HyTrEc 2

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Deliverable 3.2: Computer simulation of 5-9 tonne fork lift truck

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Introduction

Background: Small and medium sized forklifts often have electrical drivelines. The battery capacity is often not big enough for heavy use during long working days of several shifts. To extend the availability, batteries are changed during the day which requires specific equipment. To extend the operating time between charging, a fuel cell system can be installed. The original battery pack is changed to a fuel cell pack including: fuel cell package, hydrogen storage and a battery with smaller capacity and volume. The available volume is the volume left by the original battery and there is rarely additional unused volume available.

Requirements: The forklift specification is generally unchanged. The forklift is developed for its original use and there is normally no need to change engine specifications etc., but new and expensive components are added.

Fuel cells still have limited life. To increase the life as long as possible is necessary for economic reasons. Therefore, the number of large load variations and especially the number of start/stops should be kept to a minimum. This means that a battery must take the large load variations and store energy for short load peaks. Thus, the battery energy capacity can be reduced but the power capacity must remain as it was in the original battery. The hydrogen storage requires high pressure to reduce volume (typically 350 bar).

Forklift data specification:
Type: 5-9 tonne fork lift truck
Weight: 10 000 kg
Power driving: 30 kW
Power lifting: 50 kW
Fuel cell power: 15 kW
Battery capacity: 54 kWh

System model

Model concept considerations: Several options are open for modeling the driveline and other electromechanical components. For the simple case, only the electrical power source is changed, but also hydraulic equipment (if existent) could be replaced with electrical. Components are modelled from their specifications. The modeling of rotating motors is straight forward, but they have peak loads much larger than their nominal continuous load. The modeling is more difficult for linear actuators (electrical are slow or weak). Measurements in the driveline is an alternative that can be easier to use.
The energy consumption is decided by the operating cycle, but the standardized cycle in EN 16796-2 is too heavy compared to realistic use. Therefore, an estimation is required covering a working day including breaks.

Block diagram of the model: Fig. 1 shows a block diagram of a forklift driveline model. In the following each block of the model is explained in short.

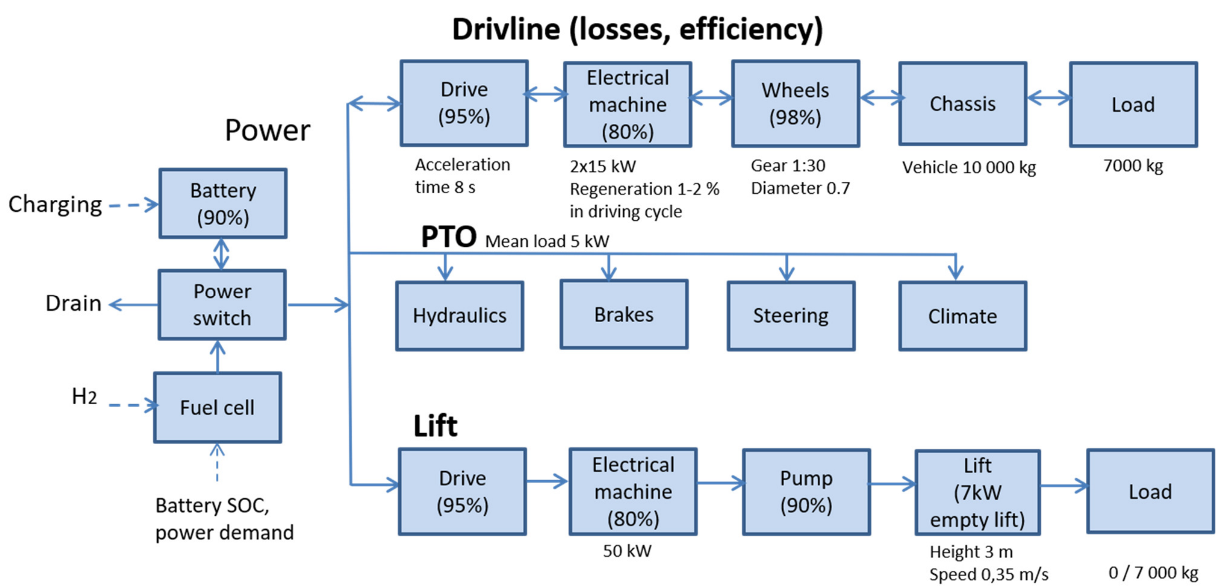


Fig 1: Block diagram of forklift model. *An example of a crude model showing energy flow and power levels (values within brackets denotes efficiency of each component).*

Fuel cell and battery: To optimize the fuel cell life it is only operating at 100% or 10% load (more precisely 93 and 13 %) and it is never switched-off during breaks. Switching between load levels is depending on battery state-of-charge (SOC). Suitable levels are decided by the battery technology. A small SOC-window (e.g. 70% - 90%) increases life for Li-Ion batteries. Fuel cell size is kept as small as possible to save space and cost.

