NTNU
Norwegian University of
Science and Technology

Electrical Power Supply for Military Ground Troops

Carl Gustaf Rye-Florentz

Master of Science in Energy and Environment
Submission date: May 2010
Supervisor: Per Finden, ELKRAFT
Co-supervisor: Sissel Forseth, FFI
Arne Lind, IFE

Norwegian University of Science and Technology
Department of Electric Power Engineering

Problem Description

The intention of this thesis is to investigate possible pathways to a more suitable electrical power supply system for both military vehicles and ground troops. Present solution is based on generation of electrical power from diesel generators or electrochemical energy stored in batteries.

The objectives in the thesis will be to investigate possible energy suppliers for military vehicles and ground troops and describe the technological solutions they can offer. Specify the selection criteria and make an evaluation of the different available technologies. Based on available equipment the electrical energy consumption for vehicles and ground troops shall be measured or/and estimated. With the data collected, a mathematical model for simulation of energy production and consumption, both for vehicles and ground troops, shall be developed.

Assignment given: 07. December 2009
Supervisor: Per Finden, ELKRAFT

Preface

This master thesis is the final work of my Master of Science at the Department of Electrical Power Engineering at Norwegian University of Science and Technology (NTNU) in Trondheim. It is a continuation of my earlier project [1] and the thesis has been developed with help from supervisors from Norwegian Defence Research Establishment (FFI), Institute for Energy Technology (IFE) and NTNU.I am grateful to my supervisors Professor Per Finden and Dr. Arne Lind for their support. In particular, I would like to thank supervisor Dr. Sissel Forseth who gave me the benefits of her criticism.

Carl Gustaf Rye-Florentz

Oslo, Norway 16 May 2010.

Abstract

This master thesis studies the possible pathways to support military vehicles and ground troops with electrical power in a more efficient way than the present solution. The present energy solution is based on generation of electrical power from internal combustion engines and/or stored energy in batteries. The usage of vehicle's engine for generation of electricity in static positions results in several disadvantages on a modern battlefield. The specific energy of batteries increases every year, but the soldier's energy need has increased even faster, resulting in a problematic weight load for the dismounted soldier.

In this thesis several new and improved solutions are investigated. The solutions are based on technology available today or within the next decade (2020) and are selected on the basis of military criteria. A flexible model, capable of simulating a wide range of different configurations based on estimated future electrical power consumption, has been implemented in a simulation program called TRNSYS. Modelling and simulation of the soldiers power system has been recommended by earlier studies [10], but similar models have not been found by the author.

The simulation results reveal that improvements of soldiers' energy solution are feasible. By implementing new or better batteries in the current energy system, considerable improvement can be achieved. Introduction of fuel cells based on methanol fuel starts to become mature, and can result in several advantages on the battlefield. Solar harvesting can give an additional energy supply, but is highly dependent on insolation and the availability of time.

Contents

Acronyms and Abbreviations

Acronyms

AC	Alternating Current
APU	Auxiliary Power Unit
a-Si	Amorphous silicon
BAT	Battery
CEM	Cation-Exchange Membrane
c-Si	Crystalline Silicon
DBFC	Direct Borohydride Fuel Cell
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
DYN	Dynamo
F34	NATO logistic fuel, kerosene
FC	Fuel Cell
FFI	Norwegian Defence Research Establishment
FLO	Norwegian Defence Logistics Organisation
FSOC	Fractional State of Charge
GPS	Global Position System
HMD	Head Mounted Display
ICE	Internal Combustion Engine
IFE	Institute for Energy Technology
IR	Infrared
JP8	US logistic fuel, kerosene
MB	Mercedes Benz
NREL	National Renewable Energy Laboratory
NTNU	Norwegian University of Science and Technology
NVG	Night vision goggles
PC	Personal Computer
PDA	Personal Digital Assistant
PEMFC	Proton Exchange Membrane Fuel Cell
P-PEMFC	Proton Exchange Membrane Fuel Cell utilising Borohydride
PV	Photovoltaic
rpm	Revolutions per minute
RX	Receive
SAT-COM	Satellite Communication
SOA	State of Art
SOFC	Solid Oxide Fuel Cell
STBY	Stand by
STC	Standard Test Condition
TI	Thermal Imager
TRNSYS	Transient Energy System Simulation
TX	Transmit
UAV	Unmanned Air Vehicle
UHF	Ultra High Frequency
US	United States of America
VHF	Very High Frequency

Abbreviations

A	Ampere
Ah	Ampere hour
Al	Aluminium
C	Carbon
Ca	Calcium
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Diselenide
CIS	Copper Indium Diselenide
CoO_2	Cobalt Oxide
Fe	Iron, Ferrum
I	Current
Kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour
L	Litre
Li	Lithium
Li Ion	Lithium ion
Mg	Magnesium
MnO_2	Manganese oxide
Ni-Cd	Nickel-Cadmium battery
Ni-MH	Nickel Metal Hydride battery
R	Electrical resistance
Si	Silicon
SO_2	Sulphur dioxide
SO_2Cl_2	Sulfuryl chloride
$SOCl_2$	Thionyl chloride
V	Voltage
W	Watt
W/kg	Power density
Wh	Watt hour
Wh/kg	Specific energy
Wh/l	Energy density
Zn	Zin

Introduction

The intention of this thesis is to investigate possible pathways to a more suitable electrical power supply for both military vehicles and ground troops. A more suitable solution could result in better mission endurance, improve stealth capabilities, reduce logistic cost and reduce the environmental footprint.

New and improved weapon systems, communication equipment and sensors have lead to more accurate and lethal weapon system, earlier detection of (possible) hostile acts and an overall improved force protection. This has also resulted in an increased power and energy requirement on the battlefield, since a large part of the improvements is based on electronic hard- and software. It is reasonable to assume that enemy forces have improved detection capabilities too, and so, low thermal signatures on the energy-power suppliers of own and allied troops are also important.

Today's electrical energy system for vehicles and ground troops is fully reliant on generating electricity from the vehicle's dynamo or stored electrochemical energy. The vehicle's engine is made for propulsion, not for generation of electrical power in static positions. Fuel efficiency for static power generation is often very poor, which leads to waste of a precious resource in the battlefield. Thermal signature and noise are also serious issues in a modern battlefield. The consequences of fuel wasting and a thermal-acoustic signature depend on the theatre and specific mission, but both are crux matters with a high potential of improvements.

Batteries' specific energy has improved over the last decade, but compared to the growth in electronic devices and their energy consumption, the weight of batteries has increased considerable for the soldier. For ground troops the battery load is approaching its maximum weight on missions of long duration and walking distance. To be able to follow the mounting power and energy needs from a variety of devices, the specific energy of the source must either increase or a different solution must be found.

Several emerging power solutions can possibly be implemented in the short term. All power supply systems investigated are for military purposes, which mean they must be able to function in rough environments and tolerate rough handling. By creating a model to simulate the most promising power sources and power need, the power system is better understood and determination of the best solution with a relative high degree of certainty can be made.

Aim

The intention of this thesis is to investigate possible pathways to a more suitable electrical power supply system for both military vehicles and ground troops.

The main objectives are:

- Investigate possible energy suppliers for military vehicles and ground troops and describe the technological solutions they can offer. Specify the selection criteria and make an evaluation of the different available technologies.
- Analyse the positive and negative consequences of introducing new technologies or energy solutions.
- Based on available equipment, measure/estimate electrical energy consumption for vehicles and ground troops. With the data collected, a mathematical model will be developed for simulation of energy production and consumption both for vehicles and ground troops.
- Investigate and analyse new solutions.

Scope of Work

This study will only consider power supply solutions valid for land soldiers, dismounted or mounted. When mounted, a typical Norwegian military mobility and reconnaissance vehicle called Multi will be used as case.

The electrical power for electrical soldier devices are of interest and the vehicle’s propulsion system and thermal and electrical energy used for heating or air-condition is out of the scope.

Only technology available today and 10 years into the future (2020) will be taken into account.

Energy consumed by soldiers and vehicles in camp will not be considered.

Background

Present Electrical Power and Energy System.

The electrical energy consumed by the modern soldier has increased considerably over the last decades and is likely to increase further. Along with technological development of new capacities, many of the former devices like map and compass have been exchanged with electrical energy consuming instruments, like digital maps displayed on a computer with a GPS. The modern and future solider depends fully upon reliable electrical power supply.

Operations based only on foot or vehicles are different to each other from an electrical energy point of view, but they share the need for electrical energy. The present electrical energy systems for soldiers and vehicles will therefore be handled separately.

Military Vehicles

All military vehicles operating on the battlefield have an internal combustion engine for propulsion. The engine drives a dynamo which is used to generate electrical power. The vehicles usually have a battery pack for operation of electrical equipment when the engine is turned off. The vehicles' battery capacity fluctuate from a few minutes to several hours, under normal energy consume. In this thesis a Norwegian military vehicle made for mobility and reconnaissance operations will be used as a case vehicle. The vehicle is called Multi and currently used by the Norwegian army in Afghanistan. Several different models are in service, but the Multi model is one of the newest developed, with a relatively advanced electrical supply system.

The Multi vehicle is built on a Mercedes Benz (MB) 2.9 litre turbocharged diesel engine with improved nozzle connection. Original has it 118 horse powers or 88kW output at 3800 rpm with turbo. However a number of modifications have been done on both the engine and vehicle.

The vehicle has two electrical sources available, the dynamo power and stored electrical energy in batteries. When the engine is turned off, the electrochemical stored energy in the batteries is the only available electrical power source. The batteries in the vehicle can be divided into start battery, power box and spare equipment batteries. The flow diagram in figure 1 shows the electrical system in the vehicle.

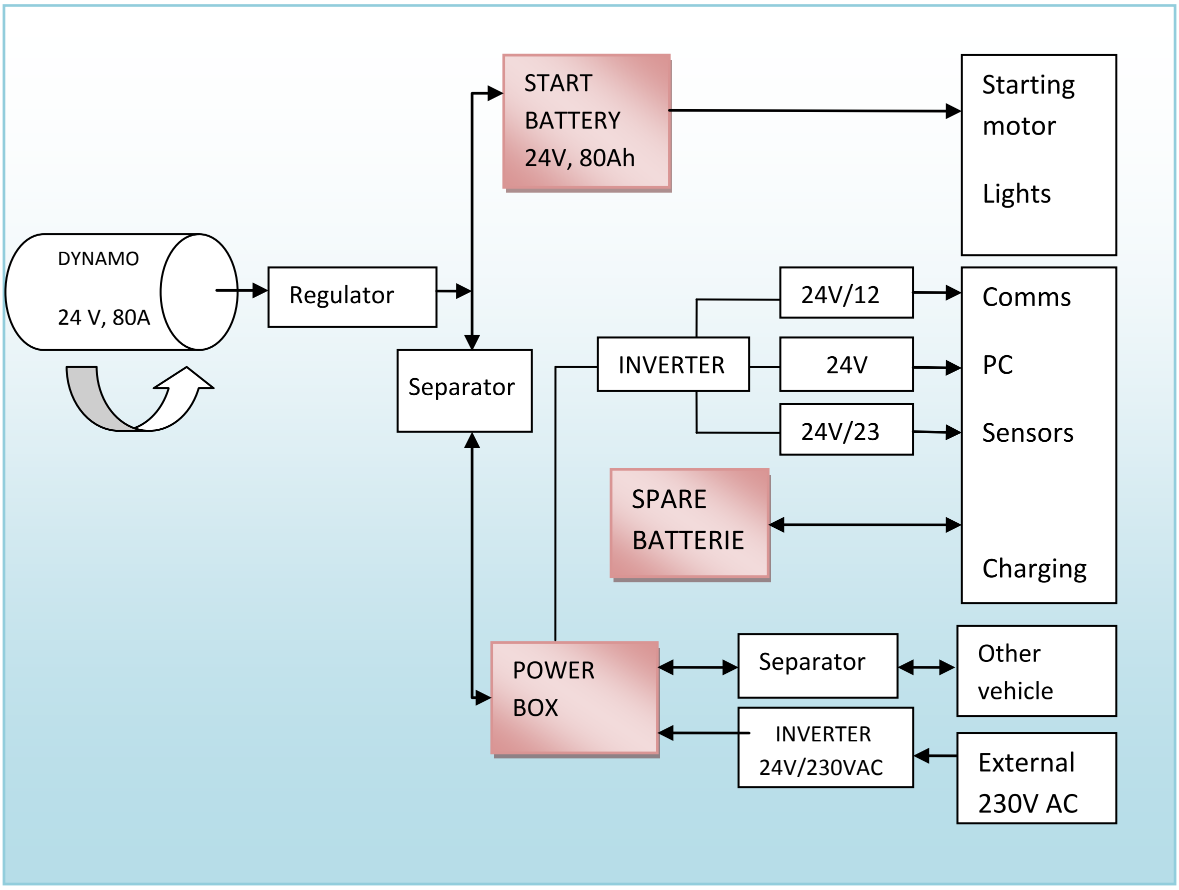


Figure 1.Flow diagram of electrical power system in Multi vehicle.

In figure 1 the dynamo (when engine runs) supplies the start battery and power box with electrical power. The dynamo is able to supply 80 A at 24 V, which gives a maximum electrical power output of 1920 W. The separator, between dynamo and power box allows charging, but prevents power flow between start battery and power box. By preventing power to be drain from the start battery to the power box, sufficient power for the start engine is always present. In emergency, if extra power is needed for start up or power supply, an override switch is installed. By using the override function the start battery and power box becomes parallel connected and extra ampere hours are available.

The battery in the power box is two lead acid 80Ah, 12V batteries in parallel, and has a total capacity of 1920 W. The power box can supply the vehicle with 12V DC, 24V DC and 230V AC by inverters. It is also able to parallel connect with other vehicle's power box or be supplied by an external 230 V AC source. The separator between the other vehicle and own power box prevent undesired discharging of own power box, by a preset minimum voltage level. This separator is also equipped with an override function if a special situation occurs. At all plugs suitable fuses are installed to prevent overcapacity.

When all available energy in the power box and start battery are consumed, and the engine is not running, little electrical energy is available. Only a limited amount of spare batteries for emergency communication are always brought into the battle field. The engine and dynamo are therefore an extremely vital part in the vehicle, both for the evident propulsion of the vehicle and the supply of electrical power. When the vehicle is static, idling must be done frequently since the power box has a depletion time between 5-10 hours, when the electrical equipment is used relatively active.

Under propulsion the power supply is never a concern and the power load is always below the dynamos maximum power output. The battery has a limited storing capacity and large part of the available electrical dynamo power is therefore unused.

Figure 1.2 Multi vehicles in Afganhistan [27].

Soldiers

Today the dismounted soldiers must completely rely on batteries brought by themselves into the battlefield. The soldiers act both as sensors and shooters and the different electronic devices increases their combat effectiveness by better situational awareness. However, the warfare benefits from all the electrical consuming devices result in a high electrical consumption. The amount of batteries is an important and essential part of the load, but also a heavy physical load of the personal gear during long missions. The electrical energy stored in batteries, is almost treated and valued as food and water and has impact on the mission endurance. A mission with lost communication due to depletion of all batteries is a great concern both for own protection and the possibility to successfully solve the mission.

Mission types and length vary from a few hours to several weeks. A two week long observation mission is several times less energy consuming per hour than a short intensive mission. However, the long mission with low to medium electrical energy need is a greater challenge than a short and energy intensive. The short mission team will probably not carry along any spare batteries due to the short mission time. The batteries in their equipment last for more than one night and spare batteries are superfluous. The long mission team must bring along spare batteries in order to operate their equipment, and the battery weight is considerable.

1 Previous work

This master thesis is partly based on a previous written project [1], *"Renewables for Military Camps and Ground Troops"*, and can be regarded as a continuation of the project's electrical power supply for ground troops. The project was based on a personal idea and developed further with assistance from Norwegian Defence Establishment (FFI) and Norwegian University of Science and Technology (NTNU).

Several defence research establishments in NATO and other establishments have ongoing and completed [8, 10, 28] projects on electrical soldiers power supply, with similar intentions as this thesis. A US National research council report [10] from 2004, which was sponsored by the US Department of Army, gave several recommendations of how to meet the energy needs of the future land warrior. Among several recommendations was: *"The army should develop a modelling capability for soldier equipment that includes power sources and also enables detailed simulation, verification and analysis of power requirements for given operational parameters"*. Development of a soldier model, which can be simulated with different power requirements and supply alternatives, is the core of this master thesis. Search in accessible and available literature sources has not identified that a simulation model of the soldiers' power requirement and supply have been constructed so far.

1.1 Project

In the project, generation of electrical energy from renewables in Afghanistan were investigated for the supply of camps and ground troops. Simple calculations and modelling were executed, based on estimations and measurements data of the electrical energy consumption from a military camp and ground troops

Several renewable sources were explored and the most appropriate energy source found was solar energy. Together with the consumption data found, simple calculations and modelling were accomplished. The life cycle cost for camps can be considerably reduced by using a hybrid diesel- photovoltaic (PV) system instead of today's diesel generators. The fuel price is the most important variable, and by using a relevant battlefield fuel price, the hybrid system was considerable cost reducing. Running the camp partly on renewable energy also yield other positive effects like reduced logistics, personnel and environmental costs. For the ground troops PV panels are a possible solution, but depend on insulation and available time and space to lay out the panels. The project did only take into account personnel operating by foot, and operations mounted on vehicles were not considered.

This master thesis will, in alteration to the project, consider all available energy sources. The energy system for camps will not be considered. With an evaluation of both vehicles mounted and dismounted troops, a more correct view of the electrical energy consumption is established. Results, measurements and estimates from the project, will be reviewed and possible reused in this thesis.

2 Technology Alternatives

2.1 Selection Criteria

The present electrical power supply system for vehicles and ground troops is well tested and fully operational, but several other systems based on improvements or new technologies are available. They could have better overall characteristics and could improve the soldier capabilities. Introduction of a new solution must offer some benefit (operational, functional or economical) compared to the existing ones. In a worst case scenario the introduction of a new energy system may result in an overall negative return. To minimise the chances that an insufficient system is introduced, a pre evaluation must be done. The pre evaluation is based on vital criteria as recognised and found by the author. The criteria are listed below and a short explanations and argumentation is given. The relevant electrical energy suppliers are investigated roughly, to make sure a feasible system is not excluded. Workload of doing this early in the process is small versus an extensive examination late in the process.

Criteria

A) Robustness/easy to handle
B) Start up time
C) Efficiency, specific energy/power
D) Thermal and acoustic signature
E) Technological readiness
F) Safety
G) Cost
H) Logistics
I) Environmental aspect

The military environment is rough, with both fluctuating climate and rough usage. A system must be able to withstand climate ranging from wet and high air humidity in the jungle to dusty and warm desert to cold arctic climate. Small and not advanced modifications for the different climate zones are acceptable. Heavy wear and tear will occur due to the handling of the system is not always being optimal, thus simple field repair should be possible. The system must manage 10 days of usage under given conditions with normal user profile, without a likely failure. A user-friendly system with low entry level for the basic usage is important to ensure that the system is applied.

A) Manoeuvrability and reaction time is of great importance for military units and a short start up time for supply of electrical power is essential.

B) High electrical conversion efficiency, high specific energy and power for weight (Wh/kg, W/kg) and density (Wh/l) are crucial since a light, compact and energy dense system is essential on the battlefield. An optimal system can operate with high efficiency in a wide power range, with good power regulation.
C) Low acoustic noise and thermal signature are vital in order to operate uncompromised. Infrared sensors are and will become more common in the battlefield and are likely to become a larger threat to own forces in the future.

D) Technological readiness of the energy system is decisive. A system may have very favourable theoretical characteristics, but if a workable military solution is not likely to be developed within the next decade, it is not considered in this thesis.

E) In an environment surrounded by ammunition, explosives and hazardous threats, a safe energy system is obviously preferable.

F) The total cost of the system is important since high expenses often terminate the implementation. High cost can be argued for, if the system gives great advantages or superiority in the battlefield.

G) Operation on existing fuels and/or goods is an advantage in order to meet the logistics requirements. Simple logistics which are easy to handle is essential both for the system, and energy carrier. The overall cost of implementing new logistics goods must be compared to the benefits it returns. Preferably a new system will replace and not just supplement the previous, and the total logistics burden will be reduced or equal.

H) High environmental impact can be justified by great advantages or superiority in the battlefield.

All criteria listed are imported, but the most vital are the five listed first, A to E. If one of the criteria robustness, start up time, efficiency-specific energy/power and density, thermal and acoustic signature and technological readiness is not satisfactory, it is likely that the system will not be employed.

2.2 Overview of All Power Source Alternatives

All potential electrical power systems found are ranked in criteria A to H in table 1. The ranking system goes from 0 to 2 points, 2 being the best. The ranking is benchmarked relative to present electrical system. A < 1 value will automatically exclude the system, independent of final score. Columns 2 to 6 have the most important criteria and if 2 points is achieved in any of these, one additional point is given. If 0 points is given, the opposite happens and -1 point is given. This is done to distinguish the final scores, as the system would be rejected regardless, with a <1 score in one of the five important criteria. Red, yellow and green colour equals 0, 1 and 2 point, respectively.

SYSTEM	Robustness	Start up time	Efficiency [%], Energy/power density [Wh-W/kg]	Thermal-acoustic signature	Technological readiness within next decade	Safety	Cost	Logistic-fuel availability	Environment	Sum	Approved
DIRECT BOROHYDRIDE FUEL CELL	Unknown	Medium	Unknown, but high Wh/kg potential	Low	Lab prototype	Good	High fuel cost	Medium	Similar to ICE	12	YES
SOLID OXIDE FUEL CELL	Problems in sub zero temp	Slow	Unknown, but high Wh/kg potential	Low	Military prototype	Good	Low fuel cost	Good	Similar to ICE	14	YES
PROTON EXCHANGE MEMBRANE FUEL CELL	Problems in sub zero temp	Medium	Depend on energy prod. 300-700 Wh/kg	Low	Commercially available	H2	Medium/high cost	H2	Similar to ICE	13	NO
BOROHYDRIDE -- PROTON EXCHANGE MEMBRANE FUEL CELL	Problems in sub zero temp	Medium	Unknown, but high Wh/kg potential	Low	Lab prototype	Good	High fuel cost	Medium	Similar to ICE	12	YES
DIRECT METHANOL FUEL CELL	Military version	Medium	Depend on energy prod. 300-700 Wh/kg	Low	Commercially available	Relative good	Medium/high cost	Medium	Similar to ICE	16	YES
PV, THIN-FILM	Good, depends on insolation	Depend on insolation	8-12%	NIL	Commercially available	High	Medium/high cost	Depends on insolation	Good	13	YES
SMALL ICE	Very good and well tested	Fast	20 %	Medium thermal and acoustic	Lab prototype	Relative good	Low cost	Good	Similar to ICE	13	YES
SMALL STERLING	Limited systems available	Fast	20 %	Low acoustic and medium	Prototype	Relative good	Medium/high cost	Good	Similar to ICE	9	NO
MICRO TURBINE	Limited systems available	Fast	20-40%	Unknown	Prototype	Relative good	Medium/high cost	Medium, pressurised gas	Similar to ICE	8	NO
PRIMARY BATTERY	Very good and well tested	Fast	600 Wh/kg	Very low	Commercially available	Possible chemical hazards	Medium/high cost	Medium	Medium	18	YES
SECONDARY BATTERY	Very good and well tested	Fast	200 Wh/kg	Very low	Commercially available	Possible chemical hazards	Medium/high cost	Needs electrical energy for charging	Medium	16	YES
SUPER CAPACITORS	Good	Fast	High Power,LOW ENERGY	Very low	Partly commercial available	Good	Medium	Needs electrical energy for charging	Medium	14	NO
THERMO GENERATOR	Well tested, proven in space.	Fast	10-15%, high energy density and low power density	High thermal signature	Prototype	Depends on heat source	High costs	Good	Depends on heat source.	7	NO
WIND TURBINE	Good, but depends highly on wind	Depend on wind	20-40%	High visual signature	Commercially available	Large rotating structure	Medium/high cost	Depends on wind	Good	9	NO
SELF GENERATING	Limited systems available	Depend on user	Low power output	Very low	Prototype	Good	Medium	Depend highly on user.	Good	13	NO

Table 1. Benchmarking matrix of the alternative energy systems.

Table 1 gives a simple overall indication of the different energy systems and their capabilities. A detailed description of them is not presented here, only short statements based on relevant literature. The final score in the last column varies between 7 to 18 points. By eliminating all systems with a red column, eight possible systems remain. A short explanation, evaluation and selection of the electrical energy suppliers are given below.

Several FC systems using liquid fuel are recognised to complement or substitute batteries. They have the potential to develop into technology solutions available for mobile and portable power supplies. The safety hazards by storing hydrogen under pressure or cryogenic liquid is evaluated to be too high in a battlefield. Hydrides could be an option, but it is heavy (especially relevant for soldiers) and no great development is believed to surface during the next decade. All FC utilising hydrogen stored as hydrides, pressurised or cryogenic are therefore not considered in the thesis. A Chemical method of storing hydrogen is an alternative. All chemical compounds which easily give up their hydrogen are in principle alternatives. Fossil fuels or manufactured hydrogen rich fuels can be used to generate hydrogen. But the manufacturing process of the hydrogen rich fuel must be simple, consume little energy and be easy and safe to handle to become a realistic H_2 source. Several hydrogen rich chemicals are potential compounds, but none are without issues. The least difficult and most promising alternatives for military applications, with a regard to safety and ease of handling in mind, are Methanol (CH_3OH) and Sodium borohydride ($NaBH_4$) [24]. To utilise the hydrogen carrier, a reformer, catalyst or a FC capable of utilising the fuel directly is required.

The direct methanol fuel cell (DMFC) uses liquid methanol as fuel. Methanol is easy to handle and easily accessible. Commercial systems made for military usage are available [18]. The present state of art DMFC has its limitations (no power regulation, can not operate in motion), but this is believed to improve to a satisfactory level within the next decade. The thermal and acoustic signatures are low and the converting efficiency of fuel to electricity is approximately 25 % [17]

Only one portable FC (50 W) prototype using common military fuel has been demonstrated [23]. US logistic JP-8 fuel, which is equal to kerosene or NATO F 34 fuel, is utilised. It uses an integrated catalytic partial oxidation (POX) reformer with a SOFC stack powered by JP-8, and is made for military applications. The SOFC's operating temperature is above 800 °C, but the thermal signature demonstrated for the prototype is relative low. In the exhaust gas exit the temperature is below 50 ° C and the outer enclosure is < 40 ° C. JP-8 has a high specific energy and the prototype's overall efficiency is over 40%. Operating on an existing logistic fuel is an advantage in order to meet the logistics requirements.

Two portable FCs which utilise sodium borohydride ($NaBH_4$) aqueous solution [25] are of interest, the B-PEMFC and direct borohydride fuel cell (DBFC). The B-PEMFC uses on site H_2 generated via the $NaBH_4$ hydrolysis reaction at the anode and air at cathode. The DBFC utilise aqueous $NaBH_{4\,s}$ solution directly at the anode and air at the cathode. Both FCs are in initial development phase and prototypes made for military applications are currently not present. But both have the possibilities to become a portable power supplier within the next decade.

Photovoltaic thin film technology has the recent years developed to be a product off the shelf with relative good efficiencies. The thin flexible cell technology which is printable on fabrics makes is usable for soldiers. The more common crystalline panels are to fragile, stiff and heavy for operation on the battlefield. Thin-film panels are a good option in areas with sufficient insolation and available time and space. This is tested and demonstrated in the previous project [1].

Wind power has a too high visual profile and dimension to be a realistic concept for multi vehicles or soldiers.

The internal combustion engine (ICE), primary and secondary battery are the main electrical suppliers today and will therefore automatically be taken into account. The ICE has several negative aspects, but is extremely proven, simple and robust. Both systems are also under intensively research and development and improved characteristics are very likely to happen in the next decade. The batteries and especial the primary achieve very high scores.

The sterling motor could be a possible system, but will not been considered further. It resembles the internal combustion engine when it comes to size, efficiency and fuel usage under the given circumstances. The number of present workable systems for small power supply is absent and the future potential limited. The main positive aspect, compared to the internal combustion engine, is lower acoustic noise, but the overall impression is poor.

Capacitors have excellent specific power, but very low specific energy. The maximum power need for soldier is relative low and can be handled by batteries. Capacitors are therefore not relevant as a power supply solution for soldiers. Capacitors with higher specific energy is under development, but unlikely to reach the batteries specific energy level in the near future.

Self-generating of electrical power was investigated as an energy source for soldiers in project [1]. The main disadvantage is the low power output and limited amount of energy harvested. For passive sensors or other low consuming devices it could be an option. Self generation systems will not be given any further attention, due to the low energy opportunities.

Thermo generators utilise materials that are able to convert temprature differences to electricity. The device has relativly low efficiency (5-10%). A large heat gradient is therefore needed, resulting in a high thermal signature. The system is not applicable for several reasons: high thermal signature, low efficiency resulting in low specific power and little development is expected in the next decade [10].

Based on this rough evaluation and the matrix in table 1, eight systems are chosen for further investigation: B-PEMFC, DBFC, SOFC, DMFC, PV Thin-film, internal combustion engine and primary and secondary batteries. These power sources will be considered further in the thesis and described more in detail in the next chapters.

2.3 Fuel Cells

A fuel cell (FC) is an electrochemical device that converts chemical energy of a fuel and an oxidant directly to electrical energy. The FC has a positively charged anode and a negatively charged cathode separated by an electrolyte which is an ion conducting material. At the anode a catalyst oxidizes the fuel and separates it into a positively charged ion and a negatively charged electron. The ions can pass trough the electrolyte to the cathode, while the freed electron travel trough a wire and creates an electrical current. At the cathode the ions reunite with the electrons and react with a chemical, usually oxygen, and create water or carbon dioxide.

The FC is in principle similar to a battery, but the essential different is the fuel and oxidant supply. In a FC the fuel and oxidant can be supplied continuously from an external source, when electrical power is required. In the battery the fuel is an integrated part and when consumed, the electricity production will stop. The FC itself has no moving parts which make it a quite and reliable source of power. Additional FC components such as pump and valves are present, but they have a considerable lower acoustics level than an ICE.

Many combinations of fuels, oxidants and different FC technologies are available, but they all work in the same general manner. The three main components, anode, cathode and electrolyte are usually made flat and sandwiched together. In the interface between the three segments two essential chemicals reactions at the anode and cathode occur. Several inappropriate chemical reactions, resulting in loss, are also carried out. However, the overall result is that fuel and an oxidant are consumed, water or CO_2 made and an electrical current created [7].

