.9
Lubricant cost	(€ per hour idled)	-	0.05	-	-	1.1	-
Engine overhaul cost	(€ per hour idled)	-	0.05	-	-	1.1	-
VSCF Generator							
Installed generator power	(kW)	3	5	10	0.7	1.1	2.6
VSCF Generator capital cost	(€ per kW)	455	676	910	0.9	1.1	1.3
Capacitor/battery cost	(€ per kWh)	750	2500	4000	1.1	1.1	1.1
Diesel acceleration time	(s)	3	5	8	1.1	1.1	1.1
Heater and air conditioner cost	(€)	-	1260	-	-	1.1	-
APU installation cost	(€)	-	1050	-	-	1.1	-
APU O&M cost	(€ per hour idled)	0.14	0.26	0.37	1.0	1.1	1.1
Plumbing and wiring cost	(€)	-	250	-	-	1.1	-
APU diesel consumption	(L per kWh)	0.13	0.18	0.19	1.0	1.1	1.1
Market							
Inflation (labour, overhaul)	(%)	-	3	-	-	1.1	-
Inflation (diesel)	(%)	-5	5	15	1.2	1.1	1.0
Discount rate	(%)	-	10	-	-	1.1	-

COST ANALYSIS AND ESTIMATED PAYBACK TIME

A cost analysis of the VSCF-Generator for all given applications is difficult to do as very few information are available. Most promising analysis can be generated for long-haul trucks, as several researches were made towards emission and cost reduction due to idling reduction.

Cost estimates for an application as idling reducing equipment include beside of investment costs also higher weight for extra-equipment and reduced payload. The weight for a VSCF generator can be considered as comparable to a conventional diesel APU with a weight of 140 kg, a volume of about 140 L and costs between 500$ and $1000 (350€-700€) per kW [13]. Although carrying this extra weight would have a negligible effect on the fuel consumption of the main engine (less than 0.4% for a long-haul truck [14]) resulting costs for reduced payload need to be considered in a cost analysis. A net present value analysis which considers the principal influencing factors as well as a sensitivity analysis for these factors was presented by Brodrick et al. in [15] for a fuel cell APU. This analysis is projected here to a VSCF generator with updated data and by considering the installed output power of the system. Prices for diesel fuel can be estimated as much higher as assumed by Brodrick et al., the average price in 2010 in the US was 2.98$ per gallon (0.55 €/L) and is expected to increase until 3.97$ per gallon (0.73 €/L) [16]. Prices in Europe are generally higher and ranged between 0.80 €/L and 1.20 €/L in the EU [17].

The costs for generator and inverter for a conventional generator can be estimated as 30% of the total price of a gen-set. For a VSCF generator additional costs for inverter and controller occur so we consider a double price compared to the conventional generator as a good assumption. This would lead to a total cost increase by the factor 1.3 resulting in 455€ - 910€ per kW. Costs for battery/capacitor depend highly on the acceleration time of the diesel engine as the power demand needs to be buffered until the diesel reaches maximum speed in order to provide peak power. Generally, prices between 750€ and 4000€ per kWh can be expected. Overhaul and maintenance costs for a VSCF generator are not expected to exceed those of a conventional generator and are assumed as 0.37 $ per hour for APUs with an output power of 6 kW as described in [18] and [14]. A range of 0.14€- 0.37€ per hour seems to be a realistic assumption in our analysis. The consumption of the VSCF generator was calculated as the average of the measured cycles in Table 2 with variable speed and start/stop function with the highest and the lowest measured consumption as upper and lower boundary and scaled to litre per kWh.

Table 3 shows the results of the net present value analysis. Almost every parameter variation results into a payback period shorter than two years. Figure 9 shows the net present value of the VSCF generator for different consumptions of idling trucks. For a very low consumption of the truck's