Power switch: Feeds power between sources and loads as shown in Fig 1. The power switch from battery and fuel cell can be combined. When there is no power requirement and the battery reaches maximum SOC the fuel cell power is feed to the drain.

Drive: The drive is the power electronics driving the motors. The drive efficiency is shown e.g. (95%).
The drive engines can be overloaded during short peaks. The acceleration time is the time it takes to increase the motors to peak load. Allowing ramp-up time to peak load increases safety and drivability. Modelling of the drive can be done from measured behavior which is simpler than finding the algorithms.

Electrical machine: An induction motor is selected. It has low efficiency (80%) but is a low-cost and reliable engine. The efficiency is actually a complicated function of load and speed but is here simplified to a single number. The peak power is given by the drive-in combination with the machine. The acceleration time is the period the power is ramped up to peak. This is set in software to achieve safe and comfortable driving and to limit current at low engine speed.

Wheels: The rolling efficiency given (98%), is for hard surfaces.

PTO – power take off: There are several additional loads. Their total load is limited and it has to be considered how detailed their models shall be. E.g. the brakes have a quite high peak load which makes it efficient to use hydraulics with energy stored in an accumulator. To make a detailed model of how this works gives only a limited contribution to energy balance since the average load is small.

Lift: The model of the lifts has similarities with the drive line. In this concept the lift motor is hydraulic. Lifting the forks without load requires a quite high power (estimated to 7 kW).

Driveline modeling

Fuel cells and batteries are expensive components and it is important to optimize their life time. The state of charge (SOC) for a battery should be kept within limits that are depending on battery technology, for example between 70and 90% (SOC window). In order to avoid start/stop-problems the fuel cell shall be kept running, for example, by switching power between 10% and 100%. To accomplish this, modeling is needed for balancing of energy (battery SOC) and power (from battery or fuel cell).

The driveline can be modelled in different ways depending on what type of results that are expected/needed. For a detailed model it is required to have the engine map from the manufacturer, drive performance control software (decides maximum accepted overload and how power is ramped up during acceleration), and a driver model. All these inputs are probably difficult to find.

The driveline can also be modeled based on measurements of speed, acceleration, fork load and lift speed, in a semi-empirical model.

Power demand and Simulink model tool

A system based on the components described above, with battery capacity of 54 kWh and fuel cell of 15 kW, was modeled using a Simulink program tool. The battery SOC should be kept between 70 and 90% and the fuel cell power was either 14 kW (93% of max) or 2 kW (idle, 13% of max). An assumed operating cycle was taken from the standard EN 16796-2 and adapted to a full working day under realistic conditions. The operating cycle includes lifting a cargo-load of 4,900 kg from one shelf and transporting it 30 meters to another shelf. The resulting standardized power demand profile is given in Fig. 2 and it includes: forward drive 30 m, lift 2 m and reverse drive 4 m, which is repeated twice.