Hydrogen fuel is oxidized at the anode to protons that flow through the electrolyte and recombine at the cathode via the reduction of oxygen to form water. The overall reaction for proton exchange membrane fuel cell (PEMFC), which is a basic FC fuelled with hydrogen and oxygen as oxidant, is given by equation [7]

$$2H_2+O_2 \rightarrow 2H_2O \quad \text{(Overall)} \qquad (2.1)$$

The anode and cathode reaction for the basic PEMFC depends if an acid or alkaline electrolyte is used. If an acid electrolyte is used, H^+ will be released at the anode. The hydrogen gas will ionises and release electrons and creating H^+ ions. The anode reaction is described by equation (2.2) [7].

$$2H_2 \rightarrow 4H^+ + 4e \quad \text{(Overall)} \qquad (2.2)$$

With the electrons from the electrode and H^+ from electrolyte, the oxygen at the cathode forms water and the reaction is given by equation (2.3)

$$O_2+4e^- + 4H^+ \rightarrow 2H_2O \quad \text{(Cathode)} \qquad (2.3)$$

In an ideal FC with no loss the cell voltage is 1.23 V and the electrical work is equal to the Gibbs free energy released. The Gibbs free energy can be defined as the energy available to do external work, neglecting the work done by changes in volume and/or pressure [7]. External work in the FC involves moving electrons around an external circuit. The real FC performance involves losses and can be characterised by a polarization curve. The shape is a result of irreversibility and the three main and most important are listed below (A-C) and with its regions in figure 2.2.

A) Activation losses are caused by the slowness of the reactions taking place on the surface of the electrodes.

B) Ohmic loss is the voltage drop from the ohmic resistance to the flow of electrons through the materials of the electrodes and the various interfaces.

C) Mass transport or concentration losses are a result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. Because the reduction in concentration is the result of a failure to transport sufficient reactant to the electrode surface, this type of loss is also often called mass transport loss.

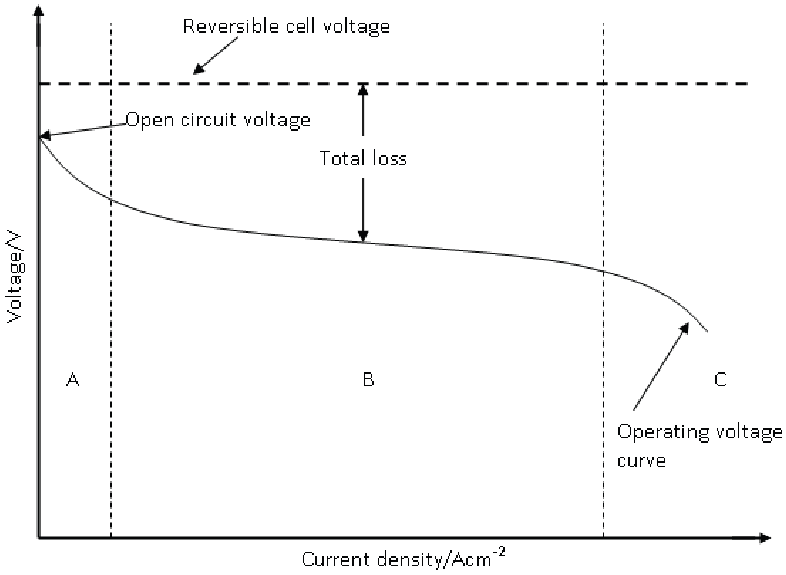


Figure 2.2 Characteristic shape of the voltage/current density results from the major irreversiblies.

The voltage of an operating FC is quite small, about 0.7 V instead of the reversible cell voltage of 1.23 V. This is a result of the losses (A-C) in figure 2.2 [7]. Therefore are multiple cells set together in a stack and connected in series to achieve a useful voltage.

The FC technology can be classified into two main categories, direct- and indirect systems. In a direct system the fuel reacts directly into the FC and typical fuels are: hydrogen, methanol and hydrazine. For indirect systems, the fuel is first converted by reformation to a hydrogen rich gas which is then fed into the FC. For portable power system the reformer must be an integrated part of the system and the hydrogen fuel is then produced on site.

The FC has several advantages properties compared to the internal combustion engine. The main are better efficiency, lower acoustic noise due to fewer moving parts, less emissions, lower thermal signature (depend on FC type) and power ranges from mW to kW. The disadvantages for FC are the relative early stage of development and several technical problems which must be solved in order to become a reliable power source. Today the main technical problems are fuel storage, cost and reliability.

For portable power sources the B-PEMFC, DBFC, SOFC and DMFC are found most attractive (see chapter 2.2). A more detailed description of the present status and future development potential will be given in the follow chapters.

2.3.1 Direct Methanol Fuel Cell

The DMFC is based on a modified form of PEMFC, which is fuelled on hydrogen. Hydrogen has a high energy density, but is difficult to store with a high energy density and has undesirable security issues on the battlefield. Methanol as fuel is easy storable, readily available, a low cost liquid fuel, relative energy dense (half of gasoline) and simple to use and refill. As an example has H_2 at 300 bar pressure in a composite cylinder, a net energy density of 0.2 kW/kg (storage efficiency 0.6%). Methanol in a plastic container has a net energy density of 5.26 kWh/kg [7] (storage efficiency 95%). The energy density for methanol has a practical (stored) energy density multiple times higher than H_2. The two major concerns with the DMFC are slow fuel anode reaction and fuel crossover. The oxidation reaction proceeds much slower and is more complex than with hydrogen as fuel. This result in lower power output per FC volume, compared to a hydrogen FC.

The overall DMFC reaction is represented by the equation [7]

$$CH_3OH+H_2O+\frac{3}{2}O_2\rightarrow 2H_2O+CO_2 \qquad \text{(Overall)} \qquad (2.6)$$

The complex and relative slow reaction at the anode is given by the overall anode equation (2.7) [7]. The reaction (2.7) does not proceed simply, but takes place in several steps and stages not described here.

$$CH_3OH+2H_2O\rightarrow 6H^++6e^-+CO_2 \qquad \text{(Anode)} \qquad (2.7)$$

The H^+ ions and electrons from equation (2.7) move through the electrolyte and an external circuit respectively. The ions and electrons react with oxygen at the cathode and produce water as showed in the equation (2.8)

$$\frac{3}{2}O_2+6H^++6e^-\rightarrow 3H_2O \qquad \text{(Cathode)} \qquad (2.8)$$

Fuel crossover occurs in all FC, but the methanol leak from the anode mixes very easily with the essential water part (present in all equations) and reacts with oxygen at the cathode. Methanol that reacts directly with the oxygen results in self discharge of methanol which provides heat instead of electricity and reduces the anodes cell voltage. As a result the cell voltage can be as low as 0.5-0.7 at open circuit, despite the fact that the theoretical cell voltage is approximately 1.2V.

The main strategies to avoid it are: keep anode catalyst as active as possible, control the fuel feed, lower the methanol concentration and thicker electrolytes [6]. However, they all have their negative aspects like cost, slower reaction and increased cell resistance. Electrolyte membranes which are less permeable for methanol is under development, this will in addition to reduce the fuel crossover, allow the system to be stored at lower temperature due to higher methanol solution can be obtained [6].

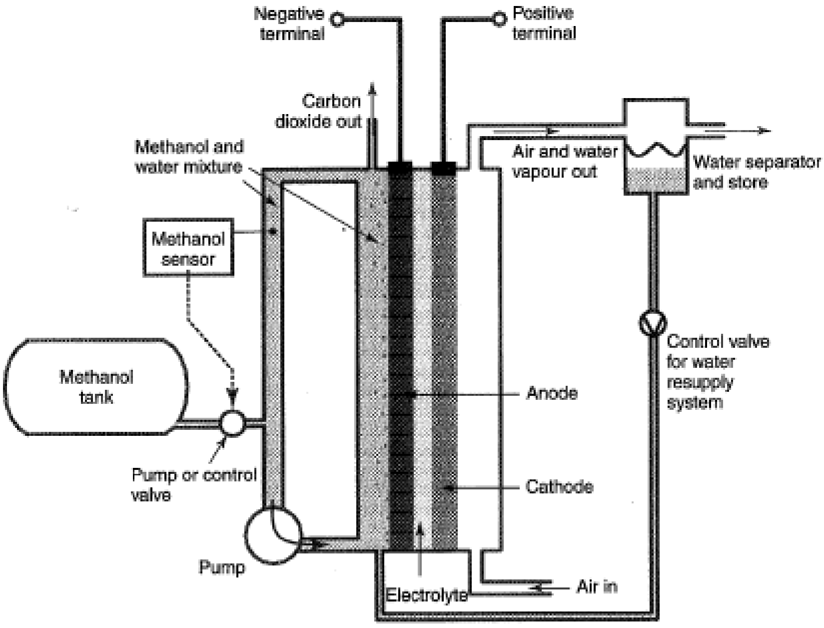


Figure 2.3 The main components of a DMFC [6].

Anode feeding of pure methanol fuel cannot be used (equation 2.7) and the methanol concentration has to be around 3% by weight [7]. To maintain a high specific energy of the system, the fuel must be pure. Water is therefore reused by condensation and added to methanol.

2.3.1.1 Development Activities for Direct Methanol Fuel Cell

The development of small portable DMFC which can be “recharged” by replacing a container of fuel, competitive in size and specific energy with batteries, has made progress the last decade. Several commercial producers have announced that they have workable portable DMFC (20-50 W). However, testing and experience have unfortunately demonstrated that most of the DMFC systems are unstable and not workable under battlefield conditions [9]. A 25 W portable DMFC [18] has been tested at FFI, at the same time as writing this thesis, with relative good results. It has a start up time of a few minutes, but delivers power instantaneous by an internal battery. The power output is fixed to 25 W with a fuel converting efficiency of 22 %. It has low thermal and acoustic signature and operates in temperature range -20 to 45 °C at maximum 7200 feet. It only operates satisfactory in static position and has no power regulation, but the overall impression is promising [9]. Smart Fuel Cell is the manufacturer of the DMFC and has a future development prospect within the next decade. The component weight shall be bisect, the convert efficiency improved by 10-15% and able to operate under movement in all angles up to 13000 ft (3900m) [37].

The major technical challenges in development of a better DMFC are the slow reaction and fuel crossover (described in 2.1.2). As a result the DMFC has relative low electrical conversation efficiency. The fuel has a relative low specific fuel energy (compared to gasoline) and with the low efficiency, the overall specific energy (for a typical mission) becomes around 300-700 Wh/kg (depends on the amount of energy produced by the DMFC). However, the DMFC tested [18] is probably today’s state of art FC concerning military requirements.

2.3.2 Solid Oxide Fuel Cell

Since storage of pure hydrogen is evaluated to be unsuitable under battlefield conditions, direct or FCs with a reformer technology are the options. A military solid oxide fuel cell (SOFC) prototype with integrated desulfurized JP-8 partial oxidation (POX) reformer, has recently (2009) been demonstrated successfully [23]. The reformer adds weight and volume to the system, but with high specific fuel energy and high overall electrical conversion efficiency, a favourable system can be obtained.

The reformer breaks down the hydrocarbon trough a catalytic partial oxidation (POX) process. The catalytic POX reformer converts the JP-8 fuel to a mixture of monoxide and hydrogen as given by the equation (2.9) [29]

$$C_{10}H_{22} + 5O_2 \rightarrow 11\ H_2 + 10\ CO \quad \text{(Reformer)} \qquad (2.9)$$

The SOFC has an oxygen ion conducting ceramic material as electrolyte and has a high, 600-1000 °C, operation temperature. Both hydrogen and carbon monoxide (CO) can be act as fuel in the SOFC. Therefore two anode reactions occur and given in equations (2.10-11) [7].

$$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^- \quad \text{(Anode)} \qquad (2.10)$$

$$2CO + 2O^{2-} \rightarrow 2CO_2 + 4e^- \quad \text{(Anode)} \qquad (2.11)$$

The negative charged O^{2-} ion is transferred from the cathode trough the electrolyte to the anode. The cathode reaction is presented in equation (2.11)

$$O_2 + 4e^- \rightarrow 2O^{2-} \quad \text{(Cathode)} \qquad (2.12)$$

The 50 W prototype system demonstrated has a 40 minutes start time from ambient temperature. A long start up time comes from the preheating of reformer and FC stack, before the intended reactions (2.9-12) occur. The reformer and stack requires a temperature of 180-250 °C and 800 °C, respectively. Due to the high reformer and stack temperature, the thermal signature is a possible issue. But the thermal signature of the prototype unit is proven to be below 50 °C at the exhaust gas exit and below 40 °C at the outer enclosure. The overall electrical power conversation efficiency is 46% after reforming and FC losses. JP-8 has a specific energy of 12 kWh/kg [10] and the system has an opportunity to achieve a high specific energy. The weight of the system is unknown, but the integrated SOFC (50 W)-POX package has a relative large volume of 4.2 litres and the SOFC are in general relative heavy due to the solid stack with ceramic electrolytes.

2.3.3 Direct Borohydride Fuel Cell

Sodium borohydride ($NaBH_4$) is an attractive FC fuel due to its benefits as H_2 supplier and storage. The theoretical H_2 content is 10 % by weight, it is stable in solution for months and non-flammable [26]. Direct borohydride FC utilise aqueous $NaBH_4$ solution directly at the anode and air at the cathode. There are three types of DBFC which all depends on the electrolyte applied. The electrolyte options are potassium hydroxide solution, anion exchange membrane or a cation-exchange membrane (CEM). Each system has its own advantages and disadvantages, but the CEM electrolyte is currently the most efficient DBFC [26] and therefore described further. The CEM-DBFC electricity is produced by the overall reaction [25]

$$NaBH_4 + 2O_2 \rightarrow NaBO_2 + 2H_2O \qquad \text{(Overall)} \qquad (2.13)$$

The overall equation (2.13) is produced via the following anode and cathode reactions, equation (2.14) and (2.15) respectively [25]

$$NaBH_4 + 8OH^- \rightarrow NaBO_2 + 6H_2O + 8e^- \qquad \text{(Anode)} \qquad (2.14)$$

$$2O_2 + 4H_2O + 8e^- \rightarrow 8OH^- \qquad \text{(Cathode)} \qquad (2.15)$$

Theoretical one mole of $NaBH_4$ can generate eight moles of electrons as shown in equation (2.10). In real system the number of electrons utilised per BH_4^- is less. The reduced electron generation leads to a decrease in energy density of the fuel from 9.3 kWh/kg at eight electrons to 7.6 kWh/kg and 5.8 kWh/kg for six and four respectively [25]. The most vital factor for the number of electrons generated is the applied anode catalyst. A key problem is how to obtain a complete eight electrons reaction.

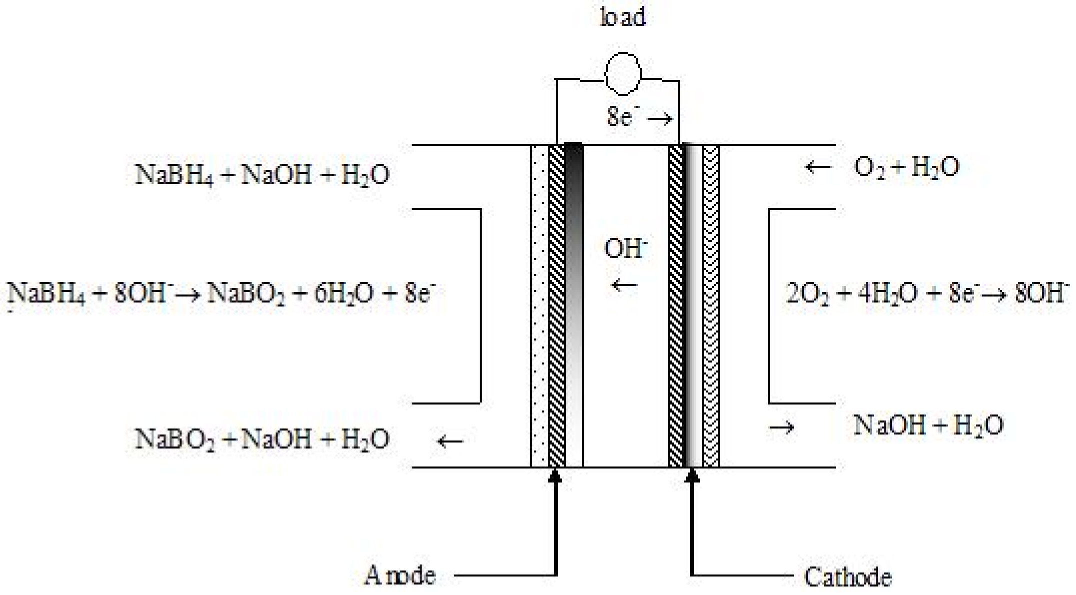


Figure 2.4 Mechanism for electricity generation and mass transfer of CEM-DBFC [25]

The advantageous features of the DBFC system are the high theoretical fuel density, safe fuel, low cost anode catalyst, fast start up time and low stack temperature (60 °C). The disadvantages are the high price of $NaBH_4$ and lack of present workable military system. The remaining challenges to achieve a workable DBFC system is to develop a catalyst for the anode reaction (achieve generation of eight electrons) and the general design for better crossover tolerance, power density and simpler fuel maintenance.

2.3.4 B- Proton Exchange Membrane Fuel Cell

The B-PEMFC is a proton exchange membrane fuel cell (PEMFC) which utilise the on site generated H_2 from the $NaBH_4$ hydrolysis reaction. H_2 is rapidly generated when NaBH4 reacts with water and the hydrolysis reaction is shown in equation (2.16) [25]

$$NaBH_4\,(aq) + 2H_2O \rightarrow 4H_2 + NaBO_2\,(aq) + \text{Heat} \quad \text{(Hydrolysis)} \quad (2.16)$$

Equation (2.16) show that half of the H_2 produced is derived from water. The $NaBH_4$ is chemical stable with NaOH and do not generate significant amounts of H_2 at room temperature with a typical 20%-10%-70% solution with $NaBH_4$, NaOH and H_2O respectively. This solution is therefore used as the electrochemical fuel storage for the FC. Several catalysts can accelerate the hydrolysis reaction and Ru-based catalysts are the most effective for H_2 generation. A conversion rate of nearly 100% is achieved [25]. The hydrolysis reactor (figure 2.5) is coupled to the PEMFC and generates electricity equal to PEMFC's overall, anode and cathode equations (2.1-3) in chapter 2.3.

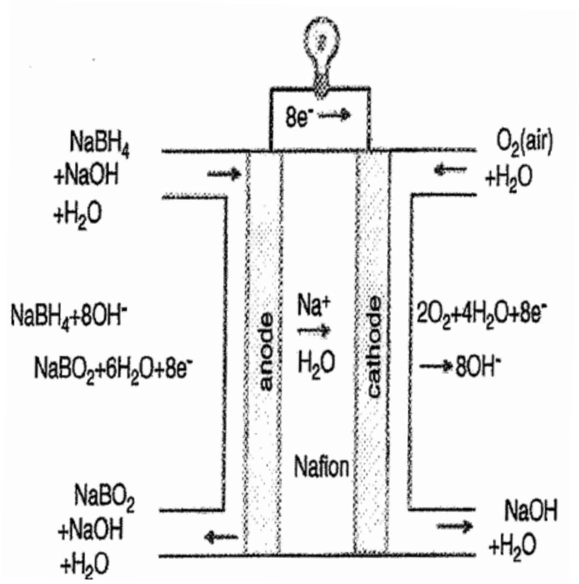


Figure 2.5 Schematic diagram of B-PEMFC [25]

The B-PEMFC has several advantageous characteristic in the stable, easy to handle and high energy dense fuel with enables on site generation of H_2. The PEMFC is one of the simplest and most reliable FC demonstrated to date and commercially available [10]. The FC in the B-PEMFC system has proven its maturity, but the development of an economic, efficient and optimum hydrolysis reaction and a effective system connection to the PEMFC is at an early development stage [25].

2.3.5 Analysis and Discussion of the Fuel Cell systems

Four FC systems have bee described more in detailed based on the simple evaluation in chapter 2.2. Several comparison studies for portable FCs [8, 10, 25, 26], both for military and commercial applications, have been carried out the last decade. The B-PEMFC has been considered to be more competitive than the DBFC [25], and the DBFC has then been evaluated to be more competitive than the DMFC [26].

The present status for military FC is that a DMFC is commercially available and a SOFC prototype with a JP-8 reformer is made. Independent of the theoretical or laboratory results for DBFC and P-PEMFC, the technological readiness for the DMFC is several steps ahead [9], even if its theoretical potential is lower. The SOFC has a higher specific energy potential than the DMFC, since it is utilising a fuel with higher specific energy. But the SOFC's long start up time, requirement of reformer and lower technological readiness makes it unfavourable. The challenges may be solved within the next decade, but the DMFC will probably also become more favourable in less fuel crossover, lighter components weight, better power regulation and robustness.

2.4 Photovoltaic

The basic theory of photovoltaic (PV) effect will not be given here, but can be found in relevant literature [19] or project [1]. Crystalline silicon (c-Si) solar cells have been and are used as the light absorbing semiconductor in most solar cells. The main disadvantage for the c-Si panels is the high cost, which makes up 40-50% of the cost of the finished module. This has led the industry to search for cheaper solar cells materials and has resulted in the development of thin film solar cells [19].

2.4.1 Thin-film.

Development of thin film cells has made PV to a possible power source for soldiers, since it flexible, robust and light compared to the heavy, stiff and fragile c-Si panel. The flexible thin film PV panel can and are implemented on fabric, se figure 2.2. With further improvement in implementation and material technology, thin film can be possibly successfully implemented in soldiers' existing fabrics.

Thin film materials are strong light absorbers and only need to be about 1 micron meter, which is considerable thinner than the several hundred microns meter thick s-Si panels. This reduce the material cost significantly. The most common and promising thin film materials are polycrystalline materials, such as cadmium telluride (CdTe) and Copper indium (gallium) diselenide (CI(G)S), and amorphous silicon (a-Si). All the thin film technologies are complex and it has taken several decades from promising research to the first commercial available products. The efficiency is lower than for c-Si, but since the production cost is lower the W/cost is competitive.

Figure 2.4 show the best research cell efficiency for all types of solar cells. The thin film CIGS, CdTE and a-Si technology have an efficiency of 19.9, 16.5 and 12 % respectively. The figure also displays the efficiency trend for the last decades for thin films technologies and the most common PV technology, the single crystalline cell.

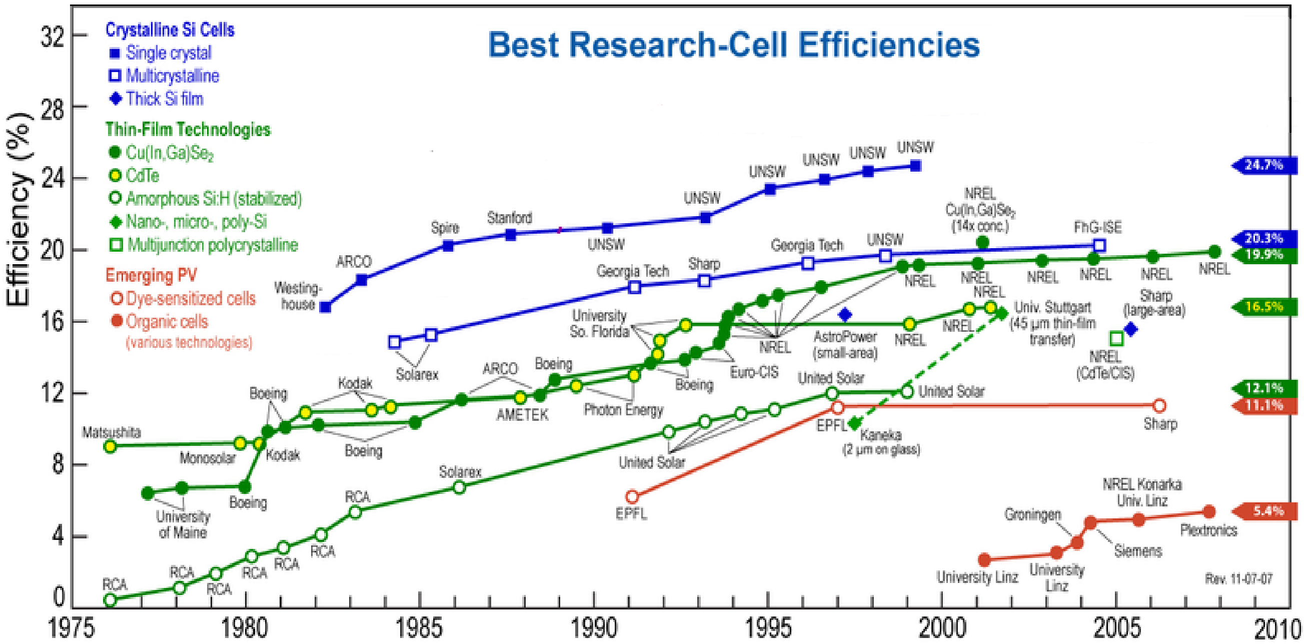


Figure 2.4 Best research-cell efficiencies per 2007 for crystalline, thin film and emerging PV technologies [30]

The National Renewable Energy Laboratory (NREL) in USA has made a ratio between available product efficiency from manufactures and their performance compared to laboratory efficiency, table 2 [20].

1 Research efficiency [%]	2 Commercial module efficiency [%]	3 Module	4 Temp. coefficient	5 Technology	6 Present performance ratio, (2008)	7 Future commercial module performance (80% of current record cell efficiency) [%]
19.9	12	Solibro Q-Cells	-0.38%/C	CIGS	60 %	15.9
16.5	10.8	First Solar FS-277	-0.25%/C	CdTe	63 %	13.2
12.1	10	Sharp NA-V142H5 (128W)	-0.24%/C	a-Si/nc-Si	70 %	9.7

Table 2. Efficiency and performance of thin-film modules [18]

Column 2-4 in table 2 is data gathered from thin film manufactures websites [20]. 6th column indicates the present performance ratio of commercial modules. The ratio is given by the commercial module efficiency from second column and the best research cell efficiency from first column. NREL expected in 2008 that future commercial module performance will become 80 % of present best cell research performance. The time-frame consider in the term “future” is not stated. It is therefore unknown if 80% efficiency performance of present efficiency is realistic to achieve within 10 years.

Based on table 2, CIGS seem to have the most commercial potential. However, the CIGS is a complex alloy between the four elements, and uniform deposition over the entire panel is required. The complexity and scarcity of Indium could moderate the development.

The main disadvantage with CdTe panels is the toxicity of Cadmium and the scarcity of Tellurium. A-Si has the lowest efficiency of the major thin film technologies, but silicon is an abundant and non-toxic material with a well establishes industry.

Today’s soldiers normally carry a camouflage tarpaulin (figure 2.3) for weather protection (rain, frost and sun) in their gear. In high insolation areas the tarpaulin is often used as sun cover during halts, lay up positions and observation posts. By implantation of thin film cells in the fabric, it will have a double function and reduce the weight increase of the PV cells implemented, since the fabric is already a part of the soldiers gear.

Figure 2.2 Harvesting with thin film panel.

Figure 2.3. A military tarpaulin used for shelter.

Results from a FFI experiment and from the project work [1] indicate a decrease in the efficiency of thin film panels. The exact reason is uncertain, but material corrosion, degradation of PV material, mechanical wear and tear resulting in breakage of PV material and delaminating are possible reasons [40].

Other developing PV technologies are concentrators and electrochemical cells. Concentrators use lenses or mirrors to focus the light in to special designed cells. The system will probably be more complex and fragile, and not applicable for a portable soldiers applications. An emerging PV technology is electrochemical cells where a dye sensitizer is used to absorb the light. The cell is made of low cost material and made into flexible and robust sheets equal to thin film panel. The technology is still in the start of development and assumed to not to be available for portable soldier solar harvesting, within the next decade.

2.5 Battery

Batteries are devices that electrochemically convert stored chemical energy into electrical energy. The battery contains of two electrodes, which have different electrical potential. The negative electrode (anode) and the positive electrode (cathode) are separated, but ionically connected via an electrolyte. When these electrodes are connected by an external device, electrons flow from the negative to the more positive potential. Ions are transported through the electrolyte, maintaining the charge balance. The battery and FC (se chapter 2.3) are in principle similar, both use an electro chemical reaction to create electrical current. The major difference is that the battery carries a limited supply of fuel and oxidant (for most batteries) and when consumed, can not be refilled. A more detailed description can be found in relevant literature [6].

Two main battery types are available, primary and secondary (rechargeable). Primary batteries are not rechargeable and have higher specific energy than the rechargeable batteries. Primary batteries are currently used in most of the soldier's electrical devices due to the higher specific energy. The recharge possibilities are limited on the battlefield. The secondary battery can be recharged electrically, nearly equal to their original condition, by passing a current in the opposite direction to that of the discharge current.

2.5.1 Primary Battery

The primary battery technologies relevant for soldiers are the alkaline, a variety based on lithium and the emerging metal-air batteries. The different lithium alternatives and metal-air batteries are the most promising and therefore be described in detail. In table 2 the characteristics of several metals with an oxygen (air) cathode are presented [6]. Lithium is an ideal material for battery anodes since the theoretical specific energy potential is very high.

Metal anode	Electrochemical equivalence of metal [Ah/g]	Theoretical cell voltage [V]	Theoretical specific energy (of metal) [kWh/kg]
Li	3.86	3.4	13.0
Ca	1.34	3.4	4.6
Mg	2.20	3.1	6.8
Al	2.98	2.7	8.1
Zn	0.82	1.6	1.3
Fe	0.96	1.3	1.2

Table 2. Properties of different metal anode metals and cell voltage with oxygen cathode [6].

The metal characteristics in table 2 are theoretical and will in practice always be considerable lower.

2.5.1.1 Lithium batteries

The general mechanism for the discharge of the lithium anode is the oxidation of lithium to form lithium ions and the release of electrons. The reaction for a general primary battery based on a Lithium anode is given by equation (2.17)

$$Li \rightarrow Li^+ + e^- \tag{2.17}$$

The electrons from equation (2.17) move through an external circuit to the cathode where it reacts and reduces the cathode material. Simultaneous the lithium ions (Li^+) move through the electrolyte to the cathode and reacts to form a Lithium compound. A number of materials have been examined for use as the cathode for primary lithium batteries. The most relevant materials, with lithium as anode, are listed in table 3.

Cathode material	Theoretical cell voltage [V]	Theoretical specific cell energy [kWh/kg]
SO_2	3.10	1.17
$SOCl_2$	3.65	1.47
SO_2Cl_2	3.91	1.41
MnO_2	3.50	1.01

Table 3. Cathode material used in Lithium primary batteries [6]

Robustness and good performance are vital in wide temperature ranges (-30 to 50°C) is essential for military a batteries. Most of the lithium batteries perform well in cold climates since their electrolytes conductivity decrease moderate with reduced temperature [6].

2.5.1.2 Lithium/sulphur dioxide (Li/SO_2)

Lithium/sulphur dioxide (Li/SO_2) is probably the most common military battery (BA-5590). The present BA-5590 battery has a specific energy of 190 Wh/kg [Appendix C]. The theoretical specific energy is 1170 Wh/kg [6]. Lithium is used as the anode and a porous carbon cathode electrode with sulphur dioxide as the active cathode material. The cell reaction mechanism is given by equation (2.18) [6]

$$2Li + 2SO_2 \rightarrow Li_2S_2O_4 \qquad \text{(Overall)} \qquad (2.18)$$

The Li/SO_2 battery performs well at a wide temperature range, -40 to 55 ° C, and has a flat discharge curves even for cold temperatures. This due to the electrolyte's conductivity is only moderate reduced with decreasing temperature [6]. The shelf life of the battery is excellent even at high temperatures.