Table 4. Net present value analysis for a constant speed generator

		Parameter (conventional generator)			Payback periods for varied parameters		
	(unit)	Low	Middle	High	Low	Middle	High
Annual vehicle idling	(hours)	1818	2121	2424	1.3	1.1	1.0
Diesel							
Idling diesel consumption	(L per hour)	2.27	3.79	8.52	3.5	1.1	0.4
Diesel fuel cost	(€ per L)	0.80	1.00	1.20	1.4	1.1	0.9
Lubricant cost	(€ per hour idled)	-	0.05	-	-	1.1	-
Engine overhaul cost	(€ per hour idled)	-	0.05	-	-	1.1	-
Conventional generator							
Installed generator power	(kW)	3	5	10	0.7	1.1	4.4
Generator capital cost	(€ per kW)	350	520	700	0.9	1.1	1.3
Heater and air conditioner cost	(€)	-	1260	-	-	1.1	-
APU installation cost	(€)	-	1050	-	-	1.1	-
APU O&M cost	(€ per hour idled)	0.14	0.26	0.37	1.1	1.1	1.2
Plumbing and wiring cost	(€)	-	250	-	-	1.1	-
APU diesel consumption	(L per kWh)	0.2	0.27	0.29	1.0	1.1	1.2
Market							
Inflation (labor, overhaul)	(%)	-	3	-	-	1.1	-
Inflation (diesel)	(%)	-5	5	15	1.3	1.1	1.0
Discount rate	(%)	-	10	-	-	1.1	-

motor the VSCF generator has a payback period of 2.5 years. With a high installed output power installation costs increases which leads as well to longer payback periods (2.6 years).

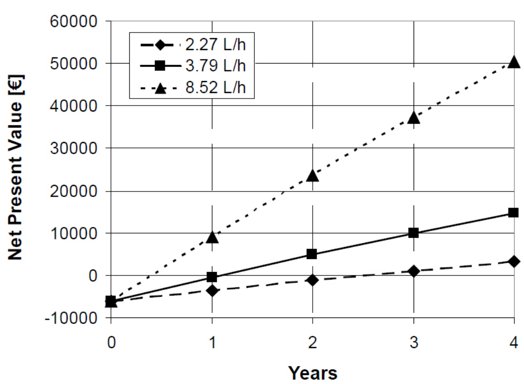


Fig. 9. Net present value evolution of a VSCF generator

Beside of the cost analysis of the system compared to an idling truck, extra costs for a VSCF generator to a conventional generator need to be justified, too. For this reason a second net present value analysis was done obtaining data of a conventional generator at constant speed (Table 4). For determination of the constant speed generator's consumption the average value of the measured consumption of a constant speed generator was used (see Table 2).

Comparing payback period of the VSCF generator with one at constant speed we can conclude that both generator types have a payback time of less than two years for every tested configuration. Although payback periods of a VSCF generator do not differ significantly in our analysis from one at constant speed a VSCF generator shows quickly a higher net present value. Figure 10 shows the net present value evolution of both systems for a middle parameter configuration. A significant advantage of the VSCF generator compared to a conventional generator occurs at higher installed generator power and lower consumption of the idling diesel.

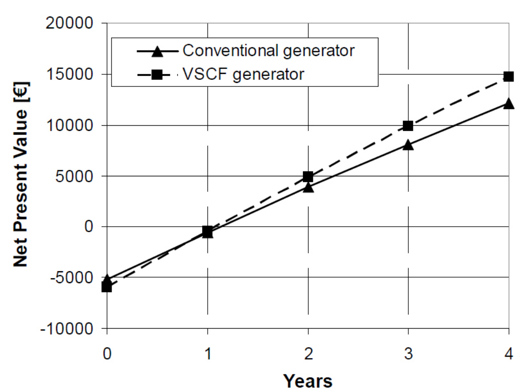


Fig. 10. Net present value evolution of a VSCF generator and a constant speed generator

CONCLUSION

The results have shown that operating an APU at variable speed enables a remarkable reduction in fuel consumption of about 30% for all considered load cycles. This is a very high reduction despite the fact that the tested profiles (which must be expected for APUs and stand-alone systems) have a rather low load factor. Certainly, other load profiles with higher load factors (not relevant for APUs) will exhibit a lower but still significant fuel reduction.

A net present value analysis has shown that the VSCF technology provides an economic and ecologic way to produce energy for auxiliaries, particularly for long-haul trucks. Payback periods of approx. 1 year have been determined when used as an anti-idling technology for trucks which is below an acceptable limit of two years for truck fleets [19]. Compared to a conventional generator the VSCF system reaches a higher net present value at periods of less than one year.

After the proof of fuel reduction the system will be tested with a buffer battery in order to optimize the system and to show the fuel reduction in a real environment with dynamic load changes.

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