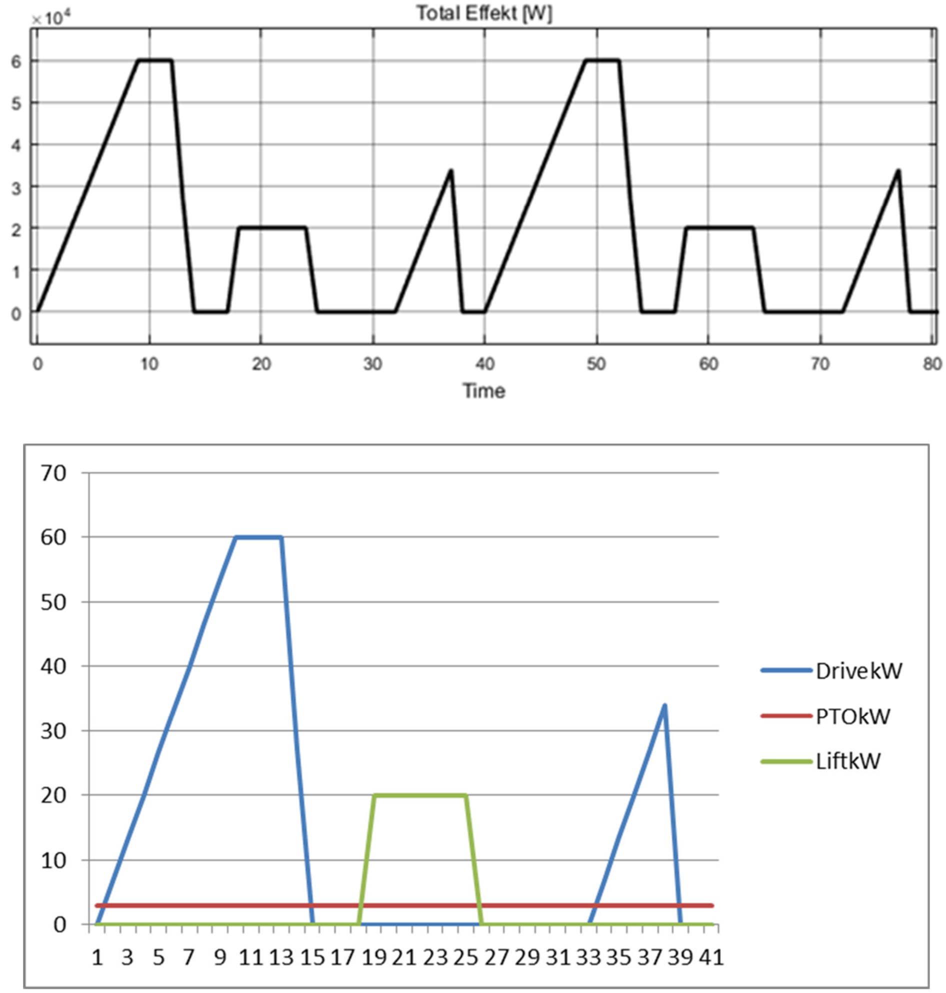


Fig. 2 Standardized operating cycle. *a) upper, power demand in a standardized operating cycle of 80 seconds. b) lower, power demand of different parts of the powertrain.*

Results

The standardized operating cycle of Fig. 2 has been applied in a simulation scenario where the forklift is assumed to be running 50% of the time, meaning 80 seconds operation followed by 80 seconds standstill. The total simulation time was 24h assuming a 2-shift operation (16 h) and a 15 minute "coffee-brake" after every 2.5 h. During the night the fuel cell was idling, and excess electricity was drained if the battery was fully charged.

Fig 3 shows the battery SOC during the first 2.5 hours (9000 sec). The wavy shape is due to the varying power demand illustrated in Fig. 2. Initially, the battery SOC is gradually decreasing to the lower SOC limit: 70% at around 4600 s. The control logic then increases fuel cell power to 14 kW and the battery SOC increases again.

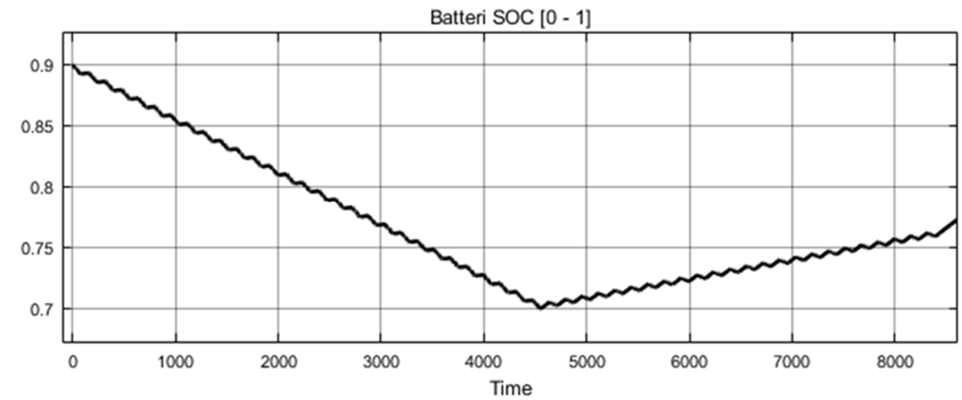
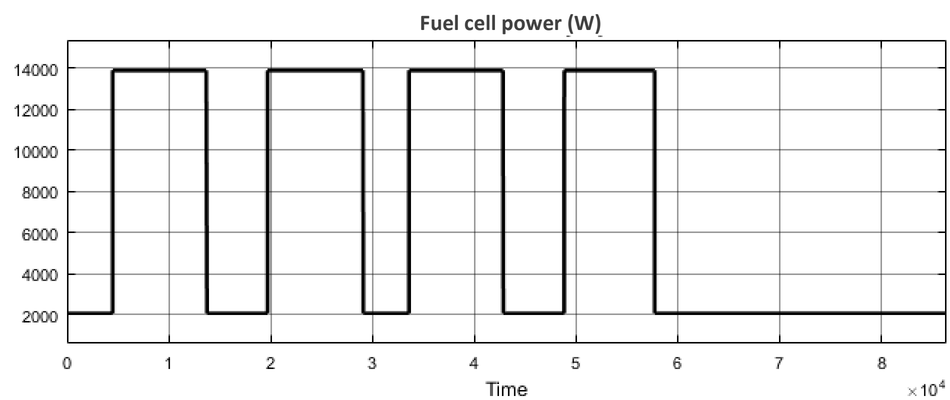
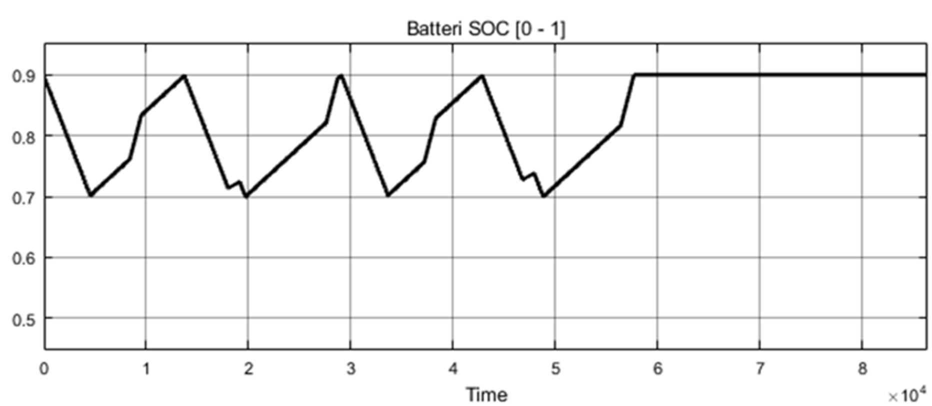