2.5.1.3 Lithium/thionyl chloride (Li/$SOCl_2$)

The lithium/sulphur dioxide (Li/$SOCl_2$) battery has one of the highest specific energy of all practical battery systems with 590 Wh/kg and theoretical 1470 Wh/kg [6]. The overall reaction mechanism is given by equation (2.19)

$$4Li + 2SOCl_2 \rightarrow 4LiCl + S + SO_2 \qquad \text{(Overall)} \qquad (2.19)$$

The electrolyte has a low freezing point and enables the cell to operate at wide ranges of temperature, since the conductivity only decrease slightly with the temperature. The battery then has a flat discharge profile with good performance for low temperatures. The shelf life is long since the electrolyte forms a protective film at the anode with a capacity loss of 1-2% per year.

2.5.1.4 Lithium/sulfuryl chloride (Li/SO_2Cl_2)

The Li/SO_2Cl_2 is similar to the Li/$SOCl_2$ battery, but has advantages in higher operating voltage (see table 3) and greater safety [6]. Sulphur, which is a cause of thermal runaway in the Li/$SOCl_2$ (equation 2.19) is not formed in the Li/SO_2Cl_2 battery. However, the battery has several drawbacks and is not as widely used since it is more sensitive to temperature and has a higher self discharge rate. The overall discharge reaction of the battery using a lithium anode is showed in equation 2.20 [6]

$$2Li + 2SO_2Cl_2 \rightarrow 2LiCl + SO_2 \qquad \text{(Overall)} \qquad (2.20)$$

Commercial batteries utilising with specific energy of 480 Wh/kg [6] are available. The battery decrease more in capacity at low temperature than the $SOCl_2$, but even at -20 °C the capacity is good [6].

2.5.1.5 Lithium/manganese dioxide (Li/MnO_2)

The theoretical specific energy for the Li/MnO_2 battery is 1005 Wh/kg. Present military batteries applying MnO_2 cathode and Lithium as anode has a specific energy of 250 Wh/kg [Appendix C]. The overall reaction (equation 2.21) [6]

$$_xLi + MnO_2 \rightarrow Li_x\, MnO_2 \qquad \text{(Overall)} \qquad (2.21)$$

The battery has good performance over wide temperature ranges, is safe, has long shelf life and relative low cost per module [6].

2.5.1.6 Metal-air

By coupling a reactive metal anode (table 2) to an air electrode, a battery with an inexhaustible cathode reactant and very high specific energy can be obtained. Of the metals in table 2, Zinc received most attention and batteries with specific energy of 280 Wh/kg [33] are available for military applications. Button size batteries with a specific energy of 400 Wh/kg [6] are available and used in hearing aids.

The generalised reactions for the battery may be written as equations (2.22-24) [6]. The M is the metal and the value n depends on the valence change for the oxidation of the metals from table 2.

$$4M + nO_2 + 2nHO \rightarrow 4M(OH)_n \qquad \text{(Overall)} \qquad (2.22)$$

$$M \rightarrow M^{n+} + ne^- \qquad \text{(Anode)} \qquad (2.23)$$

$$O_2 + 2H_2O + 4e^- \rightleftharpoons 4OH- \qquad \text{(Cathode)} \qquad (2.24)$$

Metal air batteries are a battery of the future, and several technological breakthroughs must be achieved before primary Lithium-air or rechargeable metal-air batteries are commercially available. The obstacles are insufficient power delivery, operating at wide temperature ranges, rapid loss of power, dry out of cell and recharge and cycling problems.

2.5.2 Secondary Battery

Several secondary batteries like Li ion, Ni-MH, Ni-Cd and lead acid are commercial available. An emerging rechargeable battery with an exceptional theoretical potential (see table 2) is the Li–air which utilise the oxygen from the air. Yet, there are still a number of issues that need to be solved before rechargeable lithium-air batteries become a practical commercial product [32]. It is therefore not considered relevant in this thesis (see also chapter 2.5.1.5)

For portable storage systems, the specific energy and density carry great importance for the soldiers. The present status and development potential for Li ion in specific energy is superior compared to other rechargeable batteries, see figure 2.4. Hence, these are the only battery options that will be exploited in this thesis.

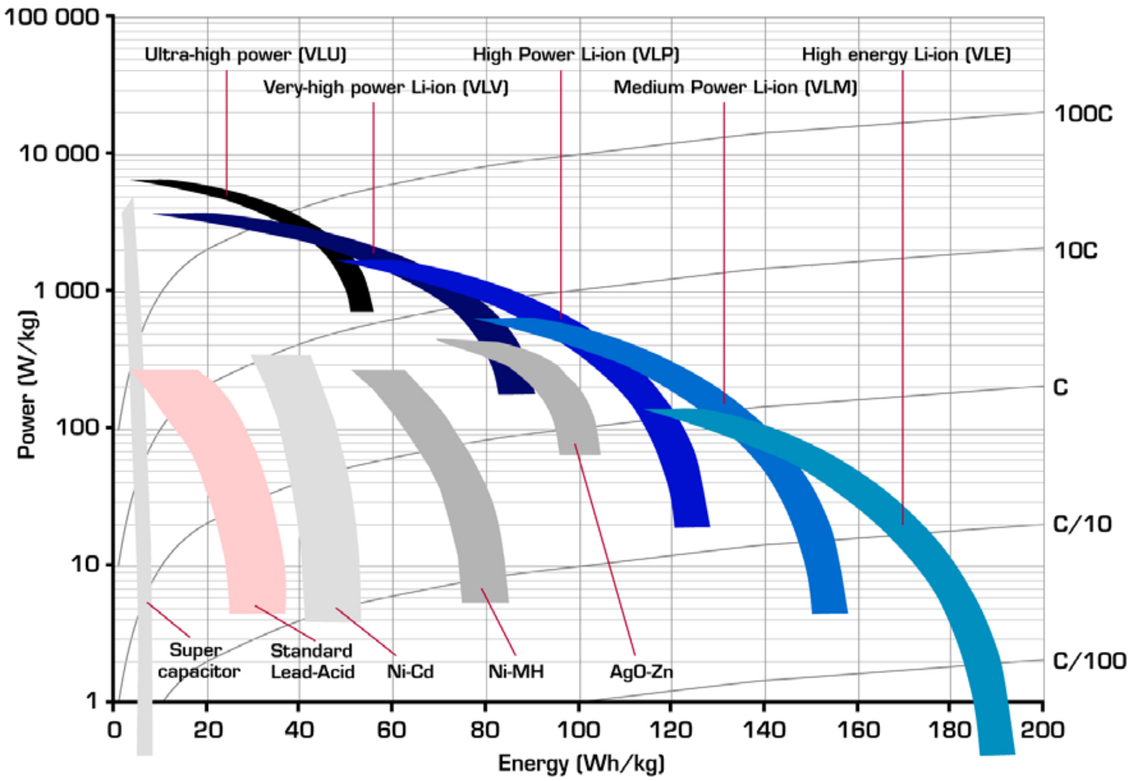


Figure 2.4 Specific power/specific energy of rechargeable commercial batteries [31].

The soldiers' power need is relative low and the high energy Li ion battery area, in figure 2.4, shows the characteristics for a typical soldier battery.

2.5.2 Lithium Ion batteries

Lithium ion batteries have lithium compound as the positive and negative materials. The Lithium ions exchange between the positive and negative electrodes as the cells is discharged or charged. The positive electrode material is generally a metal oxide such as lithium cobalt oxide ($LiCoO_2$) or manganese oxide ($LiMn_2O_4$), but several other cathode materials are feasible. The negative electrode is usually made of graphite carbon. Both the cathode (positive electrode) and anode (negative) are made of materials which lithium can move out or into. When discharging, lithium is extracted from the anode and inserted into the cathode. The reverse process occurs at charging. The equations for a Li ion cell with a $LiCoO_2$ cathode is shown in equations (2.25-27). The equations are given in units of moles, which make it possible to use the coefficient x. When charging the equations goes forward and backwards at discharge [6].

$$LiCoO_2 + 6C \rightleftharpoons Li_{1-x}CoO_2 + Li_xC_6 \qquad \text{(Overall)} \qquad (2.25)$$

When the Li ion call is charged the cathode material is oxidized and the anode reduced.

$$LiCoO_2 \rightleftharpoons Li_{x-1}\,CoO_2 + xLi^+ + xe^- \qquad \text{(Cathode)} \qquad (2.26)$$

The C in equation (2.22) is the carbonaceous negative graphite-carbon anode material.

$$6C + xLi^+ + xe^- \rightleftharpoons Li_x\,C_6 \qquad \text{(Anode)} \qquad (2.27)$$

The general Li ion battery operates with high cell voltage, high specific energy, long shelf life and a broad temperature range of operation.

Present commercial Li ion batteries for military applications have a specific energy of approximately 150 Wh/kg (se figure 2.4) [31].

2.5.3 Development Activities

There is intensive research for new or improved technology. Industries like electrical vehicles manufactures and electronic equipment manufactures are leading in the search for better battery characteristics. The main principles to maximise the stored energy is as follows [14].

- Having a large chemical potential difference between electrodes.
- Making the mass/volume of the reactants per each exchanged electrons as small as possible.
- Ensuring that the electrolyte is not consumed in the battery (only for rechargeable batteries).

In most fuel cells air is used as oxidant at the cathode. This could also be possible for batteries. Oxygen as cathode oxidant together with a metal at the anode is under development (se chapter 2.5.1.6). Oxygen (air) at the cathode and metals like lithium, aluminium, magnesium and zinc at the anode has a very large theoretical specific energy potential (se table 2). Lithium-air has a theoretical specific energy of 13 kWh/kg (similar to gasoline), and in a practical battery estimated to be around 2.5 kWh/kg [10]. But the technology will not be available until critical scientific challenges are solved and a metal-air battery is not likely to be commercial the next decade.

The ability to charge batteries in a matter of seconds rather than hours can be a characteristic for new Lithium based battery materials. By improving electron transport or reducing the path lengths, which electrons and Li^+ ions have to move, ultra fast charging can be obtained [38]. A fast charge capacity can be relevant for soldiers, but the maximum power available will probably be the bottleneck. The vehicle dynamo has the possibility, with a powerful ICE and dynamo, to deliver several kW of electrical power, while the dismounted soldiers will probably have no high power sources for fast charging.

In the next decade specific energy improvements similar to the last decade are reasonable to expect. The specific energy and power will increase, but a chemical revolution of storing electrical energy is not very likely to happen in near future. Based on present state of art military batteries, it is believed a specific energy of 500 and 200 Wh/kg for primary and secondary batteries is within the reach of the next decade. This is a yearly capacity (Wh/kg) increase of approximately 3 and 7 % for the primary and secondary battery technology. The secondary battery will probably be a Li ion battery while the military primary battery can be a Li/SO_2Cl_2, $Li/SOCl_2$ or Zinc- air battery.

2.5.4 Battery Safety

With the increasing complexity and energy content in batteries it is a concern about the safety. However greater attention is being given to development regulation and standards [6]. The goal is to promote to safe operation and transport.

Proper design of the battery is important to assure optimum, reliable and safe operation. Most of the safety problems attributed to the battery may have been prevented if proper handling had been done. The most common causes for battery failure are [6]:

- Short-circuiting of battery terminals
- Excessive high rate discharge or charge
- Charging of primary batteries
- Improper charge control when charging secondary batteries.
- High-temperature environments

On the battlefield several possible hazards like heat, projectiles, ammo and explosives are also present. However, fuel also has its safety issues, but in generally it do not reduce soldiers' operation. Several of the lithium batteries may have safety issues and can explode if fired into or abused. But it is believed the safety level of all batteries described is sufficient when proper handling is assumed.

2.6 Internal Combustion Engine

The main advantage of the internal combustion engine (ICE) system lies in the high specific energy potential of a fuel-based system. Even with relatively low overall system efficiency the specific energy for a combustion engine will be high when the amount of produced energy becomes large, due to the very high specific energy of the fuel.

The development of the ICE technology is driven by the automobile industry and under intensive investigation. The propulsion system of the Multi is out of the scope, but as a consequence of that the automobile technology probably will influence other and smaller ICE engines, the main development potentials are here described [35]. The intention from the researchers is to reduce the fuel consumption, not military issues like thermal and acoustic signature.

Turbochargers increase the pressure inside the cylinder and more air and fuel in the cylinder results in better power output. A smaller cylinder volume can then generate more or equal peak power and fuel is saved due to the reduce cylinder volume. A smaller engine will also give a lighter vehicle and become even more fuel economic. Homogeneous charge compression ignition (HCCI) injection results in a more uniform combustion and combustion by compression rather than a spark can be achieved for gasoline engines. Because the fuel and air are premixed they burn more evenly and better fuel efficiency is achieved. In figure 2.5 the HCCI concept in showed and an option for both diesel and gasoline engines.

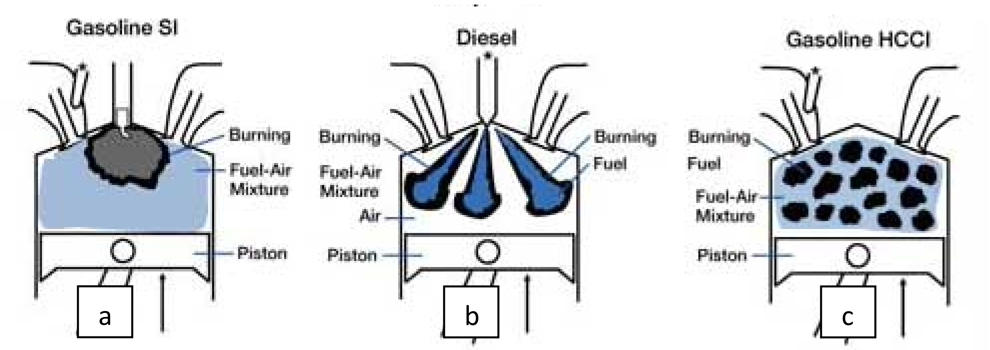


Figure 2.5. Present injection for diesel and gasoline engines in 2.5a-b and the HCCI in figure 2.5c.

Figure 2.6 show the reduced fuel consumption and CO_2 emissions. It comes mainly from the technological improvements described.

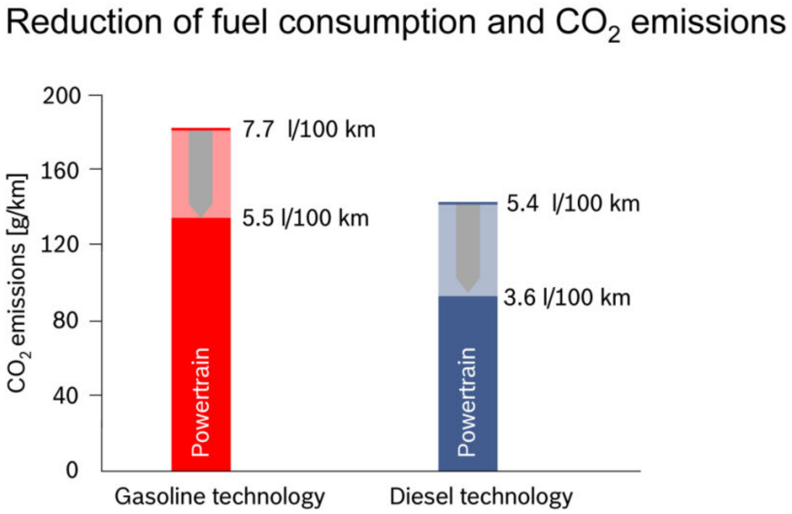


Figure 2.6. By 2015, technology improvements could increase fuel efficiency of diesel and gasoline engines by 30%, thus reducing CO_2 emissions by the same amount [35].

2.6.1 Auxiliary Power and Portable Power Units

The electrical power and energy need for soldiers and vehicles is differing, both in the individual energy need and distribution design system (described in 2.6). A small generator with an electrical power output of 20-500W is the ideal size for soldiers and Multi vehicles. ICE systems with an electrical power output of >0.7kW are available today. They are relatively durable and reliable, and have an efficiency around 15-20% [10].

Portable ICE system for the individual soldier, with an electrical power output 25-100W, are currently not available. Small ICE engines made for model airplanes and gardening tolls (chainsaw, trimmers) may be adapted for military needs. A chainsaw typically have a specific energy of approx 500W/kg (not electrical power), the smallest size is around 3 kg (excluding cutting equipment) [12]. To be usable for soldiers it also needs an electrical generator, which will add considerable weight to the system. Only for missions with a very high power requirement that last for several days, and no issues with thermal and acoustic noise, can it be an option.

Small ICEs for hobby model planes are widely used and could be an alternative. Small ICEs typically have problems with bearings, lubrication and incomplete combustion which contaminate the engine. All this gives poor durability and reliability. Minimal progress has been made the last years solving these problems, and there appears to be little hope of solving it within the next decade [10].

Portable micro gas turbines engines with high specific power are under development and could be the future. But several technical issues must be solved before the micro turbines can be successfully introduced. Technical problems both in materials and in total system design must be overcome. Micro gas turbines are not considered a viable alternative for implementation as portable energy unit or APU within the next decade [10].

Light ICE systems for portable power (20-100 W) are currently unavailable and are unlikely to be so within 2020. For vehicles with a higher power need, small generators (0.7 kW) are commercially accessible, robust and a reliable power source.

2.7 Hybrid System

A hybrid power system usually combines a high energy/low power source with a low energy/high power source or use one energy source when the other is inaccessible. A typical inaccessible example is the hybrid system in an ordinary vehicle. Chemically stored energy from the battery makes the engine run by supplying the start motor with electrical energy. Once the engine is running, the dynamo generates electrical power and recharges the battery and supplies the electrical loads.

By constructing the system with one component for the base load and one for the peak load, the systems total mass and capabilities can be reduced and enhanced. Each component will then utilise its best power range efficiency and do not need to operate in all ranges. The peak load is often several times higher than the base load and last only a fraction of the total power period. If only one power source is used it must be designed for the peak load and the system can, for some options, be over dimensioned and operate at low efficiency or with overcapacity. ICE engines typically have very low efficiency on low percent of rated power, while batteries can have high efficiency for low percent of rated power. The specific power and energy vary for the different power sources and cooperation can give several positive advantages. However, optimisation of a hybrid power source is complex and several factors such as chemical composition, power profiles, complexity, self discharge and temperature will affect the efficiency.

2.8 Power Distribution Design

2.8.1 Soldier

The electrical energy stored or generated is consumed by several different devices. There are two basic concepts to supply the device, either by a centralised or a distributed power design. Distributed power design is most common for soldiers today, but a centralised design has several favourable advantages.

In a distributed design, each device has its individual battery and when the battery is discharged, it is exchanged with a new battery. A future distribution design could be similar, but if a power generator concept is used (not today’s stored energy), an individual power generator in each device is required. An individual power generator is challenging since micro power generators (<5W) is not mature for either FC or ICE.

In centralised power distribution design there is one central power source that distributes by wires to the different devices. Regulators in the devices or in the main unit maintain the voltage at the specified level. In the various devices local rechargeable batteries are installed (similar to present distributed design) and allow the devices to be operated unplugged if needed or the centralised power sources is shut/break down. This is especially relevant if only one power generator is used as a power source.

The wires to each device are the greatest drawback with a centralised design. It will in under some circumstances reduce the soldiers mobility, add extra weight and increase energy loss due to the wires and DC/DC converting. The locally installed batteries in every device will allow, if needed, to be unplugged for a limited duration. The energy loss is probably minor, due to the small currents ($Loss=I^2R$) in the wires, even with as low voltages as 12V/24V. The advantages are a more efficient power source (one large unit), easier to maintain (only one source) and only one fixed battery in each device.

2.8.2 Vehicles

In vehicles most of the devices are fixed and plugged to the power box at all times. The majority of the devices have installed a rechargeable battery, and are able to be unplugged for a limited period of time. A centralised power design is already employed in Multi vehicles and is simply the best vehicle solution.

3 Measurements and Results

The intent of measuring and estimating the power profiles and fuel consumption in this thesis is to make reliable results for input files and parameters in the model. The measurements and estimates for the energy and power consumption are in some extent based on previous project work [1]. In that project the minimum and maximum electrical energy consumption level per soldier were identified. Only the electrical energy consumption were investigated and calculated, the power profiles were given little attention. The power profile can be essential since the energy source can be able to supply the sum of energy, but not the periods of peak power.

The device’s energy and power consumption and user profile are calculated by measurements and estimations. A 24 hour power profile with a data for every 6 minute is chosen. This interval specification is selected because it gives a detailed power profile and fits well with the radio’s power profile. It is common to divide the sum of the radio’s standby (STBY), receive (RX) and transmit (TX) ratio into ten parts. A radio usually has a STBY:RX:TX ratio 8:1:1. 80% of a period the radio is in STBY modus and 10% in RX and TX each. The ratios are in reality spread into several intervals, but to keep it simple, the periods are summarised into one period each hour. The power profile then has 240 intervals in the 24 hour period, as a result of the radio profile. The rest of the equipment also has a profile of 10 intervals per hour, but only change power level every 10th interval for simplicity. The impact on the result by doing this is minor since the equipment individual power profiles are fixed (on or off mode). To achieve a precise power profile the STBY, RX and TX power consumption has been measured. The Norwegian Defence Logistics Organisation's (FLO) subdivision Systems Management Division [15] has measured the consumed electrical power for the different levels of output power. The radio used in the test is a standard field radio with a maximum power output of 20 W, and 50 W when installed a vehicle amplifier.

Electrical equipment with such low energy consumption that battery recharging or exchange is not necessary is excluded from the list. Laser pointers, flashlights and red dot sights are typical equipment in this category.

The idling fuel consumption of the Multi vehicle is of interest since data for the modified engine is not available and idling is used as the power source when vehicle is not mobile.

3.1 Measurement and Estimate of Soldiers Electrical Power Consume

The power profiles for the soldier are based on the electrical gear presented in table 3.1.The gear table is a mix of equipment used today and equipment believed to be implemented for the conventional soldier within the next decade. A careful study of the future soldiers' electrical equipment, configuration and operation procedures has not been explored. It is based on today's equipment and with implementation of emerging equipment. The electrical equipment can be divided into 3 main categories by usage and is showed in table 3.1.

Communication	**Computer/display**	**Sensors**
Personal radio	PDA	Mini UAV Sensor
	UAV receiver	Thermal sight
	Helmet Mounted Display	Night vision goggles
		Sensor

Table 3.1.Soldier electrical equipment list.

The communication device is a personal radio with an output power of 5 W and a wide frequency range (VHF-SAT COM). Each team member has a personal digital assistant (PDA) with internal GPS, similar to a small portable computer. It is used for data TX and RX (together with radio), navigation on digital maps and screen display of UAV feed (together with UAV receiver). The helmet mounted display (HMD) is a small high-resolution eye screen which can display a variety of data. Relevant examples are UAV feed, PDA information, rifle aim and night vision and thermal pictures. Thermal imager (TI) sight suitable on a rifle is currently available and believed to be personal gear in the near future. Several devices are classified as sensors. A mini unmanned air vehicle (UAV) is a small "model plane" used for recognisance. The UAV typical have infrared and video camera sensors. The sensor in the table is a general sensor (no capabilities given).

Figure 3.0 show a typical soldier with pictures of equipment from table 3.1. Above the soldier is an external UAV asset which the UAV receiver is also capable to receive live video from. A typical TI and NVG image is showed below their equipment.

Figure 3.0 Soldiers main electrical equipment.

In the scenario made, all equipment is personal, except the mini UAV, UAV receiver and sensor. The feed from the UAV is first received by one team member, and then broadcasted over radio by voice to all team members. Every soldier could have received the feed on the HMD (with receiver), but it would probably only become overload of information. The UAV and the general sensor are not used in both power profiles, only in the high consuming.

3.2 Power Profiles for Ground troops

Based on the equipment list from table 3.1, the electrical power profiles are identified. The user profiles correlates highly with the power profiles. The user profile depends on several factors like mission type and duration. Two power profiles, normal and high, are calculated. Relative active equipment usages are assumed for both profiles.

The radio is the device with largest variation in power consumption. The radio tested [15] was a radio with a higher output power than a personal radio (5 W). The result from the test is shown in figure 3.1. The result shows that in STBY and RX mode (0 W output power) the radio consume a considerable amount of electrical power. At the radios maximum output power the true electrical power consumption is above 100 W. Based on the measurement results from the 20 W radio, the personal radio's power profile is found by using the same ratios between radio output power and the radios true electrical power consumption.

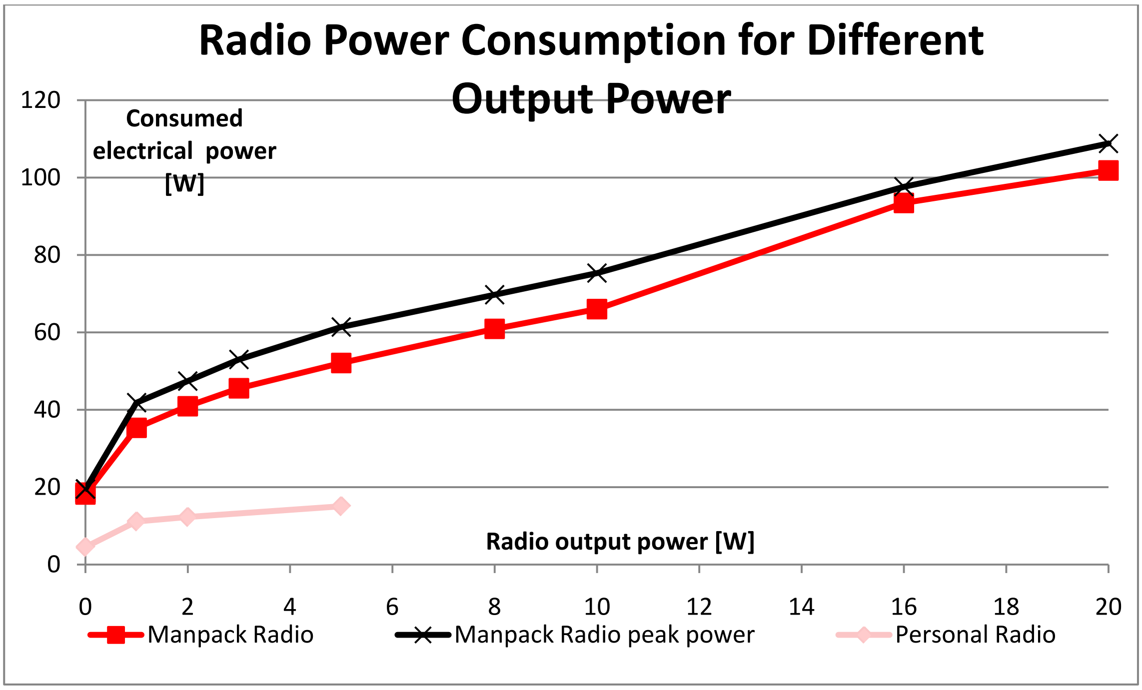


Figure 3.1 The radio's electrical power consume at different radio output power, STBY and TX.

The soldiers' normal power profile is shown in figure 3.2. The profile is displayed in each device's individual power consumption and with total energy consumption in light shading on the right axis. The distinct peak level occurs when the soldier's personal radio is in TX mode. It is assumed that the soldier is sleeping or resting 7 hours, and all systems are then shut down to save energy. Under some circumstances, example high threat, all devices can be in on/STBY modus round the clock. The system may also be turned off/partly off for longer periods, due to rest or/and if the situation allows it. The single hour of consumption at midnight is the soldier's on call duty. The difference between day and night consumption is minor. The NVG is the only consumer that under normal circumstances is not used during day time. The rest of the equipment is assumed to be time independent. The NVG has low power consumption (approximately 1 W) and do not make a substantial part of the power profile. Therefore the power profile can be simulated independently of time, since the activity level matter more than the time of day.

The average power level, when active is around 14 W, with a maximum power level of 25 W. The total energy consumption is 250 Wh/day per soldier.

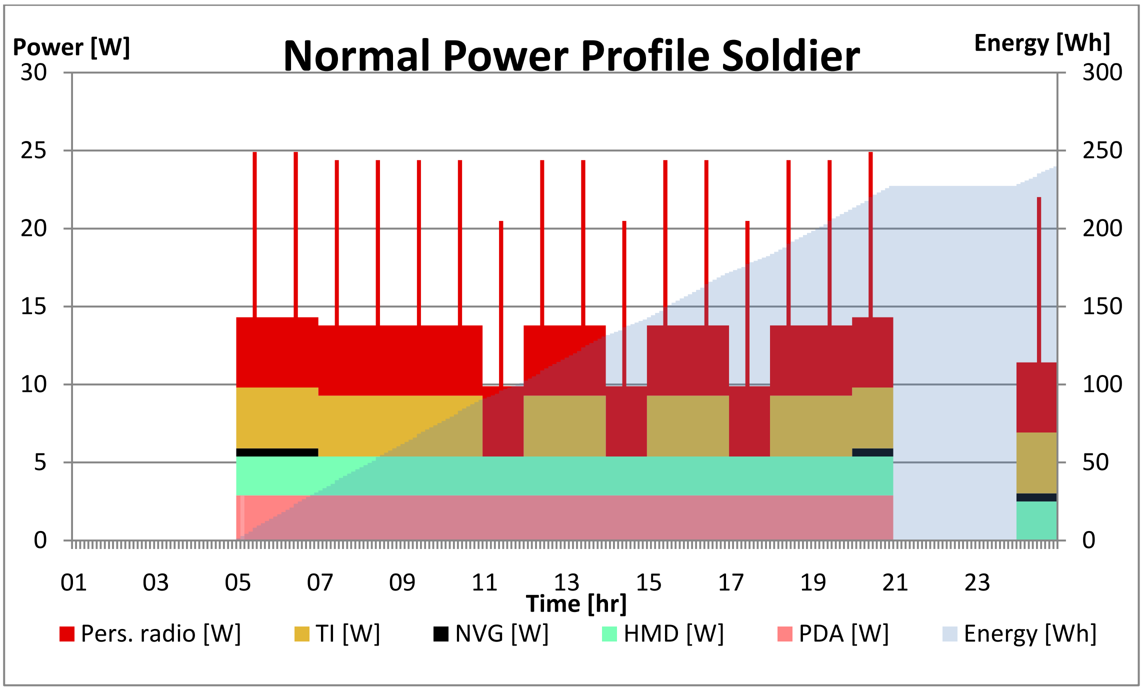
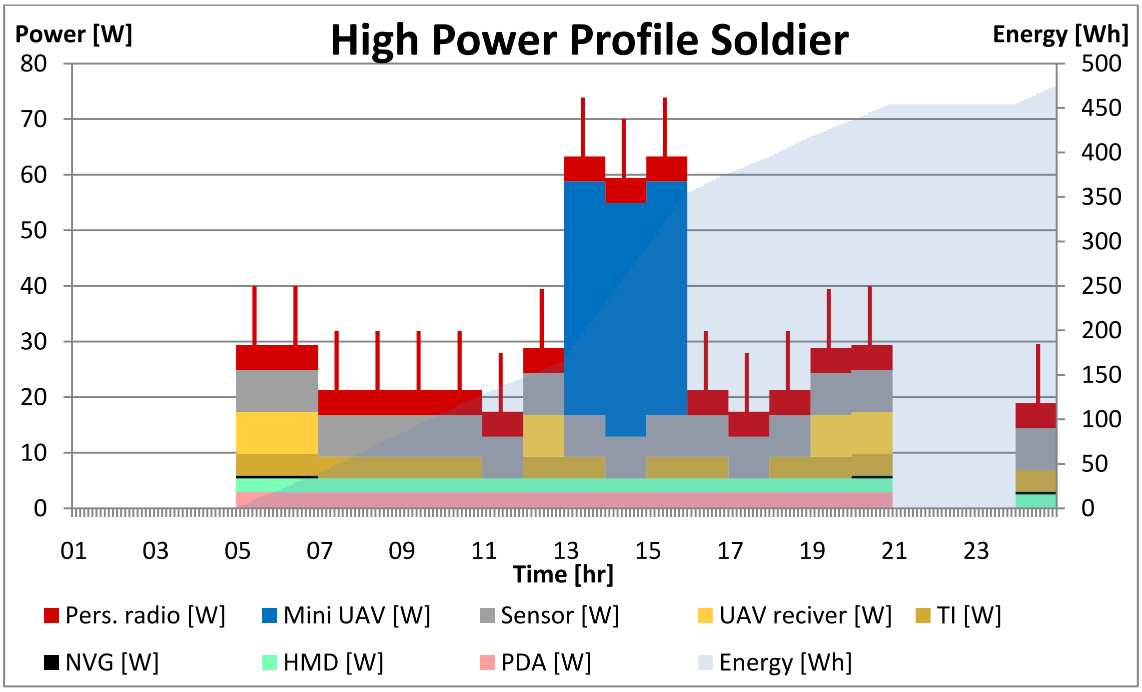


Figure 3.2 Normal 24 hr power profile for soldier.

Figure 3.3 display a soldier with additional equipment and activity level. The soldier has an UAV receiver, sensor and charges the UAV batteries, which change the power profile considerable. The peak power is over 70 W and the energy need nearly 500 Wh/day.



3.3 High 24 hr power profile for soldier.

3.3 Measurement and Estimate of the Vehicle's Electrical Power Consume

The Multi vehicle's electrical power profiles are measured and estimated on the basis of the electrical equipment. Electrical power used for the vehicles lights, winch, air compressor and start motor are excluded, since not used when vehicle is static.

The vehicle's default crew is set to 3 soldiers. On the vehicle, several devices are installed and are similar both in usage and construction to the soldier's electrical gear (see figure 3.0). The difference is that the vehicle's equipment is mostly fixed and has higher power demand due to better capabilities. The increased capabilities increase the energy and power need due to: the radios have higher output power, more equipment per person and more energy consuming devices due to more powerful versions. When the soldiers are mounted the modus of operation is different. Communication equipment and sensors are often operative at all time in the vehicle.

Communication	Computer/display	Sensors
Team Radio 1	Computer	Sensors
Team Radio 2	UAV receiver	3 x Night vision goggles
3 x Personal Radio	3 x PDA	3 x Thermal imager
	3 x HMD	Mini UAV

Table 3.2. Vehicle electrical gear list.

All equipment is in general similar to the personal gear, see figure 3.0. The team radio 2 is equal to the personal radio described in chapter 3.1 and radio 1 is a more advanced radio, with maximum output power of 20 W. By installing both radios in vehicle amplifiers, maximum output power is boosted to 50 and 20 W for radio 1 and 2. The computer is similar to the PDA, but more advanced and with a larger display. The sensors are general sensors with no capabilities given.

3.4 Power Profiles for Mounted Vehicle

Similar to the dismounted soldiers the communication equipment is a vital part of the power profile, with its distinct peak power periods. The radios vehicle adapters enhance the radio's output power, but also increase the electrical power consumption considerable. Figure 3.4 shows the power consumption for the different radio output power levels. The measurement is done by FLO [15], and similar results to the man pack radio are recognised. At the radio's maximum output power the power consumption is 5 times higher (output 50 W-consume 250 W) and a large difference between STBY, RX and TX are discovered.

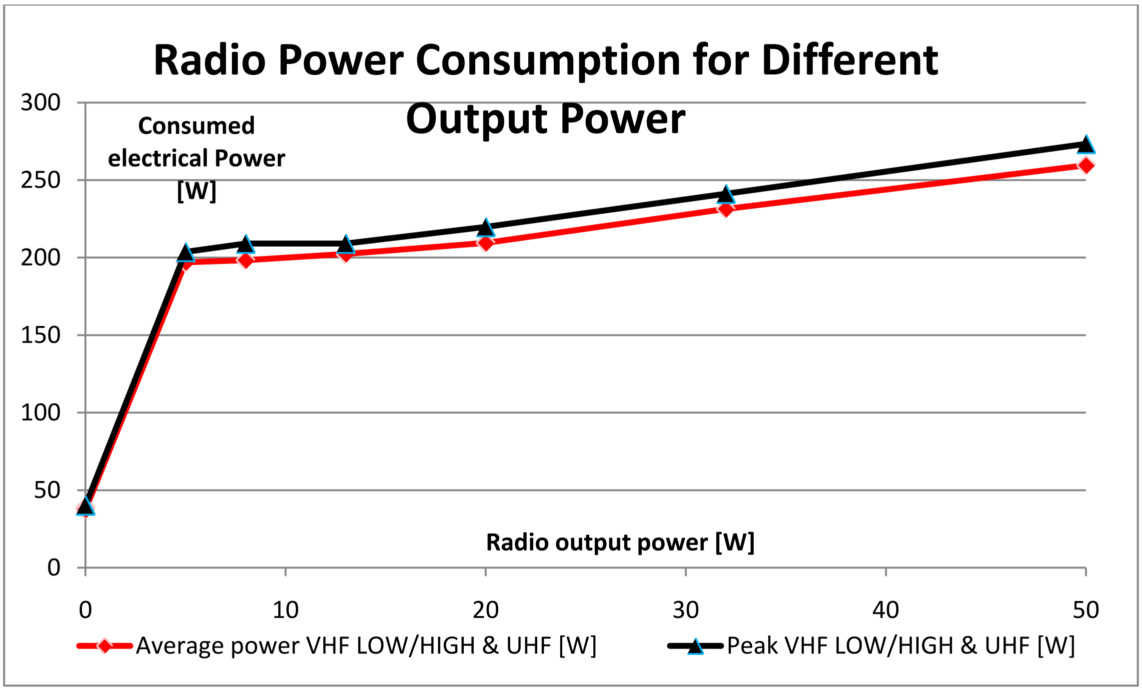


Figure 3.4 Radio's power consumption in vehicle adapter.

Two power profiles for vehicle mounted soldiers are presented in figure 3.5-6. On the right axis the total energy is calculated. The distinct power peaks in the figures are the radio's TX keying. The output power is set to 50 W on radio 1 and 20 W on radio 2. The vehicle is operated round the clock, independent of mobile or static operation.

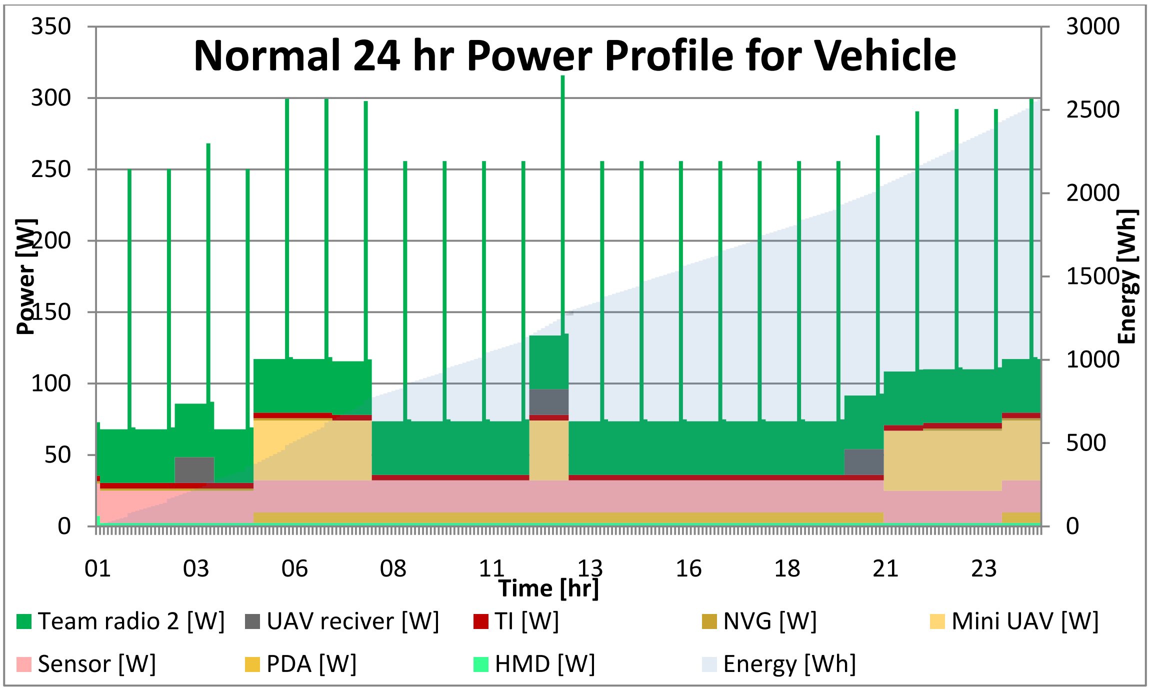


Figure 3.5 Vehicle power profile and energy usage for 24 hr.

The difference between the high and normal power profile is the amount of equipment applied. In the high profile an extra radio and team computer, compared to the normal profile, are used.

The peak power, average power and energy usage are 314 W, 107 W and 2.6 kWh/day for the normal and 425 W, 186 W and 4.5kWh/day for the high profile.

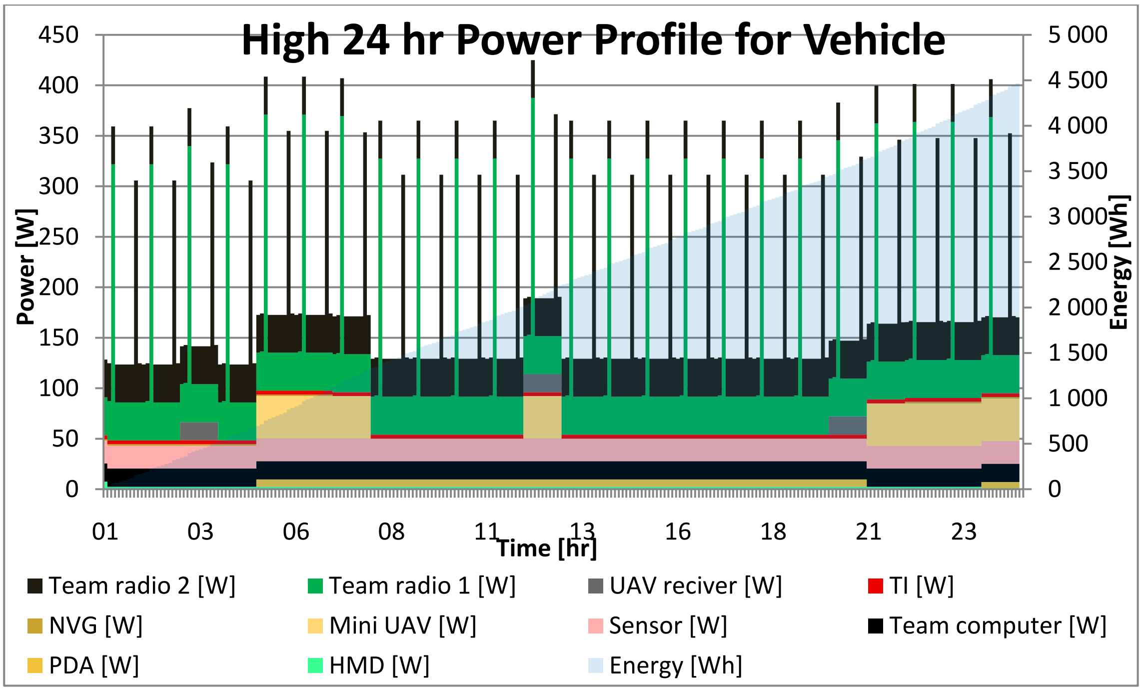


Figure 3.6 Vehicle power profile and energy usage for 24 hr.

The power profiles for the Multi vehicle are similar to the soldier's profiles and depend on several factors like mission and theatre. In both vehicle profiles the electrical equipment is widely used and could typical be a lead/commando vehicle.

3.5 Measurement Design of Vehicles Fuel Consumption

The internal combustion engine gives a steady and very reliable supply of electrical power, but has several negative impacts for the soldier on the battlefield. The main disadvantages are the thermal and acoustic signatures and the low fuel efficiency. Idle running, where production of electrical power is the only purpose, is relative common due to the power dependence and only solution on the battlefield. Often the electrical load is small, which gives very low fuel efficiency.

The fuel consumption when idling is interesting since it, under some mission types, can be a relative large part of the engine run time. The dynamo's power production, will affect the fuel consumption due to the increased rotational engine speed and torque.

Data for idle fuel consumption for different levels of electrical power generation has not been possible to obtain through workshops [2] specialised on the MB Multi vehicle. The consumption values found were based on qualified guessing and the uncertainty is especially high when a high load is set on the dynamo. The engine has also been modified at several engineering workshop. Therefore an idling experiment with different loads on the dynamo has been done.

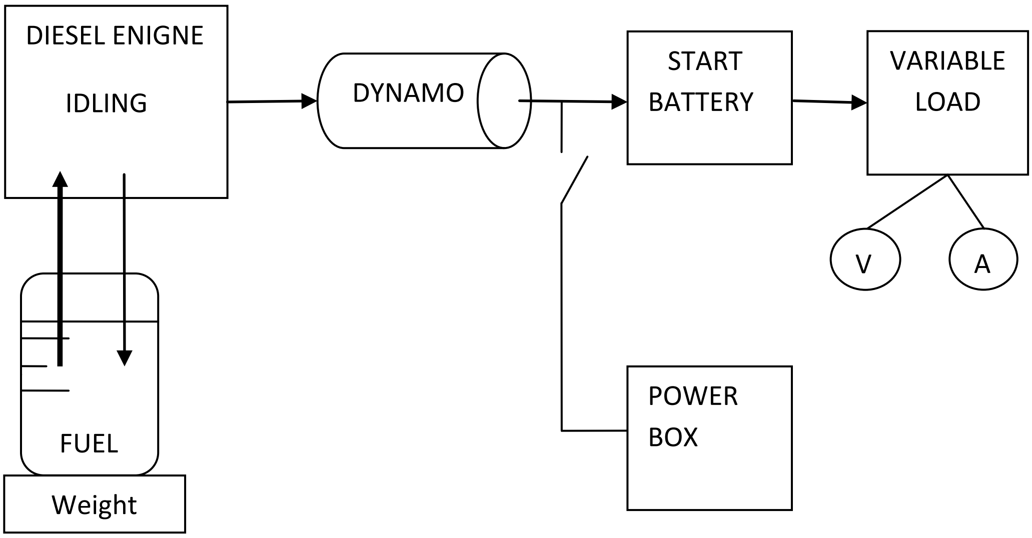


Figure 3.3 Sketch of measurement design for the engine-dynamo's fuel consumption for different dynamo loads.

Figure 3.3 show the measurement design for the experiment and were set up with help form a mechanic from Elverum military mechanical workshop. The design is fairly simple in set up. Instead of consuming fuel from the original tank, a small external fuel container was used. The fuel induction and return were reconnected to the external container, which was set on a weighing balance. By using a two digit kg weight and benchmarks resolution of 0.1 litre at the fuel container, two measuring parameters were available. The vehicle's power box was disconnected to prevent charging or discharging of the power box batteries.

A digital load [3] was set on the battery poles, which is equivalent to applying a load on the dynamo. Voltage and ampere was continuously digitally measured by the load and occasional measured at the battery poles by a handheld volt- ampere meter.

Three vehicles, all unused after recently arriving from complete vehicle maintenance, were chosen for the test. The test was done indoor in a garage at 15 ˚ C. Pre idling of the engine until operating temperature at around 75-77˚C, which is equal to the cool exchanger temperature, was executed before each test period. To measure the engine's temperature, a digital infrared thermometer [5] was pointed at engine block.

In the preheating period of engine the dynamo delivered a small current for charging of battery. When the engine was at operating temperature, the current was at a steady low value. All possible electrical consumers on the vehicle were turned off, and the base current measured at the battery was always between 0.8-2.1 A. According to the mechanic [4] the dynamo has an internal load which consumes around 1 A, the rest of consumption is unknown but minor. The test period was 1 hour and fixed loads of 0 W (25 W internal dynamo load), 700 W and 1300 W. The power levels were selected as a benchmarking level and as possible average and maximum power loads from the power box.

The original plan was to test three vehicles with three different loads. However, the variable load, did not work properly and a new load had to be obtained. Due to loss off time on this task, only two engines where tested on the 700 and 1300W loads.

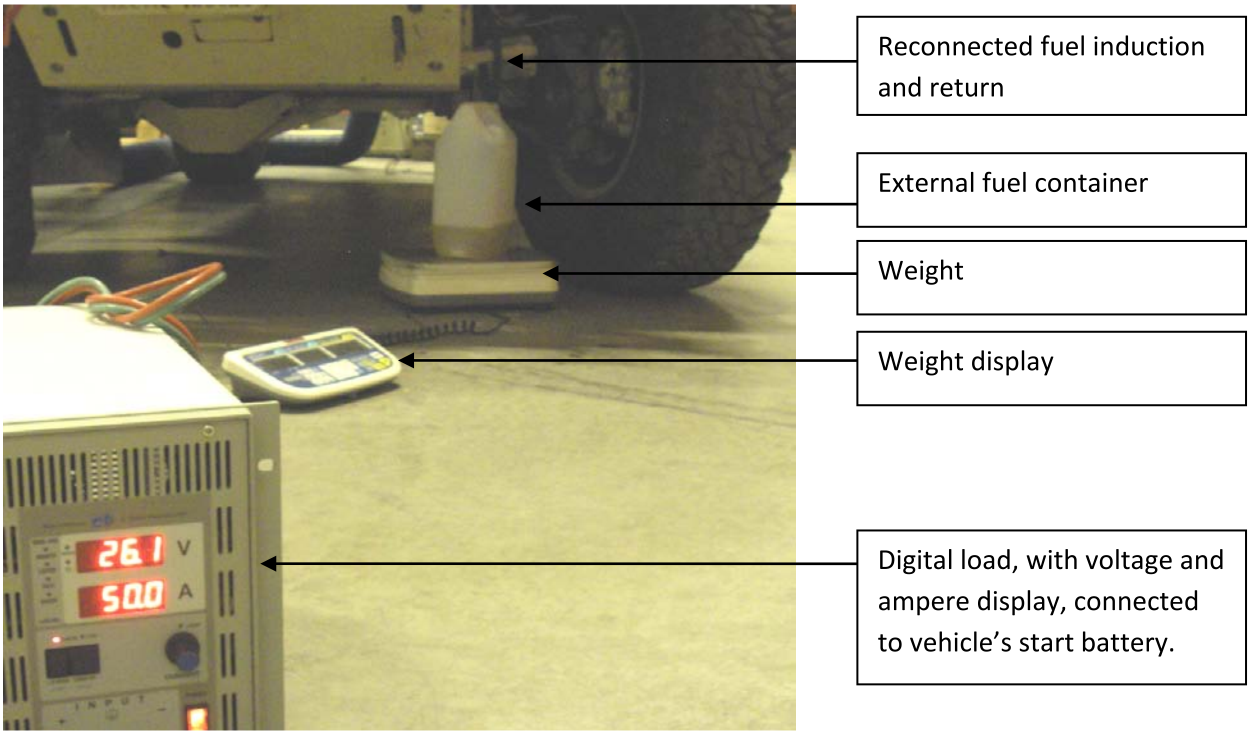


Figure 3.4 Picture of fuel experiment.

When the dynamo load increased from 700 to 1300 W, the voltage rapidly decreased over the vehicle's start battery. The voltage dropped since the dynamo was unable to deliver enough power, and power was drained from the start battery. The Multi's engine is a relative simple engine with little electronics and an automatic regulator to increase the rotational speed is not installed. When the load became 1300 W, the rotational drive to the dynamo became too low. Higher rotational engine speed, by using the hand throttle, increased the dynamo's power production and a stable voltage over the battery was achieved.

In the experiment several sources of errors influenced the result. But it is believed the results are relative accurate for the purpose of offering a reliable indication of the fuel consumption and efficiency values for different electrical dynamo loads.

The main sources of error:

- Different efficiencies on the vehicles' engines and dynamos due to wear and tear.
- Individual engine variance in the idle rotational speed due to different engine tuning.
- Different (25-50 W) electrical base load on the dynamo.
- Measuring errors from weight balance
- Errors from the digital load

The main source of error is believed to be the hand held throttle control tuning and individual engine efficiencies. The throttle tuning was done manually, and optimal (minimum) or identical rotational speed on the engines was probable not set.

3.6 Fuel Consumption Result

It was expected that the engine’s fuel consumption would rise with increasing load on the dynamo. In figure 3.7 the fuel consumes for the different load levels are presented. Idling with no external load (25-50 W) resulted in a diesel consume between 0.7 and 0.85 litre/hour. This can be set as the engine’s base consumption and will under no circumstances (static operation), be reduced.

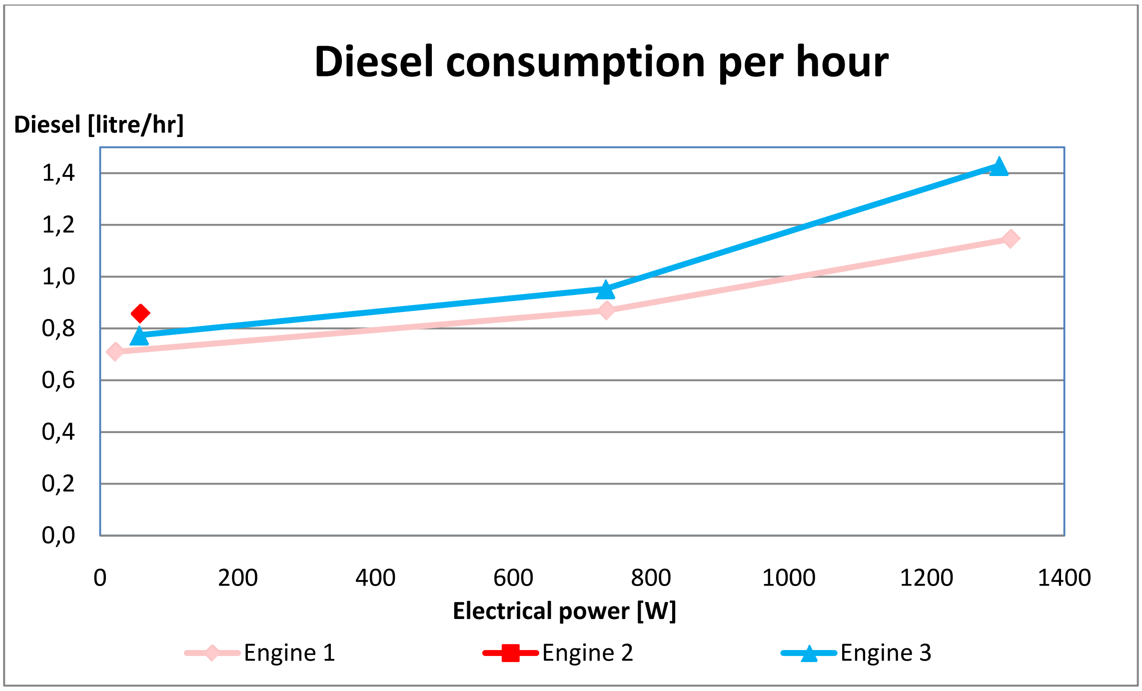


Figure 3.7. Fuel consumption at different dynamo power production

By enlarging the dynamo load to 700 W the consumption has a minor raise. The increased fuel consumptions come from the torque or moment on the engine’s rotation, since the rotational speed is observed to be equal.

A raise of the dynamo load from 700 W to 1300 W increase the diesel consumption, due to enhancement in the engine’s rotational speed. The electrical output power almost doubles while the fuel consumption grows with approximately 60 %.

The ratio between fuel consumption and electrical power output from dynamo or the engine’s electrical conversion efficiency is not linear. In figure 3.8 the efficiency, based on the result from figure 3.7, is presented. The conversion efficiency is the amount of the theoretical energy in the diesel which is converted to electrical power. In the engine, the fuel is burned and converted to mechanical movement, which further drives the electrical producing dynamo.

Calculation of engines efficiency conversion to electric power is based on the theoretical energy content in a unit diesel, measured fuel consumption and electrical power production [Appendix D].

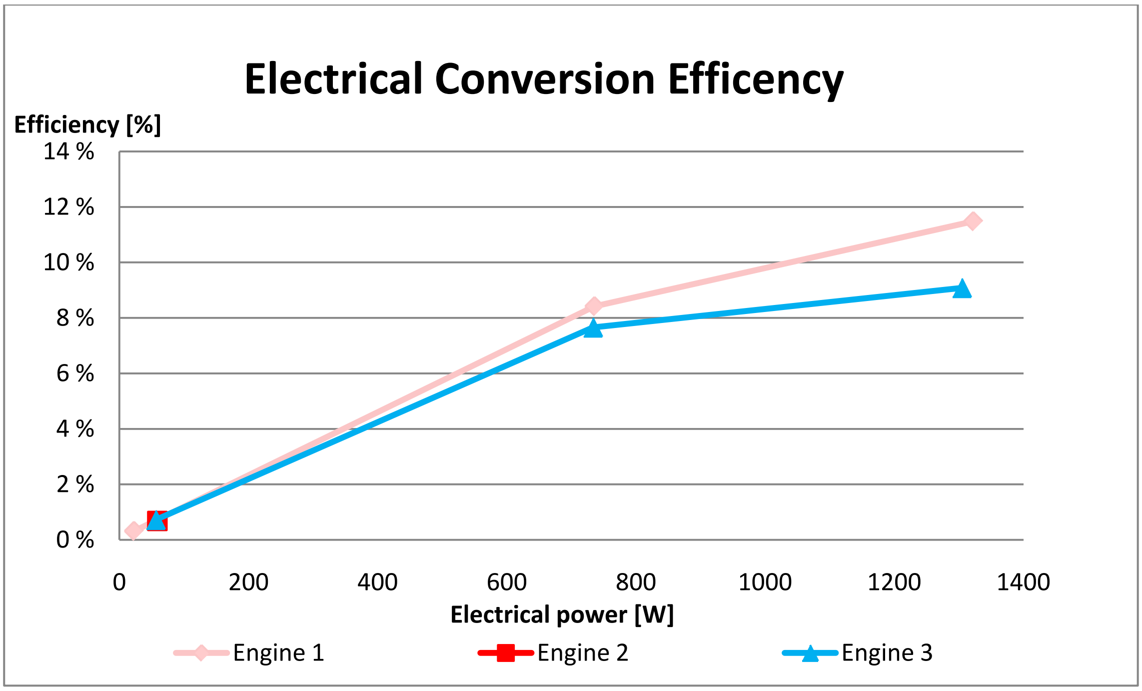


Figure 3.8 Engines electrical production efficiency

When the engine is idling for a period longer than a few minutes, it is in general used for electrical power production. The fuel efficiency when idling is therefore of interest. The efficiency and fuel mass and volume consumed can now be compared to other feasible APU technologies.

730g of diesel per hour or approximately 1 g diesel per Wh electricity is consumed when idling with a dynamo generation of 700 W. The engine's efficiency is extremely low at low power production since most of the energy is used for maintaining rotation of the engine. The efficiency improve with increased power production since a larger part of the power beyond the base rotation, is used to drive the dynamo. This is in accordance with normal diesel generators, which have the best fuel economy or efficiency at high rated power (60-90% of rated power). But the vehicle engine and dynamo are not tuned like a diesel generator, since the main task for the engine is propulsion.

The extra fuel consumed due to electrical power production for a mobile vehicle is modest. The engine's base consume, no electrical load on dynamo, is found to be approximately 0.8 litre/hour (see figure 3.7). The fuel consumes, when base consume is subtracted, for a mobile vehicle are 0.1 and 0.5 litre/hour for the 700 and 1300 W power output. The converting efficiencies (base consume defined as free) from diesel to electrical power is then 70 % and 26 % for the 700 W and 1300 W. This is an assumption since the rotational speed for an engine used for propulsion is different than the idling rotational speed. However, by assuming this the fuel consumption for mobile power generation becomes very low. The consequences of generating power, when mobile have in practise no impact on the thermal and acoustic signatures. Mobile generation of electrical power is very advantageous and should be utilised to its maximum

4 Modelling and Simulation

The reason for simulation and modelling is the possibility to simulate the real world on a simple and cost- and time efficient way. The model is a simplified version of the real system and capable of performing a high number of simulations with different input values. The simplification is what makes this possible, but also a limitation, since it will never be completely equal to the real electrical system.

The main goal is to see the interaction between the different configurations simulated, and to examine if they can manage to supply the load. The model and simulation results are not precise and adequate enough for exact system designs and final component decisions. For systems unable to fulfil the requirements, the possible causes can be highlighted on the basis of the simulation results.

4.1 TRNSYS

The program used for modelling in this thesis is called Transient Energy System Simulation (TRNSYS, version 16.01.0003) and was founded at Solar Energy Laboratory in University of Wisconsin-Madison. TRNSYS is an energy simulation tool that is written in Fortran program language. It allows the individual user to modify or make new components, and has been under continual development the last 25 years. By allowing user programming, TRNSYS has developed to be a flexible tool with a large amount of components [17].

The standard TRNSYS library consists of components commonly found in thermal and electrical energy systems. It also has general components to handle input of weather data or other external files, regulators and functions to force a component to act as intended. Each component's parameters can easily be specified and the components are affected in the manner which they are connected. In the simulation studio the components icons are visually connected with its input and output variables and the simulation results are graphically displayed.

TRNSYS's main usage is for simulation of thermal energy systems, like buildings. However, the flexibility in the TRNSYS program by user specification of the standard components, own programming and a variety of component compositions make it possible to construct an electrical energy/power system for mounted and dismounted soldiers.

4.2 Components

All technologies found to be feasible in chapter 2 will be modelled and simulated. The feasible energy sources are FC, PV thin film panel, batteries and ICE. All the power sources are not found in the TRNSYS component library. The missing components (DMFC and Li Ion) could have been made by (re)writing program code. However this is time consuming and out of the scope in this master thesis. By parameter adjustment for similar components, the desired effect and intention are believed to be obtained.

4.2.1 Fuel Cell

Simultaneously as the writing this master thesis, a DMFC from Smart Fuel Cells called Jenny (Appendix A) has been tested at FFI. It is a portable DMFC with fixed power output 25 W (within voltage range 10-30 V DC). A Jenny FC, with equal characteristics, is used as the DMFC component in the model. With a fixed power output the fuel consumption is fixed and easily calculated. In the TRNSYS library several FCs are available, but they all have in common that they use hydrogen as fuel. Due to this and since the DMFC has a fixed power output a generic diesel engine generator system component is used instead. The generator component, type 120b, can be set to deliver fixed power output and is easily controlled by its parameters. It is therefore used and the fuel consume is calculated by an own calculator component. The FC components in TRNSYS have a number of output parameters like cell pressure and air consumption, but this information is unimportant and superfluous in the simulation.