Fig 3. Battery SOC. *Battery state-of-charge (SOC) during the first 2.5 h. Fuel cell power increased at 4600 s leading to recharging of battery.*

Fig. 4 shows the full simulation results with the fuel cell power alternating between 2 and 14 kW and triggered by the battery SOC decreasing to 70% SOC. The irregularities of the battery SOC curve is due to the "coffee-brakes" when the power demand is zero leading to more/faster battery recharging.





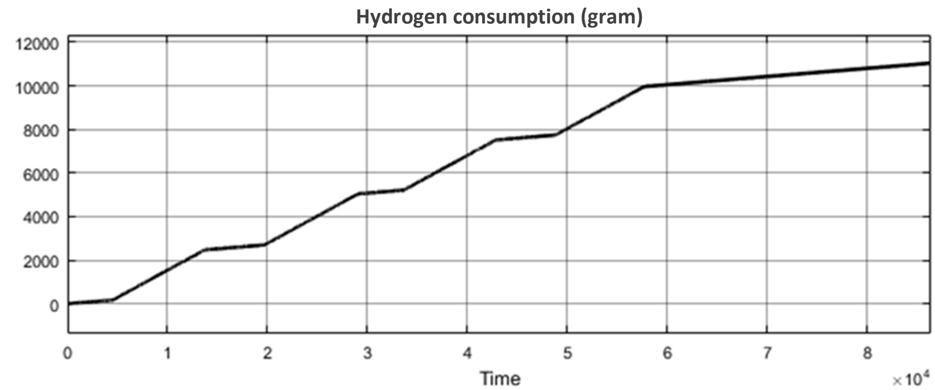


Fig 4. Full simulation results during 24 h (86400 s). *a) upper, fuel cell power alternating between 2 and 14 kW, b) middle, battery SOC decreasing to 70% SOC and being recharged to 90% when the fuel cell is operating at 14 kW. c) lower, cumulative hydrogen consumption having a stairway shape with a lower consumption when the fuel cell is at idling (low power).*

From approximately 57000 s the fuel cell is starting its overnight idling (see Fig.4c). During this period the fuel cell consumes about 1 kg of hydrogen. In order to evaluate if turning off the fuel cell overnight is better the cost for this hydrogen should be compared with the improved life-time to be obtained by not turning off the fuel cell.

Conclusions

This simulation study shows how the fuel cell can be operated in a two-level variable mode without ever being turned off and how the battery state of charge is depending on several parameters, such as: Operating cycle, fuel cell size, battery capacity, battery state-of-charge window, control algorithm, etc. Some specific findings:

- The total fuel cell generated energy was 155 kWh during 16 h use which is equal to 3 x battery capacity.
- 12 kWh was wasted into the drain during the 8-hour standstill to extend the life time of the fuel cell, but this loss could have been limited by decreasing the upper SOC limit when approaching the end of the day (or by switching the fuel cell off, or using the power somewhere else as part of a vehicle to grid or vehicle to energy store system)
- A large battery can deliver high power over a longer period
- A small battery will require more frequent switching of fuel cell power
- A large fuel cell that allows frequent power switching requires less battery capacity.
- The impact of this procedure on life-time has not been experimentally verified yet, but it is believed to have a positive effect.