4.2.2 Thin Film Panel

Several photovoltaic components are available in the TRNSYS library. Type 94b, which is a thin film panel, is found best and used in both models to simulate the electrical performance of a photovoltaic array. Type 94b has a relative extensive mathematical description and only the main equations will be presented here. A complete mathematical description can be found in the TRNSYS's component mathematical reference manual.

The component employs equations for an empirical equivalent circuit model to predict the current voltage characteristics of a single module. The amount of current generated dependent on solar radiation and the I-V characteristics of the diode are also temperature-dependent.

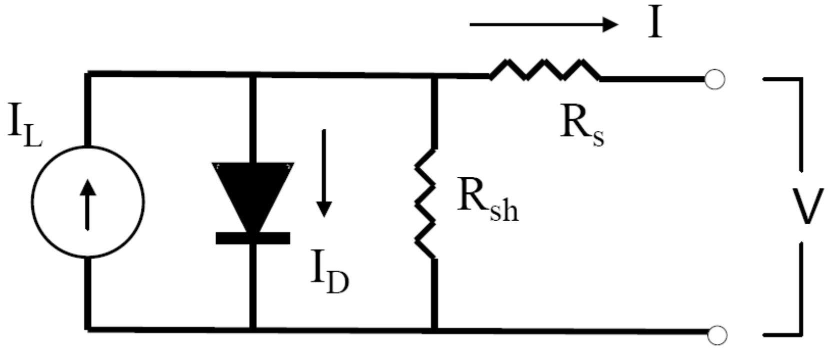


Figure 4.3 Equivalent electrical circuit in the type 94 model [17]

The current-voltage equation for the equivalent circuit in figure 4.3 is given by equation (4.1) [17]. *I* is the current and given by:

$$I = I_L - I_0 \left[exp\left(\frac{q}{\gamma k T_C} (V + IR_S) \right) - 1 \right] - \frac{V - IR_S}{R_{sh}} \qquad (4.1)$$

I_L is the module's photocurrent and a result of equation (4.2). I_0 is the saturation current shown in equation (4.3), q electron charge constant, γ empirical PV curve-fitting parameter, k Boltzmann constant, V voltage, R_S series resistance and R_{sh} the module shunt resistance.

The module's photocurrent I_L depend on the insolation and temperature of the PV module are given by

$$I_L = I_{L,ref} \frac{G_T}{G_{T,ref}} \qquad (4.2)$$

$I_{L,ref}$ is the module photocurrent at reference conditions, G_T is the total radiation (beam, diffuse and
reflect) incident on PV array, $G_{T,ref}$ is the incident radiation at reference conditions.

The I_0 diode saturation current in equation (4.1) is calculated by equation (4.3)

$$\frac{I_0}{I_{0,ref}} = \left(\frac{T_C}{T_{C,ref}}\right)^3 \tag{4.3}$$

$I_{0,ref}$ is the diode saturation current at reference conditions, T_C module temperature, $T_{C,ref}$ module temperature at reference conditions. All the reference values are calculated from further equations not explained here, but found in the TRNSYS mathematical references.

4.2.3 Regulator and Controller

The type 48c regulator component is used in both models. It is constructed for a PV-battery system and distributes DC power from the solar cell array to the battery and from the battery to the load. The FC and dynamo are also power sources than need too be regulated. By using an equation component which adds up all power sources to a single source, the regulator is manipulated and used as regulator for all sources.

The soldier's equipment operates at DC but at different voltages, a DC/DC converter would therefore be a requirement. A DC/DC converter is not available for the regulator component, but the DC/AC inverter efficiency parameter is used as a DC/DC parameter.

The regulator monitors the battery's fractional state of charge (FSOC). FSOC is defined as the current battery capacity divided on the maximum capacity of battery, fully charged equals then FSOC=1. The FSOC is tested against several parameters like max/min limit on FSOC, voltage level on battery and power requirement from load. The battery is then charged, discharged within the maximum charge and discharge rates. A priority to recharge battery, if below minimum FSOC or to meet the load, with available power from the power supplier can also be set. For both models the load has always first priority.

The regulator also control the power flow from the suppliers and charge/discharge the battery to meet the load on the most efficient way, based on comparison of several parameter. The regulator, which is made for regulation of a PV-battery system has no controller to turn on/off power the suppliers. If excess power is available and the battery is fully charged the regulator dump the power. This is acceptable if the source is PV (free fuel), but not if it is a FC or generator. A controller component is therefore set up to switch on/off the power suppliers.

The type 2 controller, which is a generic controller, is implemented in the model. This controller generates an output control function, C_{out} , that can have a 0 or 1 value. Both DMFC and vehicle dynamo are modelled as a general generator component and have a switch with the input values 0 (off) or 1 (on). The controller sends the C_{out} value which is chosen as a function of the difference between an upper and lower value, V_H and V_L. The monitoring value is received as a controller input from the battery. The difference is compared with two dead band value differences ΔDV_H and ΔDV_L. The controller is used with the output control function connected to the input control function, C_{in} , which gives a hysteresis effect. Then the controller has a “memory effect” which is important since the output control function C_{out} is dependent of the previous output C_{in}, which becomes the input with this connection. This is mathematical described in equation (4.5-8) [17]

The controller turns on the power source when the FSOC gets below the minimum set FSOC and turn off when it meets maximum FSOC. But when the battery has been charged (meet max FSOC), the power source does not receive an on signal (1) before the FSOC is below the FSOC minimum. A controllable battery charge and discharge cycle is then obtained.

For safety considerations, a high limit cut-out is included with the type 2 controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition, here $\mathrm{C_{in}} > \mathrm{C_{MAX}}$.

IF THE CONTROLLER WAS PREVIOUSLY ON

If C_{in} = 1 and $\Delta\mathrm{DV_L} \leq (\mathrm{V_H} - \mathrm{V_L})$, $\mathrm{C_{out}}$ = 1 (4.4)

If C_{in} = 1 and $\Delta\mathrm{DV_L} > (\mathrm{V_H} - \mathrm{V_L})$, $\mathrm{C_{out}}$ = 0 (4.5)

IF THE CONTROLLER WAS PREVIOUSLY OFF

If C_{in}= 0 and $\Delta\mathrm{DV_H} \leq (\mathrm{V_H} - \mathrm{V_L})$, $\mathrm{C_{out}}$ = 1 (4.6)

If C_{in} = 0 and $\Delta\mathrm{DV_H} > (\mathrm{V_H} - \mathrm{V_L})$, $\mathrm{C_{out}}$= 0 (4.7)

4.2.4 Battery

The battery components in TRNSYS are based on the lead acid battery technology. The lead acid battery is not the battery of choice for soldiers, since the lead acid battery has low specific energy and density. However, the TRNSYS’s battery components have a large number of parameters with wide constrains. By adjustment of these it is believed that a battery with characteristics suitable and reasonable can be obtained.

The type 47 which is the battery component in TRNSYS has several subtypes. The type 47c is a (lead-acid) rechargeable battery that operates in conjunction with solar cell array and power conditioning components. In this mode, the power is given as input. The other subtype has current as input, and since the load is a power profile, type 47c is chosen. The c type is based on a Shepherd modified Hyman equation. It specifies how the battery state of charge varies over time, gives the rate of charge or discharge and utilises formulas relating battery voltage and current. The other type 47 subtypes use a simpler Shepherd equation, while the Hyman version is a modification of the former model, is more realistic at low currents.

Type 47 has a large number of parameters and equations. However, the mathematical description and equations are found incomplete and difficult to fully understand. None of the equations will therefore be presented here, but a complete mathematical description can be found in the TRNSYS’s components mathematical reference manual.

The battery component characteristics are decided by a number of input parameter set by the user. Examples are max-/minimum current and voltage for charge/discharge and the cell capacity.

What are of greatest importance the soldiers are the weight and specific energy in the battery. The battery weight is calculated independently of the TRNSYS's battery component, since the component does not have a weight output variable. The weight of the battery is calculated from the energy content in the battery. The weight is found by dividing energy content with a specific energy Wh/kg.

4.2.5 Weather Component

Selected worldwide stations for more than 1000 locations in more than 150 countries are included in the TRNSYS library. The data are based on data from the period 1981-2000 from Meteonorm. The selected data set also includes locations for which no local solar radiation data are available. In those cases, the weather data is interpolated by Meteonorm, and the weather files are not as good for locations where actual solar radiation data have been recorded. From the weather data values (station data, interpolated data or imported data), it is calculated hourly values of all parameters, using a stochastic model. The data series correspond to "typical years". The effects of high horizons are also included for the most important mountainous regions of the world.

4.3 Model

For both the mounted and dismounted soldier a generic model has been developed. The two systems are fairly simple and components not used are switched off. By using a generic model simulation of one, several or all power sources are possible in the same model.

A centralised distribution design, described in chapter 2.6, has been chosen for the all electrical power generators. It is easier to model than distributed power design. Besides it is the only technical solution for the FC and ICE.

4.3.1 Soldier Model

The soldier model (figure 4.4) is constructed around the power sources and the soldier power load. The available power sources are PV array, DMFC, primary and secondary batteries. The load components are linked to an external file with the load profile. The weather data component is linked to available TRNSYS library locations data and connected to the PV panel. The rest of the components are for regulation, control, calculations, plotting and output files from simulations. The components are linked together with input and output of theirs parameters and variables. Parameters and components values from the model can be found in appendix B.

Several simulation alternatives with different power sources, amount of energy, loads and locations (insolation and temperature) will be executed. A hybrid solution with a secondary battery will at all times be modelled, if FC or/and PV are the power sources. Power management with only FC or PV as power sources is difficult, since the PV panel has no power production at low/no insolation and the FC a low power output. Batteries have the capability of high power for short periods and low power for long periods, and can be used as a single power source.

The following simulations are found relevant for the dismounted soldier:

- Battery, present system for reference values
- Battery-FC
- Battery-FC-PV
- Battery-PV
- 1-4-8 days of simulation on the different systems
- If it's found necessary all systems will be simulated with different power load profile and sun data (location and season).

Simulation of present system will act as a reference system and benchmarked to other solutions.

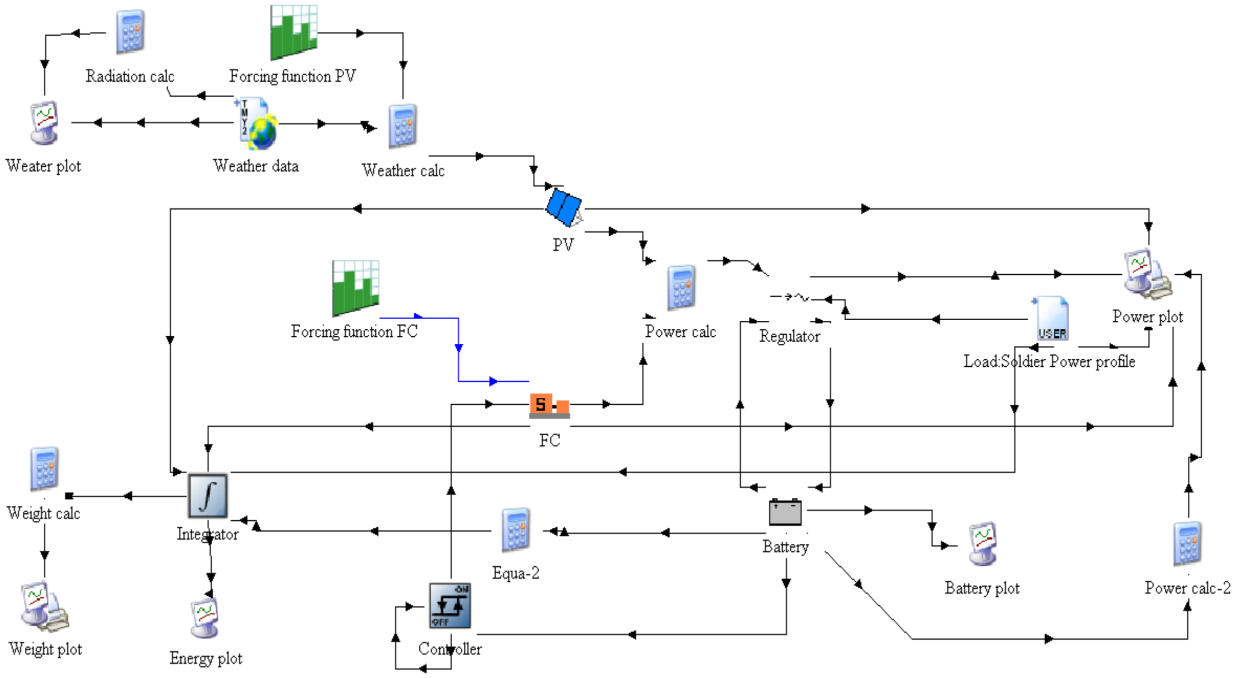


Figure 4.4. Model of soldier's energy system.

The components characteristics are controlled by their parameters, which are set to reflect the technical development potential within the next decade.

Batteries for electrochemical energy storage will always be carried by the soldiers in the model. Rechargeable batteries will in all occasions be selected for hybrid systems and the specific battery energy of 200 Wh/kg is set as default. If batteries are the only power source, primary batteries with specific energy of 500Wh/kg are used (see chapter 2.5.3).

The PV component for each soldier is a 1 m^2 thin film cells implemented in each soldier's tarpaulin. The efficiency is set to 15 %, under standard test conditions [21]. Since the thin film cells are implemented in fabric already carried by the soldier, the extra weight due to the cells is set to 1 kg. The tilt angel on the tarpaulin can be 0 to 90 degrees and in 360 degrees bearing. However, with a horizontal tilt angel, the panel bearing has no influence. This simplifies the simulation, but it is also realistic since maximum sun shade for the soldier (locations near equator) at midday is achieved by horizontal tilt. The horizontal tilt is also used since it is fast for the soldier to unwrap/pack, when panel is used for solar harvesting and placed on ground.

The FC component used in the model is similar to a commercially available DMFC. The current DMFC [Appendix A] is not functional under movement, but further development to a fully operational DMFC, is believed to be achieved within the next decade.

The total system weight for the different electrical loads and mission duration are important. A weight calculator is therefore made in the model. It computes the weight of the power source system. It is calculated by the initial component weight and the weight of the fuel used. The FC in the model has a fixed power output and efficiency. A linear fuel consumption based on the energy production can therefore be obtained. The PV panel has an initial weight and a "weight free" fuel. The weight $\mathrm{W_i}$ for the energy source *i* is given by equation (4.9)

$$W_i = Wi_i + Wf_i E_i \tag{4.9}$$

$\mathrm{Wi_i}$ is the initial component weight [kg], $\mathrm{Wf_i}$ is the fuel weight per Watt hour[kg/Wh] and $\mathrm{E_i}$ is the energy [Wh] produced by *i*. The total weight of a hybrid system is then the weight sum of the different energy sources $\mathrm{W_i}$.

The battery and FC weight is fixed and constant during the simulation period. In real the weight of the systems will decrease since primary batteries could be disposed and the FC fuel is consumed. In equation (4.9) it is not taken into account. This is not done since the start weight of the mission is most important and a mathematical comparison method for indefinable mission durations is not found. For a case mission with known duration, energy consumption and walking time, a mathematical calculation for comparison could have been used. The battery weight and fuel which depends on the energy consumed could as an example been integrated with regard to the time carried and compared to other systems. The weight reduction potential for primary batteries and FCs is therefore a factor which must influence the overall impression of the system.

A switch controller, described in chapter 4.3.3 is linked between the power generator and battery. The controller switches the power source on and off, when the desired FSOC is achieved.

4.3.2 Vehicle Model

The vehicle model is constructed similar to the soldier model. The main difference, except different load profiles and parameters, is the dynamo component which gives an extra available power source. The dynamo will always be a part of the model, since it is fixed to the vehicle.

A switch controller is linked to the dynamo and FC component. The controller switches the power source on or off, when the desired state of charge is achieved. The controller is only attached to one of the components. Under simulation with a FC, the controller is linked to the FC. The FC has higher priority than the dynamo in static position and a forcing function controls the vehicle's mobile periods.

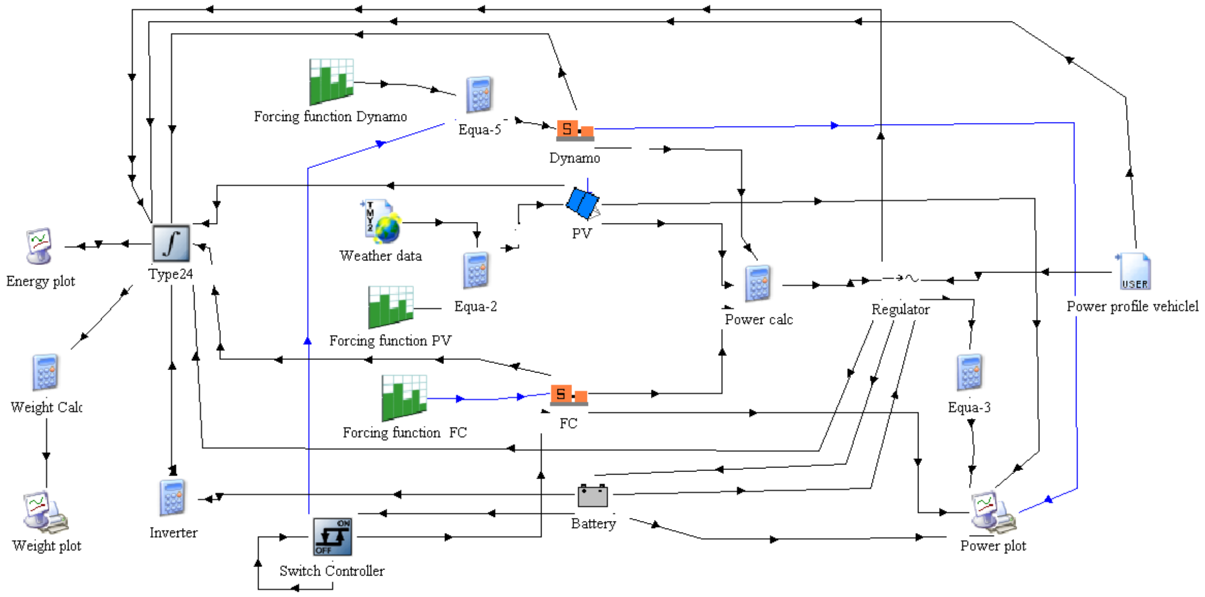


Figure 4.5 Model of Vehicle Energy system

The following simulations will be done for the vehicle model:

- Dynamo-Battery, present system for reference values
- Dynamo-New Battery-FC-PV
- New Battery-FC-PV
- New Battery-FC
- 2-8-14 days of simulation.
- If it's found necessary all systems will be simulated with different power load profile and sun data (location and season)

The default power output used for the dynamo component in the simulation is a 700 W. Approximately 700 W is measured to be the available power output from generator with no usage of hand throttle. It therefore used as the default dynamo power generation. The fuel efficiency is known and used in the weight calculation (equation 4.9)

With a crew size of 3 on each vehicle a PV panel size of 3 m^2 is used. The soldiers' individual panels are attached together and used as one large.

A DMFC with a fixed power output of 300 W is chosen on the basis of the power profiles. A 300 W DMFC produce sufficient power for both load profiles and has surplus of power for power box charging. The vehicle is then able to operate in silent watch mode with the power box for energy storage and peak power periods. A weight ratio per W, equal to the portable 25 W and 1.7 kg DMFC, result in weight of 23 kg. A fix power output and fuel consume per W, equal to the 25 W DMFC is obtained in the weight calculation.

4.4 Model Reliability

A model will always be a simplification of the real world. The advantages are time and cost savings relative to a real test, possibilities for a large number of simulations with a wide parameter span and a quick indication of the systems abilities. The two main factors that determine the quality of the simulation results are the composition of the model and the input data.

A complete model of the real energy system is neither feasible nor realistic. Assumptions, without affecting the simulation results considerably, are done to minimise the work load. It will always be a virtual model of the real system and diverge from the real since not all factors are included (unknown) or ignored (to complicated, irrelevant, minor impact). A complete model will not give reliable results if the quality of the input data is poor.

The main sources of error in the model results from

- The components in TRNSYS will never describe the system fully correct.
- Several required components are not included in the TRNSYS library. Example DMFC and Li Ion battery.
- Errors in input data will result in errors in the result, independent of the quality of the model. The two load profiles used as input are based on measurement and estimation of a future usage, with its intuitive uncertainties. The profiles are repeated every 24 hour. In real world the load profile will change for every 24 hour period.
- With a smaller simulation time step than 0.1 hour (higher resolution) would give more accurate results. But the trends and main results are believed to be captured (figure 5.6a-b).
- Over/under dimensioned battery and PV panel capacity.

In the TRNSYS studio, the simulation time step is a variable set before simulation. This variable is used in the simulation statement to fix the value for the time step to be used. The plots from the simulation deviate with different step values, due to TRNSYS's interpolation. In figure 4.6a the time step is set to 0.1 hour (6 minutes), which is equal to the input power profiles time step. In figure 4.6 b the time step is 0.01 (0.6 minutes or 36 seconds). The figures show a clearly deviation, especially in the maximum values for the load and power.

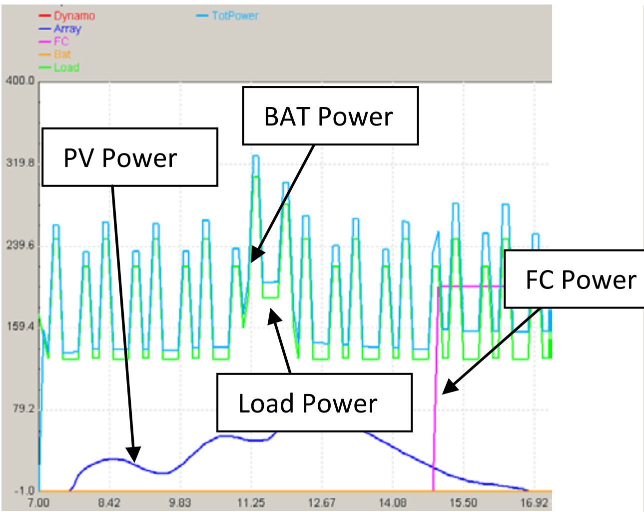


Figure 4.6a. Simulation time step 0.1 hr.

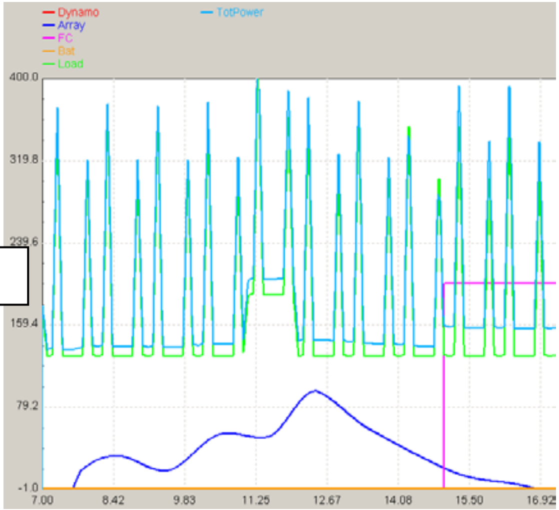


Figure 4.6b Simulation time step 0.01 hr.

However, the FC (controlled by the battery's FSOC) is switched on at the exact same time. This means that the energy subtracted (by load) and added (from PV) to the battery's capacity is equal. The interpolations done by TRNSYS results in rounded values and depend on the time step used. Especially for input data like the load with instantaneous steps, the maximum values are round down (see figures 5.6a-b). Higher resolution on the time step results in longer simulation time and since the overall result is not found different by testing, a time step of 0.1 hours is used in all simulation.

4.4.1 Battery and PV Component Adjustments

The battery and PV thin film component have several parameters and input values to specify their characteristics. The battery's energy capacity is defined by the cell energy capacity multiplied by the number of cells in parallel, series and the voltage of each cell.

The battery should be capable of delivering the majority of its start energy to a load. In the model the battery is only able to deliver approximately 50-70%, when simulated. The load has a relatively low power demand compared to the battery size. The regulator and inverter losses are set low and deep depletion is allowed (FSOC=0). The reasons for the large gap between defined start capacity and simulated capacity result are unknown. Study of the mathematical description of the component has not offered any suggestions, but is difficult to fully understand. Possible factors that may be of influence are: The battery capacity is small relative to an average TRNSYS system and internal (pre fixed) losses may consume a large fraction of the present battery capacity. The lead acid battery performance is different than the intended Li- ion battery.

For a realistic simulation, the battery capacity is therefore dimensioned and adjusted after the simulation results. The battery is first used as the only power source and with a lossless regulator. The intention is to simulate a perfect system before loss parameters are included. The battery's delivered power is integrated and compared to the intended battery capacity and adjusted so that the delivered energy is nearly equal to intended battery capacity. It is considered more important to adjust the parameters and produce reliable results, rather than uncritical modelling and simulation which achieve intuitive incorrect results**.** However, the battery parameter adjustment method is not an optimal approach. A more sophisticated approximation could be to use the current-voltage (I V) graph for charge/discharge of a desired battery. The IV graph can be modelled by using build in TRNSYS functions [39]. A more comprehensive and controllable battery component is then obtained. This has not been done since adequate results are obtained and the idea and possibility was exploited in the completion of the thesis.

A similar approach is used on the PV thin film component. Manufacture data from a panel, which was well tested in the project [1], is used as parameter inputs. The simulation power output result is lower than the power output measured in the project with same high insolation (1000 W/m^2) and location. By using insolation data equal to standard test condition (STC) [21], the PV component parameters are adjusted to the intended 15 % efficiency. This is done by increasing the parameters until the expected power output result of 150 W/m^2 is obtained.

5 Simulation Results

The most interesting and relevant results for the mounted and dismounted soldier are presented in the result chapters. The different sources capabilities to deliver sufficient electrical power and how they cooperate in a hybrid system are of interest. If the simulation shows that the system is capable of deliver sufficient power, its weight is of interest, especially for the dismounted soldier. The simulation results will be fused with other important factors, not possible to implement in the model, and a good overall understanding is obtained.

5.1 Ground Troops

5.1.1 Present Primary Battery System

A primary battery widely used by soldiers is a Li-SO_2 battery called BA-5590 with a specific energy of 190 Wh/kg [Appendix C]. In table 5.1 the systems weights for missions with duration 1-4-8 days and a primary battery with specific energy of 190 and 500 Wh/kg are presented.

	Weight [kg]			Savings [kg]		
System	1 day	4 days	8 days	1 day	4 days	8 days
Normal Load						
Primary BAT (190Wh/kg)	1,3	5,1	10,1	-	-	-
Primary BAT (500Wh/kg)	0,5	1,9	3,8	-0,8	-3,1	-6,3
High Load						
Primary BAT (190Wh/kg)	2,5	10,0	20,0	-	-	-
Primary BAT (500Wh/kg)	0,9	3,8	7,6	-1,5	-6,2	-12,4

Table 5.1 Primary battery mass and savings for different mission duration and energy needs.

The primary battery mass for a specific battery energy of 190 Wh/kg, rapidly increase to a considerable weight for missions with a high energy consume and/or long duration. An augmentation of specific energy to 500 Wh/kg, reduce the weight load considerable, compared to the 190 Wh/kg option.

In the table the battery weights rise linearly, but will in real increase step wise since the batteries are delivered in units (example 1 kg). Table 5.1 present the starts weights of a primary battery option, for a mission with given duration. The primary batteries can be disposed on the battlefield after discharged. The start weight will be equal, but the weight load will during the mission be gradually reduced. Capacity reducing factors like low temperature and incomplete discharging are not included in the table.

5.1.2 Hybrid Battery-FC

The argument of using a hybrid solution is to combine the best characteristics from two systems into one system. In figure 5.2 the weight of three different non hybrid options, 25 W DMFC, primary battery and secondary battery are presented in for different energy needs.

For short missions or/and low electrical consume, a FC option is heavier since the initial weight of the FC component is substantial. But the FC's specific fuel energy is greater (1080 Wh/kg) than for the batteries (≤500Wh/kg). When the amount of delivered electrical energy increases the FC system becomes favourable, since the systems specific energy will approach the fuels specific energy.

Periods with power need lower than the fixed DMFC power output will result in dumping of power if a primary battery is used as hybrid battery. A secondary battery is therefore of interest since it can be used as an energy storage and source. From figure 5.2 it can be seen that a hybrid system is only favourable for missions with a high energy need. The weight of a hybrid system will be between the DMFC and the secondary battery weight, and favourable when the weight is below the primary battery.

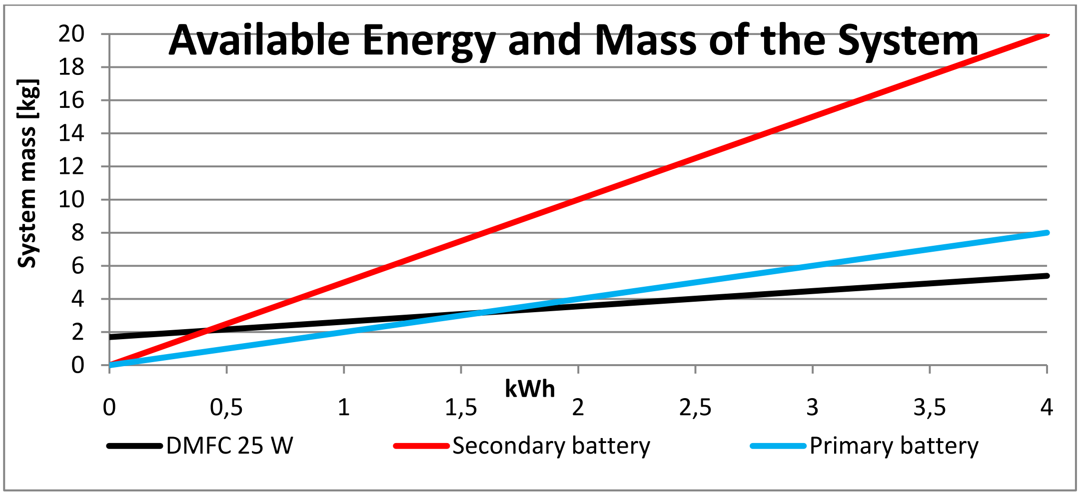


Figure 5.2 Available energy versus system mass for DMFC, secondary and primary batteries.

In all hybrid battery-DMFC systems simulated, a secondary battery will be used since it can be used as energy storage when the net power from the FC is positive. The optimal battery capacity in a hybrid system has enough energy and power for the peak power periods and available storage when surplus of power is present from the DMFC. The optimal weight is important, but an important criterion for the dimension, is emergency power, if the DMFC is damaged. The battery bank is set to 300 Wh, which gives about 14 and 24 hours operation time for the high and normal profile. In worst case the FSOC is 0.2 when DMFC breaks down, which means 60 Wh of energy is available. This is approximate 10 hours of radio usage and the absolute minimum required.

Figure 5.3 show the simulation result of a hybrid battery-DMFC system with a normal load. The battery capacity is 300 Wh with a specific energy of 200 Wh/kg and the DMFC has fixed 25 W power output. The power profiles for the DMFC, battery, load, loss and dumped power are on the left axis, while the FSOC is on the right axis. The power loss is a result of a the charge efficiency parameter which is set to 90 %. The DMFC is switched on at FSOC=0.2 and increase until the battery is fully charged (FSOC=1). The power from the battery is defined positive and net power delivered to battery (charging) negative. The simulation demonstrates that this hybrid system is able to continue as long as there is enough fuel and the components do not degrade. In the simulation the FSOC is always >0.2 and the load is covered (see figure 5.3).

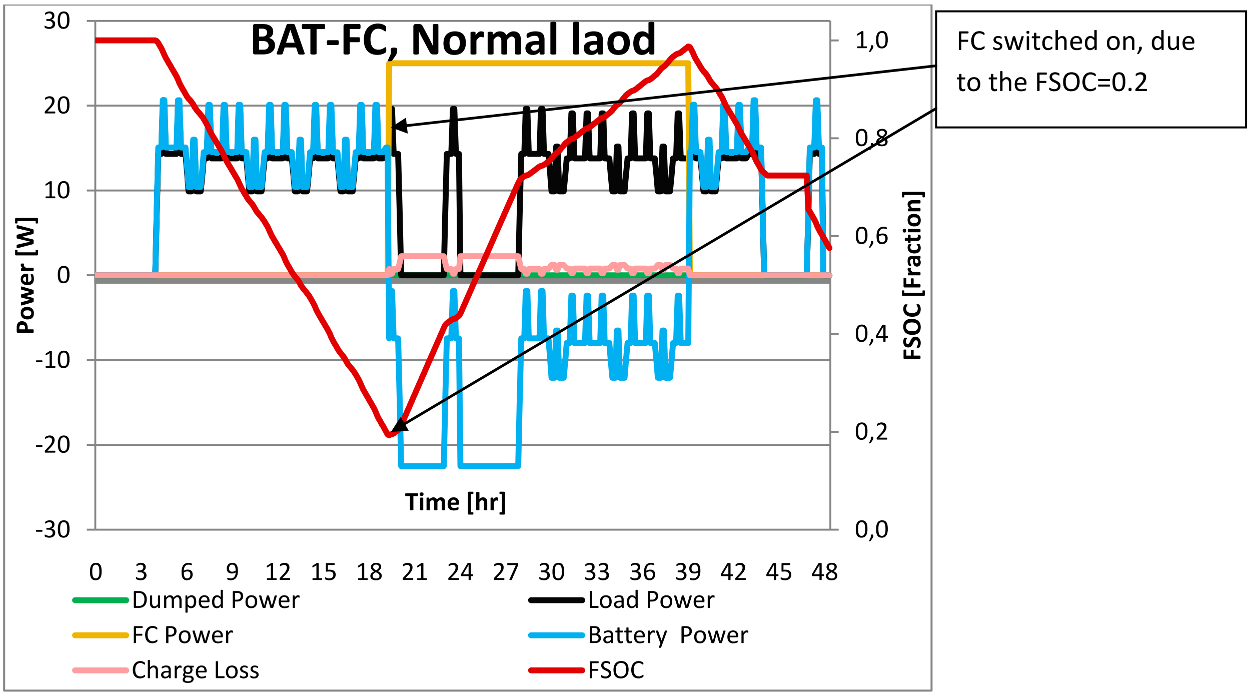


Figure 5.3 Hybrid BAT-FC with normal soldier load.

By exchanging the normal load to a high load, the simulation results show that the power delivery is insufficient before 15 hours have passed. At 13 hours the FSOS is 0.2 and simultaneous a peak power period occur (see figure 5.4 for peak period). Available battery power is then insufficient, since the FSOC is low and the DMFC power output is only 25 W. To overcome this situation the battery requires a higher capacity, the DMFC must be switched on earlier or have a higher power output.

In figure 5.4 the DMFC is controlled by a forcing function. The function force the DMFC in on mode at all time except of a 1 hour shut down period for every 18 hour for fuelling and maintenance.

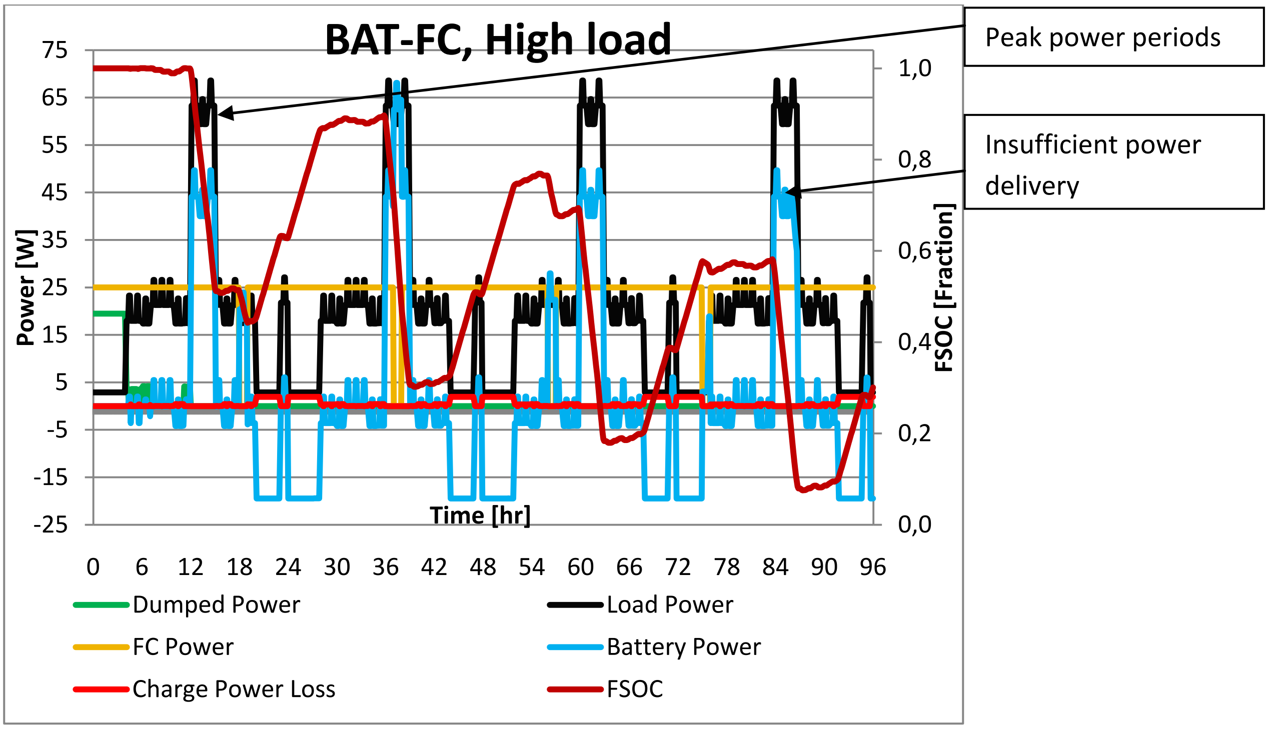


Figure 5.4 Hybrid BAT-FC with high soldier load.

The simulation plot (figure 5.4) states the first 96 hours. The FSOC has a negative trend and the battery is nearly completely discharged after 96 hours. At the fourth peak period, at 85 hours/3.5 days, the delivered power is slightly under the power demand. The figure clearly illustrates the concept of a hybrid system. The FC is the base power and the battery supply the peak power periods and stores surplus power.

By boosting the battery capacity to 500 Wh, the system successfully simulated for 192 hours. This is the smallest battery capacity found applicable. The DMFC is in on mode all times, except a one hour period every 18 hour, for maintenance and refuelling. The other alternative is to increase the fixed DMFC power output. With two DMFC units, the power supply is satisfactory, without changing the battery capacity or using the forcing function. The crux in the power supply is the peak power period every 24 hour when a low FSOC occur at the same time. Even with 50 W in base power the battery has trouble to supply enough power when the FSOC is low. The peak power period is a result of charging the UAV battery. This peak power period is initiated by connecting the batteries to the power system. It can therefore be assumed that the soldier can override the controller and turn the DMFC on, prior to the charging period. By doing this a very low FSOC is avoided, which result in better reliability and an energy and power buffer for the soldier.

The system weight for the different system configurations are showed in table 5.5. All systems have high initial weight due to the DMFC cell. The saving columns are calculated relative to present system with a primary battery with specific energy of 190 Wh/kg. Due to the high initial weight, the hybrid BAT-FC systems do not become a lighter option before 4 days. For long missions with a high energy profile the weight is halved, and reduced with over 10 kg. For the high load three different systems are represented. The first one DMFC with 25 W power output and only capable of sufficient power supply for 3.5 days, se figure

5.4. For the two others the DMFC or battery capacity is enhanced and the weight results are nearly equal.

System	BAT [Wh]	FC [W]	Weight [kg]			Savings [kg]		
			1 day	**4 days**	**8 days**	**1 day**	**4 days**	**8 days**
Normal Load								
BAT-FC	300	25	3,2	3,9	4,9	1,9	-1,1	-5,2
High Load								
BAT-FC (H)**	300	25	3,7	5,3		1,2	-4,7	
BAT-2FC (H)	300	50	5,5	7,2	9,5	3,0	-2,8	-10,4
xBAT-FC (H)	500	25	5,2	6,8	9,0	2,7	-3,2	-11,0

Table 5.5 System weights for different mission duration.** Only operational for 3.5 days.

5.1.3 Hybrid Battery-FC-PV

The PV thin film panel is a possible energy source for the soldier. However is a high reliability often not possible due to several uncertainties independent of user. It depends not only on the insolation, but the soldier must have available time and a secure place to lay out the panel. In the TRNSYS library several insolation locations are available. Kabul in Afghanistan is used as the default location in the simulations. The same location was used in the project [1], which contains measurement of solar insolation and testing of a similar thin film panel. Kabul is a geographical location with high and steady solar radiation. It is therefore reasonable to assume if a simulated system with a PV is not favourable in Kabul, it is not applicable in other locations with lower insolation.

The PV panel usage can be divided into two different harvesting profiles. In the first profile are short periods during the day used for solar harvesting. The short periods <1 hours can be under rests and halts. For the last option long periods or the whole day are available since the soldier is in a lay up position or in a static surveillance position.

In figure 5.6 the whole day during the summer is used for PV harvesting in combination with the hybrid BAT-FC system. The simulation show that a large part of the PV power is dumped (se figure 5.6). The reason is that the battery has small energy capacity and that the load is small at midday when the panel generate power. By doubling the battery capacity to 600 Wh, the DMFC operating time becomes zero. The amount of stored harvested energy is sufficient to cover the load.

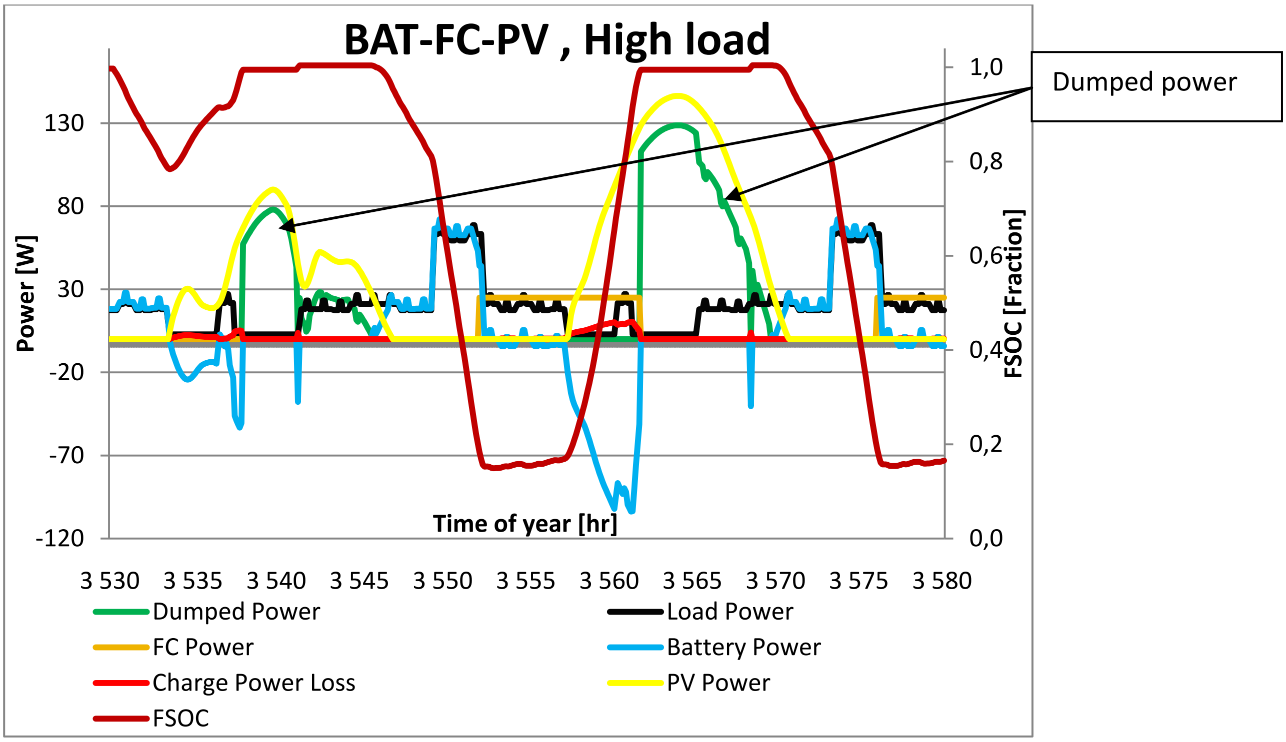


Figure 5.6. Battery-FC-PV, PV harvesting all day during the summer season with a high load.

By simple energy accounting of generated and consumed energy it may look that sufficient energy for the load is available. Modelling and simulation give a more real and better understanding of the interaction between the components. The simulation plot in figure 5.6 clearly shows that available storage for energy must be present, if not the harvested energy has no value since it is dumped. In the previous project [1], the simple self made model was not able to show the interaction between battery and power sources like the simulation program is able to. The simulations results in a better understanding of the different power sources and their influence on each other.

The PV panel has a weight of 1 kg. To compensate the weight of the PV panel, the panel must harvest corresponding electrical energy of 1 kg DMFC fuel, which equals 1.1 kWh [18]. This corresponds to 4-5 full days of harvesting with an average winter insolation and 1-2 days mid summer. Simulation of the system with a high load in the winter, results in some PV power supply. The energy support is minor, and the system depends on that peak power and PV harvest period occur simultaneously to become viable. If the peak power period is not at PV harvest time, same decreasing FSOC trend as in figure 5.4 occurs.

In figure 5.7 two periods, at timings 10-11 and 13-14, are used for solar harvesting during the summer season. The PV power supply reduce the DMFC operating time considerably and make it possible to operate with a 25 W DMFC and a 300 Wh battery, instead of a 50 W DMFC or a 500 Wh battery (described in chapter 5.1.2).

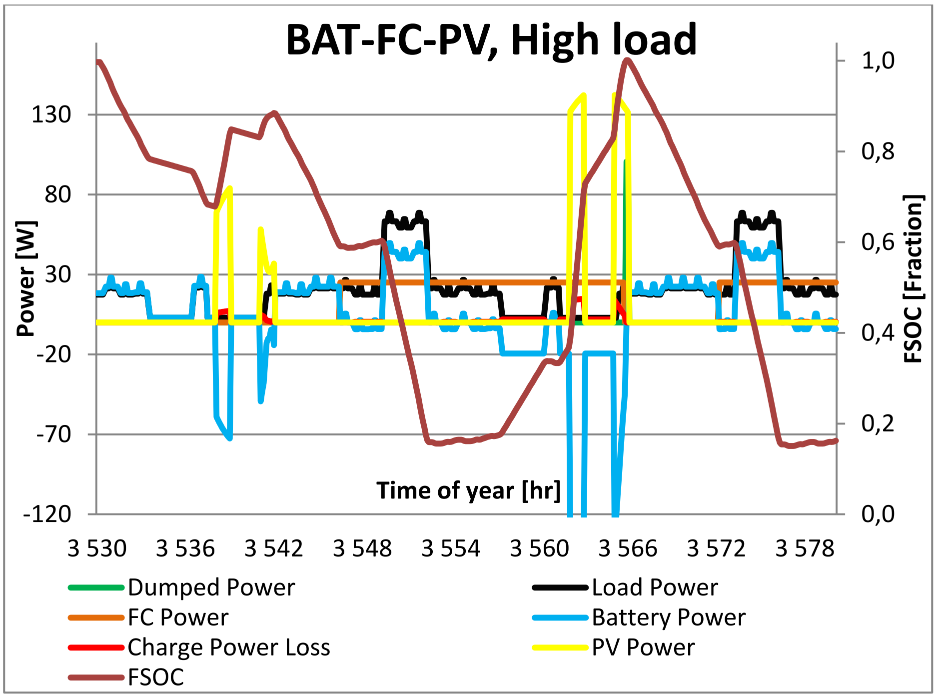
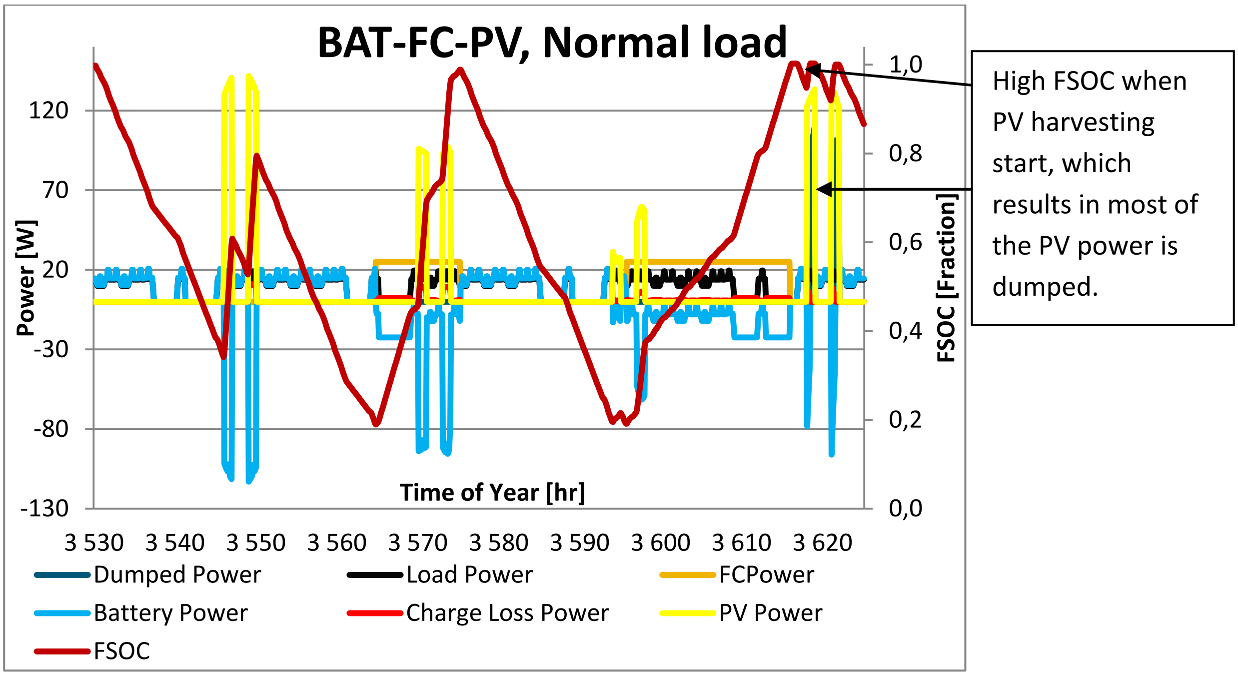


Figure 5.7. Hybrid BAT-FC-PV, high load and PV harvest from 10-11 and 14-14 during the summer.

Soldiers with a normal power need are able to harvest and store enough energy if the insolation is high and most of the day is available for harvesting. Both these parameters have elements of uncertainty and depend highly on the current situational and location.

With two solar harvesting periods during the day, 10-11 and 13-14, the usage of FC can be abridged (see figure 5.8 and 5.3 with no PV element). The second and third day in figure 5.8 have relative poor summer insolation for Kabul. The third day is an overcast day (max 380 W/m^2), but the PV power production is still notable.



High FSOC when PV harvesting start, which results in most of the PV power is dumped.

Figure 5.8 Hybrid BAT-FC-PV, normal load and PV harvest from 10-11 and 14-14 during the summer.

At start of the last solar harvesting day in figure 5.8, the FSOC is nearly 1. As a consequence a large part of the PV power is dumped since battery is fully charged. In retrospect could the DMFC been switched off before FSOC=1 and fuel saved, since the PV power is dumped immediately after. But since both insolation (like day three) and available harvesting time is unpredictable. Turning off the power supply and rely on solar harvesting next day can result in insufficient power availability if a peak power period occur.

Table 5.9 list the weight for different system options over a mission period 1-4-8 days. The highest weight saving is obtained with a BAT-PV system in the summer (S) with the whole day available for harvesting. This option depends on several factors described earlier. The system with no PV element and largest savings is the primary battery with a specific energy of 500Wh/kg. The battery-DMFC weight compared to the primary battery option is converging, but still the hybrid system is nearly 1 kg heavier on an 8 day mission.

	PV usage				Weight [kg]			Savings [kg]		
Normal Load System	**[time of day]**	**BAT [Wh]**	**FC [W]**	**PV[m2]**	**1 day**	**4 days**	**8 days**	**1 day**	**4 days**	**8 days**
Primary BAT (190Wh/kg)	-	-	-	-	1,3	5,1	10,1	-	-	-
Primary BAT (500Wh/kg)	-	-	-	-	0,5	1,9	3,8	-0,8	-3,1	-6,3
BAT-FC	-	300	25	-	3,2	3,9	4,9	1,9	-1,1	-5,2
BAT-FC-PV(S)*	10-11 , 13-14	300	25	1	4,2	4,9	5,6	2,9	-0,1	-4,5
BAT-PV(S)	All day	300	-	1	2,5	2,5	2,5	1,2	-2,6	-7,6

Table 5.9 System weights for different mission duration.*Two periods of one hour with solar harvesting.

The relevant systems from table 5.9 are plotted in figure 5.10. The present primary BAT system (190Wh/kg) is after 4 days the heaviest option of all. By using the same concept as today, but with improved specific energy (500 Wh/kg), a very advantageous power system can be obtained. Only by PV harvesting, nearly all day during the summer season, a BAT-PV systems become the most favourable after 5 days. For a soldier on move this is seldom possible, but an option for soldiers in observation posts.

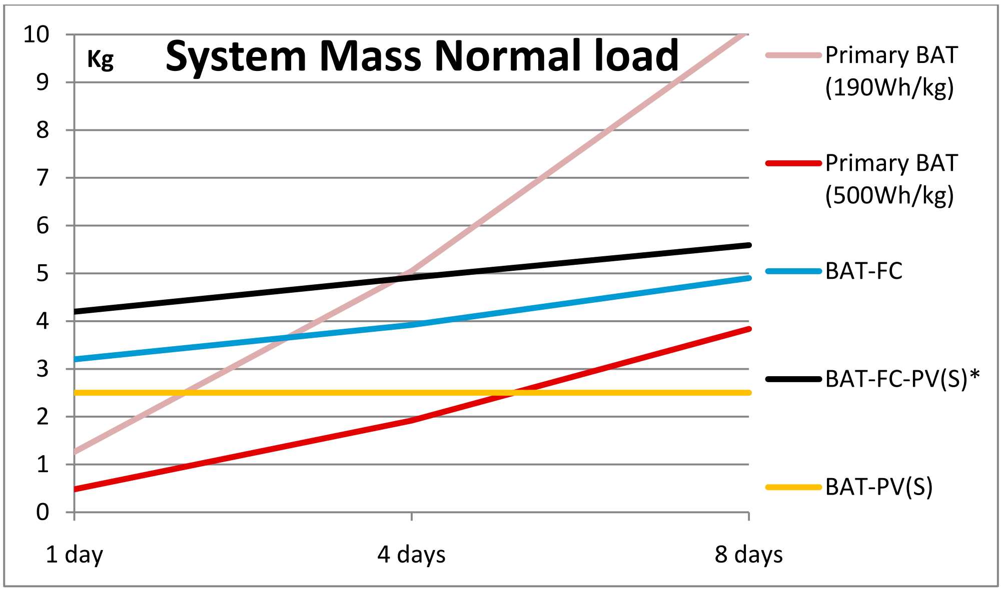


Figure 5.10 Weight of different system options. *Two periods of one hour with solar harvesting.

The PV panel increase the initial weight and decrease the DMFC's fuel consume. Still, the reduced fuel consumption by including a PV panel, with a 2 times 1 hour usage during the day, is not a weight reducing option. The little different between BAT-FC and BAT-FC-PV(S)* is a result of dumped PV power due to lack of available storage capacity (se figure 5.8). Since this option is not favourable in the summer, with high insolation, simulation with a winter insolation is unnecessary. The BAT-PV option depends on several parameters, but has an outstanding weight reduction potential. For all systems the FSOC during different mission is not showed in figure 5.10. The FSOC will vary and a low FSOC after 8 days can give a more advantageous final weight, than with a system with high final FSOC.
Similar results as for the normal load are discovered by simulation with a high load. A considerable weight reduction can be obtained with new or better versions of present power system. In table 5.11 are relevant system presented. Primary batteries with a specific energy of 500 Wh/kg, give the lightest system weight, when ignoring systems which depend on insolation. For the BAT-FC*** option the initial component weight is reduced by 50 % in according to the development plan of the DMFC manufacturer (see chapter 2.3.1.1.)

	PV usage				Weight[kg]			Savings [kg]		
High Load System	[time of day]	BAT [Wh]	FC [W]	PV [m2]	1 day	4 days	8 days	1 day	4 days	8 days
Primary BAT (190Wh/kg)	-	-	-	-	2,5	10,0	20,0	-	-	-
Primary BAT (500Wh/kg)	-	-	-	-	0,9	3,8	7,6	-1,5	-6,2	-12,4
BAT-FC**	-	300	25	-	3,7	5,3	╳	1,2	-4,7	╳
BAT-2FC	-	300	50	-	5,5	7,2	9,5	3,0	-2,8	-10,4
BAT-2FC***	-	300	50	-	4,6	6,4	8,7	2,1	-3,6	-11,3
xBAT-FC	-	500	25	-	5,2	6,8	9,0	2,7	-3,2	-11,0
BAT-FC-PV(S)	All day	300	25	1	4,3	5,1	6,1	1,8	-4,9	-13,9
BAT-FC-PV(S)*	10-11 , 13-14	300	25	1	4,4	5,6	7,2	1,9	-4,4	-12,7
2BAT-PV(S)	All day	600	-	1	4,0	4,0	4,0	1,5	-6,0	-16,0

Table 5.11 System weights for different mission duration.*Two periods of one hour with solar harvesting. **Not sufficient power supply after 3.5 days. ***The DMFC initial component weight reduced by 50%

All systems from table 5.11 are plotted in figure 5.12. Corresponding to the normal load, the primary battery system is the superior weight option for short missions (<4 days). The FC systems are always heavier and need energy support from PV to become a favourable choice regarding weight.

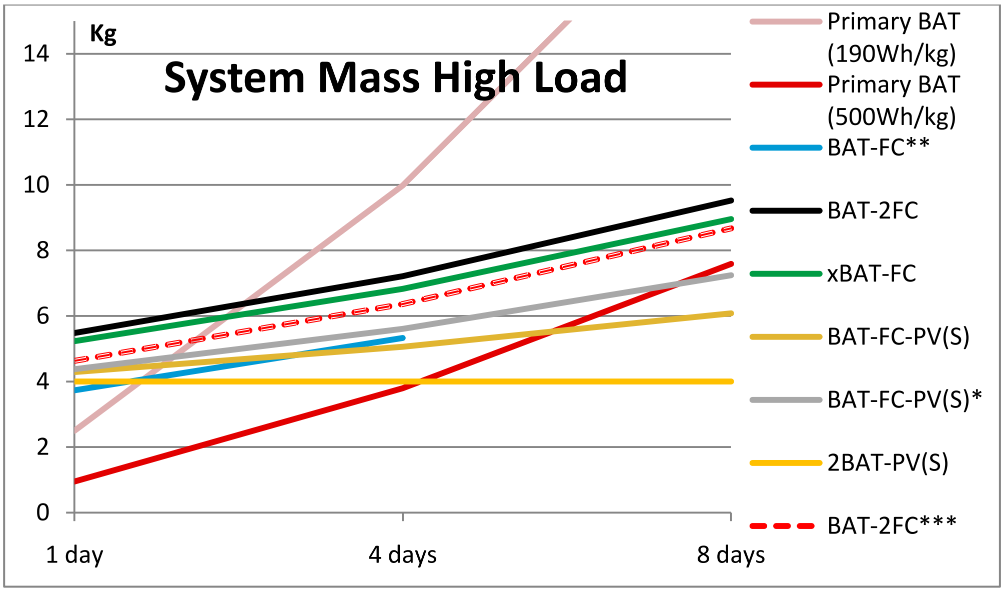


Figure 5.12 Weight of different system options. *Two periods of one hour with solar harvesting. ** Only sufficient power for 3.5 days, *** DMFC component weight reduced by 50%

The insolation on the northern hemisphere is too poor during the winter due to very short days with low sun declination. Simulation with insolation data from Arlanda near Stockholm in Sweden has been executed on the high and normal load. With good summer insolation, the normal load can be covered unaided of the DMFC during the summer period. The high load can partly be covered, but depends on insolation and operation independent is unrealistic.

5.1.4 Simulation Summary

Lighter power systems, compared to present system, are possible by using a hybrid system or/and a battery with higher specific energy.

The simulations show that the interactions between the power sources are important. The power availability is poor when the battery has a low FSOC, since the DMFC power output is low. When PV power is harvested parts of the energy is often dumped since storage capacity is not available.

For short to medium long mission (<4 days) primary batteries result in the lowest weight for both power profiles. Medium to long missions can achieve the lightest weight by harvesting solar power in combination with a rechargeable battery, but this is high uncertainty level. Hybrid BAT-DMFC systems are always heavier, even with a reduced initial component weight of 50% than the primary battery option.

5.2 Vehicle

Reduced or elimination of idling is the most important for the vehicle due to the unfavourable consequences. Reduced fuel consume and weight are also of interest, but not as important as for the dismounted soldier.

5.2.1 Today's solution, dynamo and battery

In figure 5.13 simulation of present vehicle with a battery capacity of 1920 Wh and a normal power load is plotted. The vehicle is in a static position and has no need to the start the engine, unless for electrical power production.

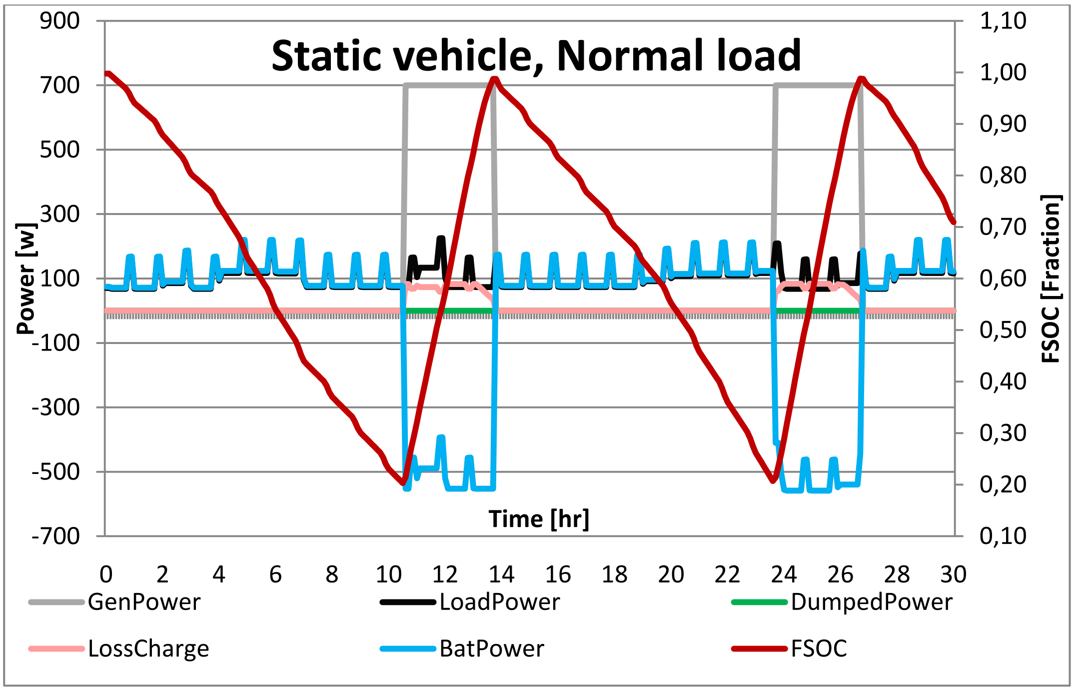
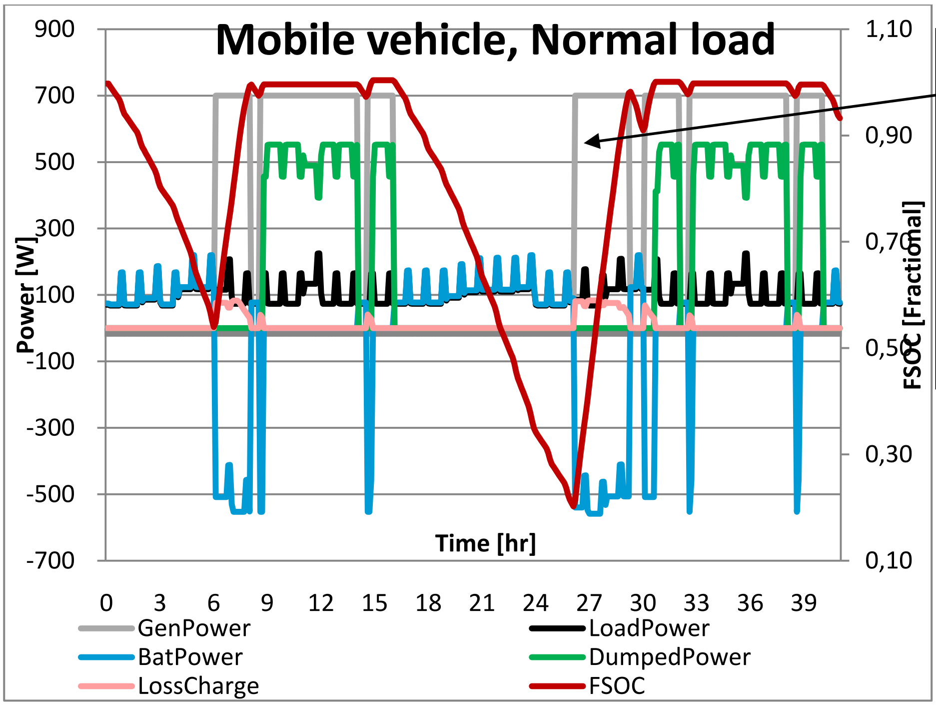


Figure 5.13 Present system for a static vehicle and normal load.

Left axis in figure 5.13 represent the power profiles for the load, battery, charge loss, dumped power and dynamo. FSOC is presented on the right axis. The FSOC decrease as energy from the battery is consumed to cover the load. When the FSOC=0.2 the generator, which is the vehicle's engine, is switched on for power delivery until FSOC=1. Power to the battery (charging) is defined negative and positive from battery (discharging). The battery is set to have a charging efficiency of 85%, resulting in a power loss. Due to loss in the regulator, the battery power is slightly above the load power profile.

The battery depletion time (FSOC =0.2) is 10.5 and 5.5 hours for normal and high load. A depletion time between 5-10 hours, agrees with real experience from the power box capacity. In general, the experience is that the vehicle must idle once per night, if electrical equipment is used similar to the power profile.



The idling period results in a high FSOC prior to mobility period and power is dumped almost immediately when mobile.

Figure 5.14 Mobile vehicle with a normal load.

In figure 5.14 the vehicle is mobile in three periods, timings 6-8, 8.5-14 and 14.5-16 for every 24 hour. A normal load is to be covered, which gives a depletion time of 10 hours and a recharge period from FSOC 0.2 to 1of 3-4 hours. After the first mobility period, the vehicle has a static period of 14 hours. The battery's FSOC is 0.2 after 10 hours and must then be recharged. The FSOC is nearly 1 at the start of mobility period. Due to this high FSOC, almost all available power from the generator is dumped in the next mobility periods.

For the mobility periods used in figure 5.14, the average idling requirement for power production in a 240 hour period is one 3.3 hour period every 24 hours. For the high load the battery must be recharged after 5.5 hours, but the fuel consumption is similar to the normal load, since the idling periods occur in the middle of the static periods. The FSOC is then low instead of high (see figure 5.14 @ 30hr) at start of mobility period.

A large amount of available power is dumped after the battery is recharged in the mobility period (figure 5.14). Even with a low FSOC, the battery is fully charged after 3-4 hours of driving with a power delivery of 700 W from the dynamo. The battery capacity in the power box is relative limited compared to the available power output from the dynamo. It also employs a battery technology (lead acid) with low specific energy and density (approx 40 Wh/kg and 110 Wh/l) [22]. Commercial Li Ion batteries are several times more energy dense and less voluminous. By exchanging the power box to a 50 kg rechargeable Li Ion battery (same weight and volume as present lead acid battery) with specific energy and density of 200Wh/kg and 500Wh/l, the energy storage becomes five times larger.

5.2.1.1 Dynamo and New Battery

In all following simulations, the battery capacity is expanded, but based on a 50 kg Li Ion battery with 200 Wh/kg. This gives the power box an energy capacity of 10 kWh instead of 1.9 kWh.

The static non idling time expand considerable by exchanging the lead acid battery with Li Ion technology. The power box is now able to supply the vehicle with electrical power for 45 and 80 hours, for the normal and high load. By simulation with same mobility periods as used in figure 5.14, the need for idling is unnecessary. The FSOC is never less than 0.7 if a high load is to be covered, see figure 5.15 and 14.

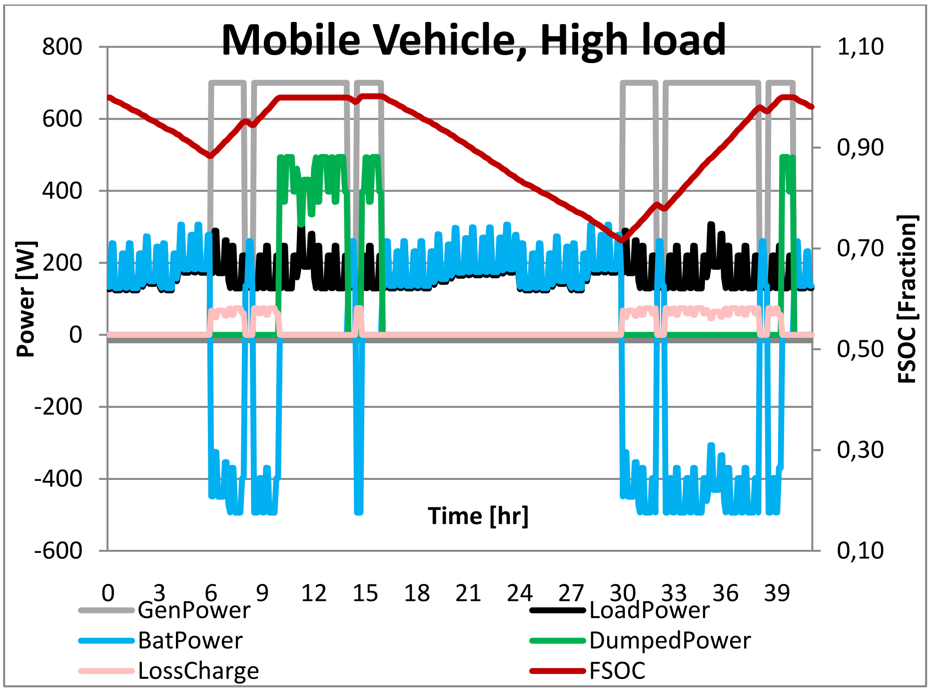


Figure 5.15. Mobile vehicle with increased battery capacity and high load.

The recharge time of the new battery, with power input of 700 W minus the load, becomes relative long. Raise of FSOC from 0.2 to 1 takes 20 hours. The maximum dynamo power output is set to 700 W, based on the maximum power output without using the throttle lever (chapter 3.5). When engine is used for propulsion, the power output can be higher and up to 1900 W. This will reduce the recharge time of the power box considerably. However in the simulation a power output of 700 W is used, since this is minimum excepted power output.

A weight summary for the different battery options and loads are given in table 5.16. The expanded battery capacity reduced the idling need, when operating with a “normal mobility” period, to zero. The weight reduction by doing this is of minor importance compared to the elimination of the engine’s thermal and acoustic signature.

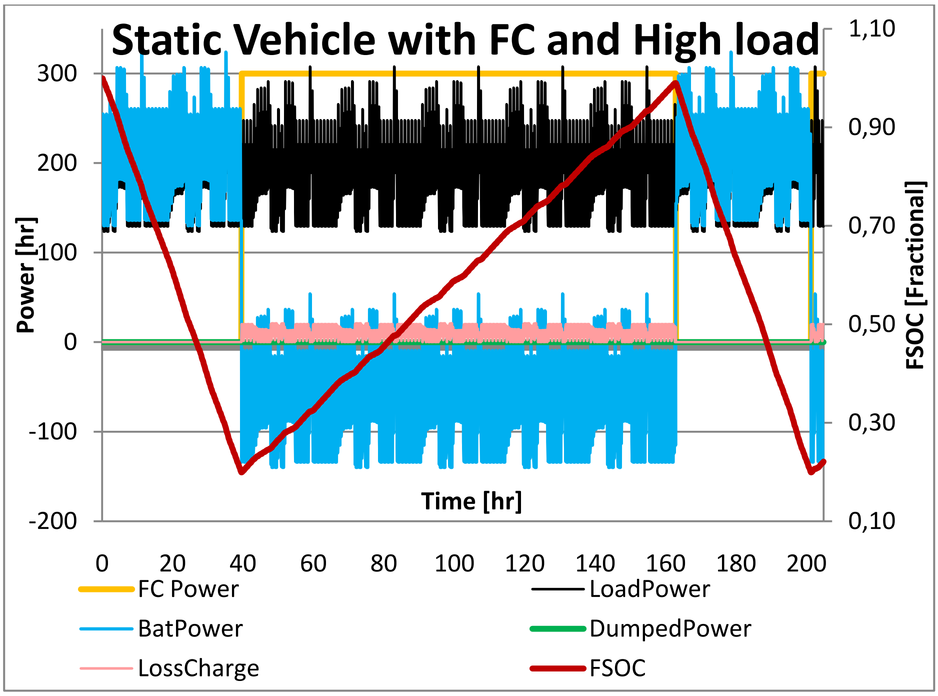
	Mobile				**Weight [kg]**			**Savings [kg]**		
System	**[time of day]**	**Idling**	**DYN [W]**	**BAT [Wh]**	**2 days**	**6 days**	**10 days**	**2 days**	**6 days**	**10 days**
Normal Load										
DYN-BAT (40Wh/kg)	-	Y	700	1 900	6,8	25,3	41,2	-	-	-
DYN-BAT (40Wh/kg)*	6-8, 8.5-14,14.5-16	Y	700	1 900	4,6	13,8	23,0	-2,2	-11,5	-18,2
DYN-BAT (200Wh/kg)*	6-8, 8.5-14,14.5-16	N	700	10 000	-	-	-	-6,8	-25,3	-41,2
High Load										
DYN-BAT (40Wh/kg)	-	Y	700	1 900	13,0	40,3	68,4	-	-	-
DYN-BAT (40Wh/kg)*	6-8, 8.5-14,14.5-16	Y	700	1 900	4,6	13,8	23,0	-8,4	-26,5	-45,4
DYN-BAT (200Wh/kg)*	6-8, 8.5-14,14.5-16	N	700	10 000	-	-	-	-13,0	-40,3	-68,4

Table 5.16 Systems weight for static and mobile Multi vehicle with present or increased battery capacity.*Vehicle mobile

5.2.2 New Battery-FC

The intension of using a FC is to reduce or/and eliminate the use of the unfavourable vehicle idling. The control component is therefore connected to the FC. Simulation with the new battery (figure 5.15) shows it is little need for additional power when vehicle is frequently mobile. In static position or periods of very little mobility time, power supply from a FC is relevant. The FC has several positive characteristics, compared to the ICE, especially in static position with an intension to remain covered.

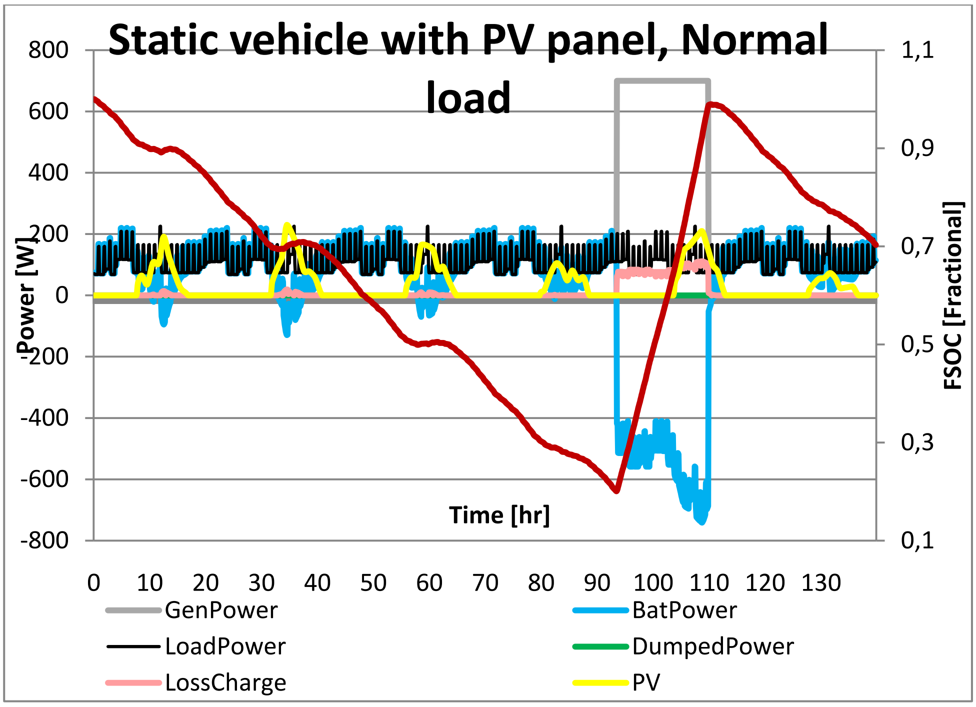
With a DMFC with output power of 300 W, the vehicle is able to operate in silent watch for both load profiles for 10 days. With an overall surplus of energy from the DMFC, recharging of the power box can also be achieved. In figure 5.17 the DMFC and power box supplies the high load for over 200 hours.



5.17. Vehicle in static position with FC and new battery.

5.2.3 New Battery-Dynamo-PV

The number of soldier mounted in each vehicle is set to be three. Their personal PV panels are linked together which results in 3 m^2 panel with an additional weight of 3 kg. In figure 5.18 the normal load is covered by the power box, 3 m^2 PV panel and vehicle idling. The vehicle is in static operation and the panel is placed horizontal all day, with a typical winter insolation in Kabul. The power supply from the panels are relative modest and idling for power supply must start after 93 hours. The power supply from the PV panel delay idling start with 13 hours. Over a 240 hour period the idling time is reduced with 2 hours every day, compared to a non PV system.



5.18 Vehicle with PV harvesting in the winter season and normal load.

In the summer the PV power production is sufficient to cover the normal load if the whole day is used for harvesting. This is not possible for the high load, but the overall idling time is reduced. Dumping of PV power is not a problem (see chapter 5.1.3) for the vehicle since the vehicles battery capacity compared to the maximum amount of energy harvested is very large.

5.2.4 Dynamo-New Battery-FC-PV

Implementing a FC eliminates the use of idling (chapter 5.2.2), and in combination with PV harvesting, reduction of the DMFC's fuel consume can be obtained. The additional weight of 3 kg solar panel equal nearly 3 kWh in DMFC fuel. Harvesting of 3 kWh electrical energy require approximately 1-2 cloudless days in the summer and 4-5 in the winter season. For winter missions with a static period shorter than 3-4 days, the weight reduction potential is therefore not present.

The different system weights for 2-6-10 days of mission are presented in tables 5.19-20 and plotted in figures 5.21-22. For the vehicle, the weight saving is not as relevant as for the dismounted soldier. For the PV system the insolation is an important variable and summer and winter insolation is marked as (S) and (W) respectively. The weight savings are from 70 kg to an increased system weight of 10 kg. However, 70 kg plus or 10 kg minus has little impact on a several tons heavy vehicle. The weights of the different systems are all concluded to be acceptable and not an excluding factor for any of the presented systems.

Normal Load	Mobile		PV usage					Weight [kg]			Savings [kg]		
System	[time of day]	Idling	[time of day]	DYN [W]	BAT [Wh]	FC [W]	PV [m2]	2 days	6 days	10 days	2 days	6 days	10 days
DYN-BAT (40Wh/kg)	-	Y	-	700	1 900	-	-	6,8	25,3	41,2	-	-	-
DYN-BAT (40Wh/kg)*	6-8, 8.5-14,14.5-16	Y	-	700	1 900	-	-	4,6	13,8	23,0	-2,2	-11,5	-18,2
DYN-BAT (200Wh/kg)*	6-8, 8.5-14,14.5-16	N	-	700	10 000	-	-	-	-	-	-6,8	-25,3	-41,2
DYN-BAT-FC	-	N	-	700	10 000	300,0	-	23,0	39,2	51,4	16,2	13,9	10,2
DYN-BAT-PV(S)	-	N	All	700	10 000	-	3,0	3,0	3,0	3,0	-3,8	-22,3	-38,2
DYN-BAT-PV(W)	-	Y	All	700	10 000	-	3,0	3,0	14,9	26,6	-3,8	-10,3	-14,6
DYN-BAT-FC-PV(W)	-	N	-	700	10 000	300,0	3,0	26,0	39,8	39,8	19,2	14,5	-1,4

Table 5.19. System weights for a normal load and comparison to different alternatives. * Vehicle Mobile.

In table 5.19-20 all systems are compared to a present system. The engine's fuel consumption is independent of the different battery capacity in static position. The energy requirement is equal over the period, is start FSOC is equal end FSOC, since the energy is supplied from the engine's idling. With a mobile vehicle the new battery capacity eliminates the required idling. The lowest system weight for the normal load profile is the PV-BAT, but the system depends in both insolation and available harvest time.

In figure 5.21 the mass and mission duration values from table 5.19 are plotted. The systems which require idling have dotted lines. The DYN-BAT-FC system, which eliminate the need for idling under all circumstances, increase the weight only by 50 kg for a 10 days mission.

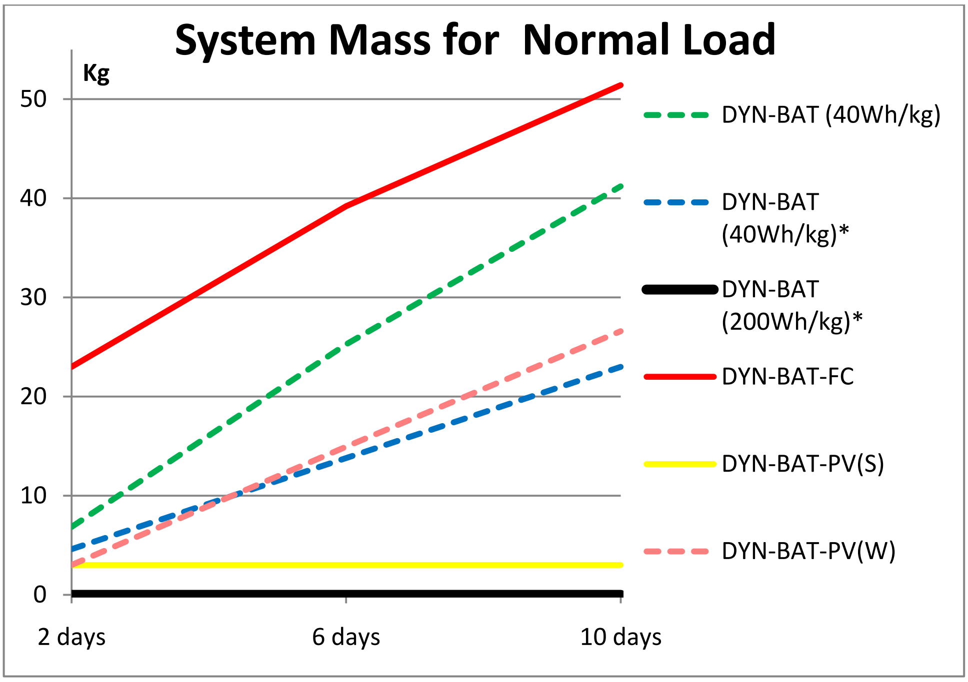


Figure 5.21 System mass for different alternatives. Systems which require idling is marked by dotted lines.

Similar results as for the normal load are found for the high load profile. Increased power box capacity gives benefits in both weight reduction and elimination of idling. PV harvesting is probably more relevant for vehicles than for dismounted soldier. The vehicle has always sufficient power when mobile and the power problem occur in static positions. In static positions will PV harvesting be simple, possible and give a considerable energy contribution to the power balance. The available storage issue, showed by simulation of the soldier and PV harvesting (see chapter 5.1.3), is not a problem.

The DYN-BAT-PV system has the lowest weight for both summer and winter season when vehicle is static. The high initial FC component weight does not manage to reduce the final weight considerable, but the FC has several advantageous characteristics.

High Load	Mobile		PV usage					Weight after days [kg]			Savings [kg]		
System	[time of day]	Idling	[time of day]	DYN [W]	BAT [Wh]	FC [W]	PV [m2]	2 days	6 days	10 days	2 days	6 days	10 days
DYN-BAT (40Wh/kg)	-	Y	-	700	1 900	-	-	13,0	40,3	68,4	-	-	-
DYN-BAT (40Wh/kg)*	6-8, 8.5-14,14.5-16	Y	-	700	1 900	-	-	4,6	13,8	23,0	-8,4	-26,5	-45,4
DYN-BAT (200Wh/kg)*	6-8, 8.5-14,14.5-16	N	-	700	10 000	-	-	-	-	-	-13,0	-40,3	-68,4
DYN-BAT-FC	-	N	-	700	10 000	300	-	25,4	52,0	68,0	12,3	11,7	-0,4
DYN-BAT-FC-PV(W)	-	N	All	700	10 000	300	3,0	26,0	50,5	67,8	13,0	10,3	-0,6
DYN-BAT-FC-PV(S)	-	N	All	700	10 000	300	3,0	26,0	42,1	46,0	13,0	1,8	-22,4
DYN-BAT-PV(W)	-	Y	All	700	10 000	-	3,0	3,0	32,3	45,7	-10,0	-8,0	-22,8
DYN-BAT-PV(S)	-	Y	-	700	10 000	-	3,0	3,0	12,8	25,9	-10,0	-27,4	-42,6
DYN-BAT-FC-PV(S)	-	N	-	700	10 000	300	3,0	26,0	38,0	50,4	13,0	-2,3	-18,0

Table 5.20 System weights for a normal load and comparison to different alternatives. * Vehicle Mobile.

Plot of the mass values for different mission lengths from table 5.20 are presented in figure 5.22. If the vehicle is frequently mobile the lightest option is to increase the power box's battery capacity described in chapter 5.2.1.1. The DYN-BAT-FC option eliminates the need for idling completely and has the same overall weight as present system for a static 10 days mission. By introducing PV panels to the DYN-BAT-FC system, the weight is further reduced, if more than 1 day of average summer insolation is harvested.

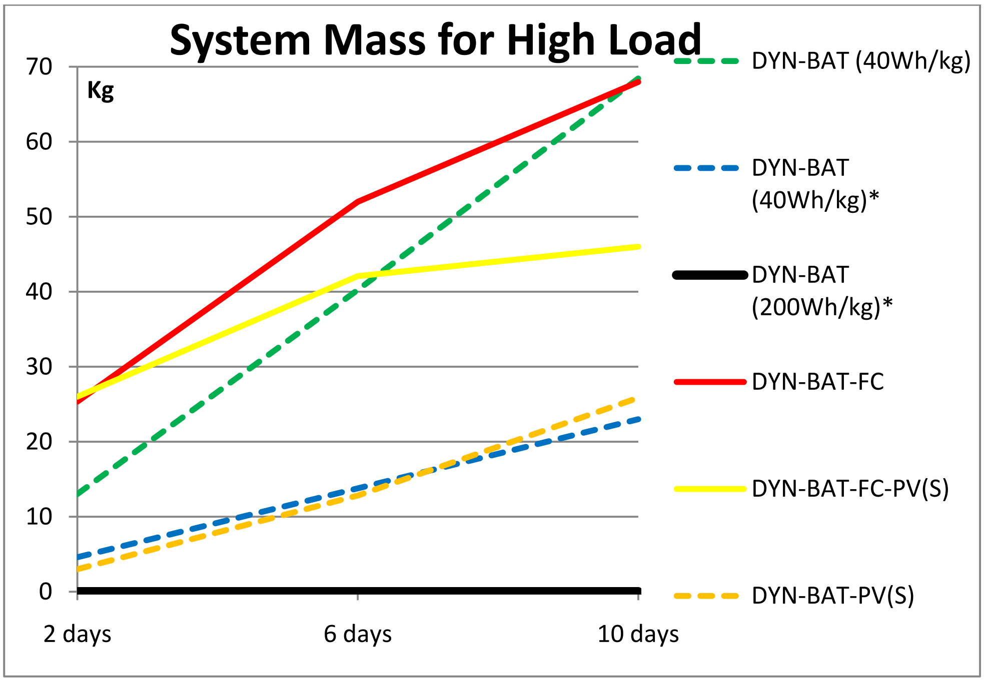


Figure 5.22 System mass for different alternatives. Systems which require idling is marked by dotted lines.

5.2.5 Simulation Summary

The simulations show that the available power from the dynamo is a large unused source when the battery has present low energy capacity. The capacity can be increased by no weight or volume increase, and the need for idling is considerable reduced. The need for idling can be totally reduced by implementing a DMFC or/and with harvesting of PV panels under the right conditions.

6 Analysis and Discussion

6.1 Difference in technologies

The four different power sources used in the model are not only different in technology, but also in the concept of energy delivery. The PV technology alters from the other technologies in the availability of electrical energy. For the ICE, FC and battery, electrical power is available at all time, if the primary energy source (fuel/chemical energy) is present. The electrical energy source is then reliable since the storage of fuel/chemical energy usually is known. In contrast, the PV panel has a “free and unlimited” energy source in both weight and cost, but depend on insolation, space and time. The power output from PV will fluctuate and the stability is often poor and operation in a hybrid system is required.

Military operations depend highly on predictable and reliable electrical energy. In fixed installations (camps) solar harvesting is relatively reliable, since time and location for harvesting are fixed. With soldiers operating on the battlefield, the available time for harvesting and insolation will vary. Since the mission period is relative short (<10 days) the general variation in weather can result with a very low amount of harvested energy (large overcast ratio). This makes the PV harvesting concept vulnerable in military operations, and the possibilities to harvest are poor for a number of military operation categories. The utilisation can therefore often only be seen as a contribution to the energy generation, instead of a reliable and steady energy source like the rest of the energy suppliers. Usage of PV panel must therefore be considered on the basis of location, season and mission type before it is brought into the battlefield.

6.2 Modelling and Simulation

TRNSYS is as described in chapter 5 developed for modelling and simulation of thermal energy systems. Several components like Li Ion batteries are not available in the TRNSYS library. Other models and simulation programs have not been found. General programs like MATLAB can be used to build a complete soldier model, but this is a workload beyond a master thesis. TRNSYS, which has the fundamentals of energy simulation, is therefore used. The soldier’s power system has to the author’s knowledge never before been simulated in TRNSYS. It is uncertain whether it has ever been done in any program. In a large study “*Meeting the Energy Needs of Future Warriors”* by National Research Council (US) from 2004, one of the recommendations to the contractor, US Department of Army, was to develop a modelling capability for the soldiers power system.

TRNSYS is not an optimal simulation studio for modelling of the soldier’s electrical power system. Important components are missing and components behave not as intended and the reasons are uncertain. A mathematical description exists for every component, but it is often incomplete or difficult to fully understand. What is supposed to be advantage with the TRNSYS is that it allows the user to edit and has therefore been under continual development. However, this has also resulted in that the components are patch up by several authors and occasionally the mathematical description is incoherent.

6.3 Risks of Introduction

Introduction of a new system will always include risks. The main hazard is that the system does not work as intended and in worst case, not advantageous compared to the old system. The possible risk factors found are listed below:

A) The system implemented is based on incorrect/wrong arguments.

B) Readiness of technology, do not function as intended.

C) User level.

D) Logistics.

A) Implementation based on incorrect arguments can for example occur if an area or specific conflict is emphasised to high. Norway has currently a relative large military contribution in Afghanistan, and it is easy to take this conflict as basis and construct a system optimal for that specific theatre. The areas of conflict and operation will change. It is therefore important to have a robust-flexible system with a wide climate range.

B) New system often results in a challenging start-up period. To minimise the problem the system must be well tested and modified after the user's requirement, thus the numbers of surprises are kept at a minimum. However, a too careful testing may postpone the implementation and the possible advantages are unnecessary delayed.

C) Especially introduction of a new technology like a DMFC, have the potential of a too high user level and/or lack of system knowledge. Very few have user experience with the technology, in comparison to the ICE. However, proper education of the system will reduce this factor considerable.

D) Implementation of new technology often results in introduction of new logistics requirements. Ideally the implementation removes other items and result in a net reduction of goods. Optimally the goods are easy to handle and traded world wide.

6.4 Economy

The specific fuel costs will in some theatres, like Afghanistan, have minor impact on the true fuel cost. It is the logistics cost that plays the major role. Hence, in regions with extremely poor infrastructure like Afghanistan, the fuel price rises exponentially when aircrafts are used for fuel transport. The "fully burden cost" of a 1 $ gallon of gasoline, transported by helicopters to the most remote bases, are in average 400 $, and can be as high as 1000 $ per gallon [41]. This is in extremis, but in general are the logistics battlefield cost a greater concern than the specific fuel cost.

The energy content in the fuel and batteries consumed for electrical power by ground troops, are in ratio with the amount consumed in military camps minor. However the real or "fully burden cost" for the electrical energy are often higher. The fuel and batteries are consumed outside the bases, here the logistics costs are even higher than inside the camp. The actual cost for the different sources like methanol, gasoline and batteries are difficult to estimate, but they are on the basis of the energy prices for camps, very high. The gasoline price is transferable to batteries, when assuming it is the fuel mass that enhances the price of the gasoline.

Low thermal and acoustic signatures have a price which is difficult estimate. It can be significant in some theatres and unessential in other. However, low thermal and acoustic signature are an advantage for all military units.

The component cost will also influence the choice of system. The FC component price is high, but will fall as the systems become mass produced. In the long term the system's fuel price is probably more important. The cost of a battery component will depend, as for the fuel, on the logistics cost. A rough estimate based on the logistics cost, favour rechargeable batteries over primary batteries. By using a diesel with a specific energy of 13 Wh/kg and a generator with 30 % converting efficiency, the secondary batteries are favourable. The electrical energy content in the diesel, after conversion, is nearly 4 kWh/kg and considerable higher than the best primary battery.

6.5 Analysis Dismounted Soldier

The weight of the power supply system is an essential factor for the dismounted soldier. The reliability and signatures of present battery system are very good, but the weight is a concern. Of the three system found feasible for the dismounted soldier, the PV panel has several dependability issues. The technology is reliably, but the harvesting concept using available time when insolation is good is not very reliable. A battery or a hybrid DMFC-battery system is much more reliable and stable. In figure 6.1 -2 the hybrid DMFC system is plotted and compared with the specific energy for primary batteries.

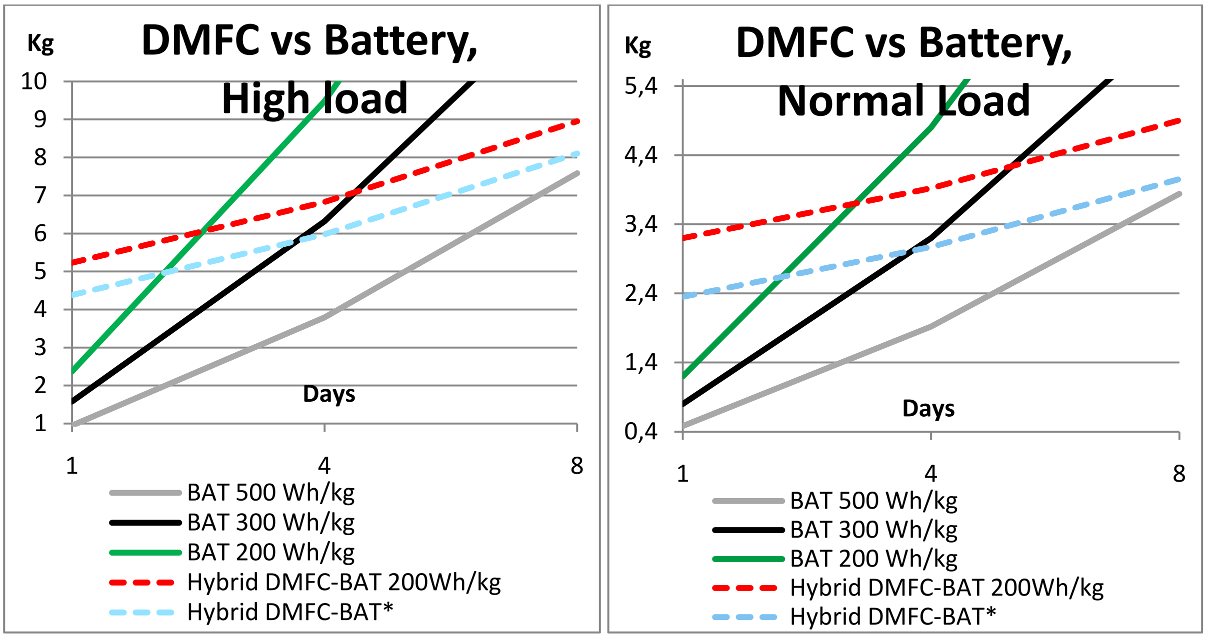


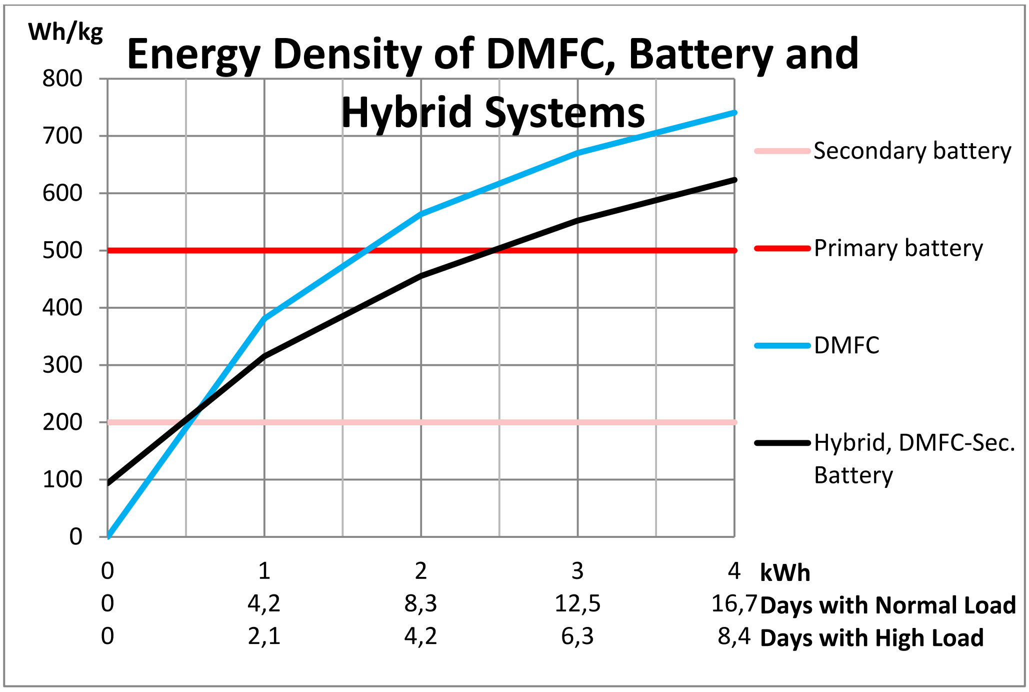
Figure 6.1 and 6.2 Weight comparison between DMFC and different batteries. DMFC* present a component reduction of 1 kg.

The hybrid system consists of a DMFC and a rechargeable battery of 300 Wh with a specific energy of 200Wh/kg. To make the hybrid system more favourable, a weight decrease of 1 kg is also plotted (marked DMFC*). The reduction may come from an initial lower DMFC component weight, higher specific energy in battery, better fuel efficiency or fuel energy density.

The figures 6.1-2 show that a hybrid system is not preferable for either normal or high load for short missions (<1.5 days). The slope of the hybrid system is gentler than for the batteries, but if a specific battery of 500Wh/kg is obtained, hybrid systems are difficult to find favourable even for long missions with a high energy consume. The hybrid's specific energy must be improved more to become a lighter option than primary batteries with a specific energy of 400-500 Wh/kg.

In figure 6.3 the specific energy for the DMFC, Hybrid DMFC-BAT and batteries are plotted for the days with normal load and high load and the energy consumed. The figure does not show the weight for different mission lengths, but the specific energy at the different timings or amount of consumed energy.

The FC systems have intuitive very low specific energy in the start due to the initially high component weight. When the amount of energy becomes considerable, the specific energy will approach the specific electrical energy of the methanol fuel, which is 1080 Wh/kg. The hybrid system may look favourable for long high load missions. The overall specific energy for a given mission length can be found by integration of the hybrid system function with regarding to the time or amount of energy consumed (x-axis). The intention of the figure is to show that the specific energy raise as the amount of consume/generated energy increase.



6.3 Specific energy of different batteries and a DMFC with a 300 Wh secondary battery with specific energy 200Wh/kg.

The commercially available Jenny DMFC is used as the present state of art FC. It has an operating temperature between -20 and 45°C (50°C with diluted methanol fuel). The minimum operating temperature can be a problem in arctic and desert areas. Expanding of the minimum temperature limit, could be possible by utilising body heat to operate it in even colder conditions. In winter warfare the dismounted soldier always has an amount (1+ litre) of water as liquid. Keeping the DMFC above -20°C should then be possible and the DMFC's waste heat could also become a heat source.

For long missions (>5days) in areas of high insolation, PV harvesting should be considered, since it has a great potential if the right conditions are present.

The DMFC has the highest introduction risk since the technology is new and emerging. FCs have not been used for portable soldier power and the user experiences under battlefield conditions are very limited. Since it is new technology and little corresponding experience exist, careful testing must be undertaken before introduction. Methanol can be handled similar to gasoline, but a new fuel must be introduced with its logistics challenges.

The logistic energy cost of using methanol instead of batteries, will probably be lower since the fuel's specific energy is higher than the batteries (see chapter 6.4). The FC component cost and operating time will then be important. The cost will probably fall and operating time increase as it becomes mass produced. In the long term the FC will probably reduce the cost for the soldiers' electrical power system.

6.6 Analysis of Mounted Soldier

In the simulation results presented in chapter 5, static operations are simulated for most of the systems. The vehicle is made for mobility operations and is seldom static for more than a few days. However, it is in static position that the electrical power supply becomes a problem and therefore the most important operation modus to simulate. The most simple and efficient method to reduce the Multi vehicle's thermal and acoustic signature is to increase the power box's battery capacity. The vehicle dynamo, which is driven by the engine, is a considerable unused electrical power source when the vehicle is mobile. The present power box is dimensioned with a small storage capacity and it is rapidly discharged when the engine is turned off. When the vehicle is mobile the power box is recharged after a few hours and available electrical power become an unused source.

The vehicle's silent watch period with better stealth capabilities is increased to a period of 2 and 3.5 days for the high and normal load, with a battery capacity of 10kWh. The weight, volume and handling of the power box are similar to present system and the introduction risks minor.

The costs for Li ion batteries are higher, but can easily be argued for by the considerably reduced thermal and acoustic signatures, which are achieved under static operation.

The need for more stored electrical energy past 2-3.5 days is limited, but with implementation of a DMFC, the need for idling will be totally eliminated. With a FC the need too increase the power box capacity can be unnecessary. An auxiliary DMFC power unit installed on the vehicle will require some space. The 25 W DMFC has a power density of 7.8 W/l and with the same ratio, the 300 W DMFC require a volume of 38 litres or an equilateral cube with 0.34 m sides. This is not considerable and should not affect the selection.

The conversion efficiency results from the engine's electrical power production (chapter 3.6) show that higher power level on the dynamo result in higher converting efficiency from fuel to electrical power.

With an increased battery capacity and technology the battery will tolerate higher maximum power input and a faster recharge time can be obtained. A vehicle dynamo with higher power output should be considered since the mobile battery charging is very advantageous in both fuel consume and signatures.

The energy content in diesel is higher, but the conversion efficiency of the FC is higher. The electrical energy price of diesel and methanol is probably relative equal. Implementing a FC will come at a higher cost than using the exciting and relative cheap vehicle engine. The power box battery can be relative expensive, and the operating and number of cycles it tolerate before replacement is important.

6.7 Reduced power and energy need

A simple, but not always the easiest way to solve a problem is to reduce the demand which cause it. The soldiers' power demand has increased considerable the last decades, even when the power efficiency of electrical equipment has been reduced. When the components power requirement raise, the overall energy requirement often increase since the component is more used and its capacity expanded. The manufactures providing the defence marked with electrical equipment are often not given any incentives to reduce the power demand by the military [10]. A better overall plan by the military, where everything from carried weight load for the individual soldier too the life cycle cost is implemented, should be carried out. Reduced electrical power needs do not only reduced the battery and fuel cost, but also reduce the logistics cost and gives lighter soldiers which are more lethal.

An efficient and straightforward way to obtain energy saving is to power down the equipment that is not actively used. It can be done by the user or with a better electronic power management design. Several approaches are possible, but by using aggressive technology tailored to the application and the user mode, the power requirement for computation and communication can be reduced significantly [10].

7 Conclusion and Future Work

The aims of this thesis, which the conclusions are based on, are stated in start of the thesis. The main objective was to model and simulate technical solutions, available within the next decade, which would result in a more favourable electrical power system for ground troops, mounted or dismounted.

This thesis has been ground-breaking in the way of evaluating the soldier's electrical power system. The modelling and simulation of the system have opened a new field of work which will, with improved simulation capabilities, become a more powerful tool. Parts of the contents and results will bring new knowledge to the Norwegian Defence Research Establishment and their work for an improved electrical power system for soldiers.

7.1 Conclusion

Five different technologies are found to have the technological readiness and adequate characteristics for vehicle mounted and dismounted soldiers within 10 years. Some are already fully or partly implemented, while other will probably not be implemented before the end of the decade (2020). The adequate technologies are: batteries, fuel cells, photovoltaic thin film and the internal combustion engine (only for vehicle mounted soldiers).

- Li ion batteries are found the most promising rechargeable battery and a specific energy of 200 Wh/kg is expected within the next decade. Several primary batteries based on lithium and zinc-air will probably be the best primary batteries with a specific energy of 500 Wh/kg.

- Commercial direct methanol fuel cells (DMFC) are currently available, and believed to be a robust and reliably portable military power system within few years. Several other FCs technologies are emerging, but the DMFC is considered to be the best choice for the next decade.

- The PV thin film panel has some very advantageous and some negative aspects. The fuel comes at no cost, but the electrical power is relatively unreliably since available harvest time and good insolation must be present. The PV thin film technology is mature and under the right conditions a superior choice regarding weight.

- The internal combustion engine will be represented on the battlefield as the vehicle engine and the main electrical power generator for mounted soldiers in the next decade. Improvements in the engines fuel economy, specific power and volume will happen. Small portable power systems (< 50 W) for dismounted soldiers will probably not become reality due to unsolved technological problems. Other technology like FC and batteries will be more competitive, which will lower the incentives to develop small ICE.

Normal and high power profiles for a 24 hour period have been measured and estimated for both the mounted and dismounted soldier. The profiles are based on a power need for the next decade.

A model of the soldier's mounted and dismounted electrical power system has been constructed and simulated. Modelling and simulation of the soldier's electrical power system may seem like a neglected field of work since very little literature, modelling programs and simulation results are available. The modelling and simulation in this thesis has given a much better understanding of the interaction between the power suppliers, energy storage and power need, than the simple project model [1]. The simulation highlights, that available power is not necessarily stored for later needs, since storage capacity are unavailable. Simple energy accounting of generation and need will probably omit this important issue. Modelling and simulation will probably be even more relevant in near future when more complex hybrid system emerges.

Both for the dismounted and mounted soldier there exists commercially available technology, which will improve their capabilities. Primary batteries with a specific energy of 500 Wh/kg is found to be a lighter system than a DMFC with a rechargeable Li ion battery. The hybrid DMFC-rechargeable battery system is an emerging technology with high future potential, but must be further improved to become the system of choice. The introduction risk is also found higher for the DMFC, than with batteries. PV thin film panels have a too high degree of uncertainty to become a permanent power supplier, but should under the right conditions be used.

The vehicle's dynamo, when mobile, is a substantial unused power source in the present system. By exchanging present power box with a state of art secondary battery, the vehicle will be able to operate without idling for 2-3.5 days. This is probably the easiest and most cost-benefit action and should be done first. With expanded battery capacity a dynamo with increased electrical power output should be considered since the electrical power production, when mobile, is very advantageous.

For total elimination of idling and inconvenient thermal and acoustic signature a DMFC should be installed. A DMFC will result in low signatures and a higher specific energy than batteries since the amount of energy produced is considerable. PV thin film panels can give an important energy contribution and should be considered in areas of high insolation and when the modus of operation allows it.

7.2 Recommendations for Future Work

- Develop better modelling and simulation capabilities for the soldiers' electrical power system.

- More detailed measurements of the soldiers' power consumption based on future equipment usage at different mission types and conditions should be made. Classification of different mission types and climate zones instead of a general and relative inaccurate terms like normal, high and low consume. This will improve and give a better understanding of the different energy needs and improve the quality of the simulation input data.

- The possibilities to reduce the power and energy need for the soldier must be investigated. This may be the simplest and easiest approach to a lighter electrical power and energy system for the soldier.

8 References

[1] Carl Gustaf Rye-Florentz, NTNU student Project 2009 "Renewables for Military Camps and Ground Troops"

[2] Norway, Elverum Tekniske Verksted Tlf: 62 40 20 00.

[3]Digital load from Nortelco AS, Oslo. Load: Vin:0-50 DC, Cin:1-60A DC, Pin:1500W

[4] Elverum Tekniske Verksted, Tlf: 62 40 20 00

[5] Infrared thermometer, Mircron Model:M103 IR MAN, Temperature range: -50-500˚C

[6]David Linden, Thomas B. Reddy, Handbook of Batteries third edition, McGraw-Hill 2002.

[7]James Larminie & Andrew Dicks, Fuel Cell System Explaned second edition, Wiley 2006.

[8]The Research and Technology Organisation of NATO (R&T NATO), *Fuel Cells for Land, Sea and Air Vehicles,* Report TR-AVT-103 May 2006

[9] Sissel Forseth, DMFC test at Norwegian Defence Research Establishment (FFI).

[10] Committee of Soldiers/Energy Systems, *Meeting the Energy Needs of Future Warriors,* National Research Council 2004

[11] Maxwell Technologies: http://www.maxwell.com

[12] Technical data from Husqvarna products: http://www.husqvarna.com/

[13] R&T NATO, *Micro Turbines from the Standpoint of Potential Users,* Report RTO-EN-AVT-131 2005

[14] M. Armand, J.-M Tarascon, *Building better batteries*, Nature 451, 652-657 (2008)

[15] Captain Torkel Haugen, tlf: 40036201, FLO/S/L system integration. Test of a radio with 20 W power output.

[16] TRNSYS official website: http://www.trnsys.com

[17] TRNSYS 16 Documentation

[18] SFC Jenny data sheet

[19] Tomas Markvart, Solar Electricity Second Edition, Wiley 2007.

[20] B von Rodern, H.S Ullal NREL, The Role of Polycrystalline Thin-Film PV Technologies in Competetive PV Module Markets, NREL/CP-520-42494 May 2008.

[21] Standard test conditions (STD) specifies a temperature of 25 °C and an irradiance of 1000 W/m^2 with an air mass 1.5 (AM1.5) spectrum

[22] Power Box battery: Chairman AGM 1280T, 25.5kg, 25.6x16.7x22.6 cm, 12 V 80 Ah

[23] *Design, integration and demonstration of a 50 W JP8/kerosene fuelled portable SOFC power generator*, Journal of Power Sources 193 (2009) 797-803

[24]James Larmine, Andrew Dicks, Fuel Cell Systems Explained second edition, Wiley 2006

[25]Jung-Ho Wee, *A comparison of sodium borohydride as fuel for proton exchange membrane fuel cells and for direct borohydride fuel cells*, Journal of Power Sources 155 (2006) 329-339

[26] Jung-Ho Wee, *Which type of fuel cell is more competitive for portable applications: Direct methanol fuel cells or direct borohydride fuel cells*, Journal of Power Sources 161 (2006) 1-10

[27] Norwegian Defence homepage: http://www.mil.no

[28] Committee on Electrical Power for the Dismounted Soldier, *Energy-Efficient Technologies for the Dismounted Soldier,* National Research Council 1997

[29] Ivan C. Lee, *JP-8 Reformation for Fuel Cell Applications*, US Army Research Laboratory 2004

[30] National Renewable Energy Laboratory (NREL), website http://www.nrel.gov/

[31] Battery manufacture SAFT homepage: http://www.saftbatteries.com

[32] Argonne National Laboratory (U.S Department of Energy) website http://www.anl.gov

[33] Electric Fuel Battery Corporation website http://www.efbpower.com

[34] Ultralife batteries website: http://www.ultralifebatteries.com/military

[35] Article from Teknisk Ukeblad (Norwegian Science magazine), http://www.tu.no/innsikt/nyeteknologier/article217888.ece

[36] Technology Rewiev article: http://www.technologyreview.com/energy/19139/?a=f

[37] E-mail correspondence with Project Manager André Ofner from Smart Fuel Cell, E-mail address: Andre.Ofner@sfc.com.

[38] Byoungwoo Kang, Gerbrand Ceder, *Battery materials for ultrafast charging and discharging* Nature 485, 190-193 (march 2009)

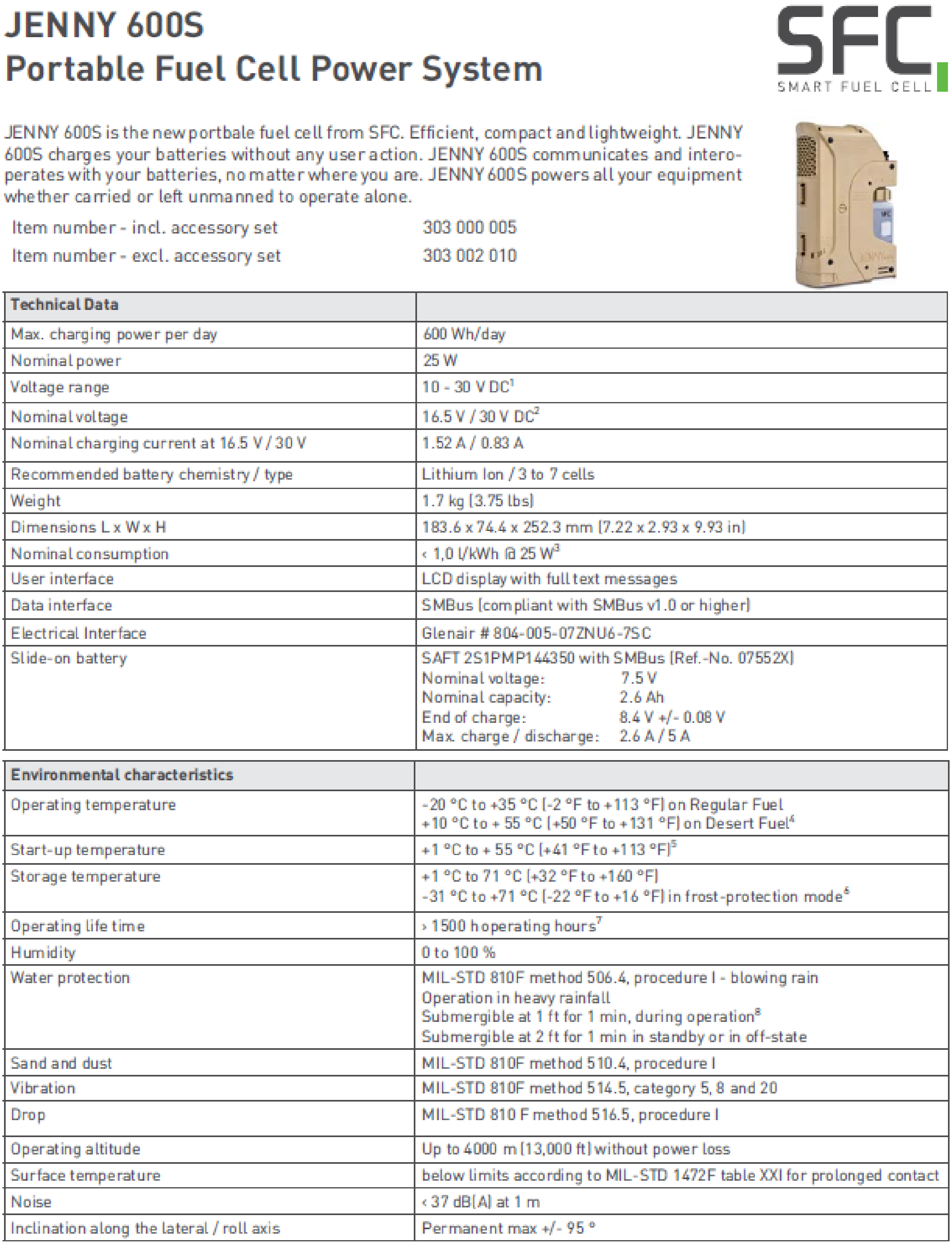
[39] Øystein Ulleberg at IFE, mail: oystein.ulleberg@ife.no

[40] Erik Stensrud Marstein at IFE mail: erik.stensrud.marstein@ife.no

[41] The Hill article*"$400 per gallon gas to drive debate over cost of war in Afghanistan" http://thehill.com*

9 Appendix

Appendix A Jenny DMFC



JENNY 600S
Portable Fuel Cell Power System

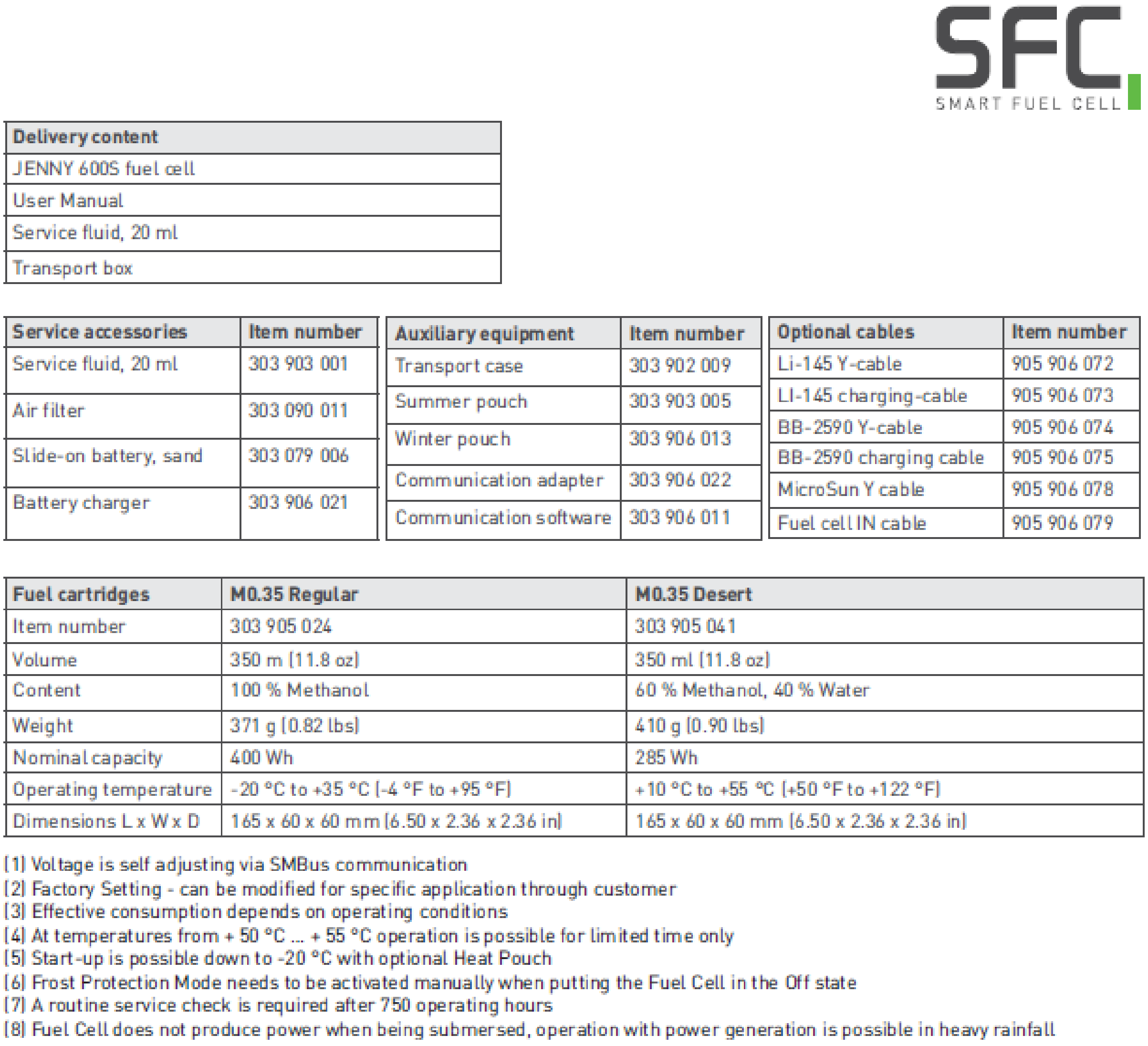
SFC
SMART FUEL CELL

JENNY 600S is the new portbale fuel cell from SFC. Efficient, compact and lightweight. JENNY 600S charges your batteries without any user action. JENNY 600S communicates and interoperates with your batteries, no matter where you are. JENNY 600S powers all your equipment whether carried or left unmanned to operate alone.

Item number - incl. accessory set	303 000 005
Item number - excl. accessory set	303 002 010

Technical Data	
Max. charging power per day	600 Wh/day
Nominal power	25 W
Voltage range	10 - 30 V DC[1]
Nominal voltage	16.5 V / 30 V DC[2]
Nominal charging current at 16.5 V / 30 V	1.52 A / 0.83 A
Recommended battery chemistry / type	Lithium Ion / 3 to 7 cells
Weight	1.7 kg [3.75 lbs]
Dimensions L x W x H	183.6 x 74.4 x 252.3 mm [7.22 x 2.93 x 9.93 in]
Nominal consumption	< 1,0 l/kWh @ 25 W[3]
User interface	LCD display with full text messages
Data interface	SMBus [compliant with SMBus v1.0 or higher]
Electrical Interface	Glenair # 804-005-07ZNU6-7SC
Slide-on battery	SAFT 2S1PMP144350 with SMBus [Ref.-No. 07552X] Nominal voltage: 7.5 V Nominal capacity: 2.6 Ah End of charge: 8.4 V +/- 0.08 V Max. charge / discharge: 2.6 A / 5 A

Environmental characteristics	
Operating temperature	-20 °C to +35 °C [-2 °F to +113 °F] on Regular Fuel +10 °C to + 55 °C [+50 °F to +131 °F] on Desert Fuel[4]
Start-up temperature	+1 °C to + 55 °C [+41 °F to +113 °F][5]
Storage temperature	+1 °C to 71 °C [+32 °F to +160 °F] -31 °C to +71 °C [-22 °F to +16 °F] in frost-protection mode[6]
Operating life time	> 1500 h operating hours[7]
Humidity	0 to 100 %
Water protection	MIL-STD 810F method 506.4, procedure I - blowing rain Operation in heavy rainfall Submergible at 1 ft for 1 min, during operation[8] Submergible at 2 ft for 1 min in standby or in off-state
Sand and dust	MIL-STD 810F method 510.4, procedure I
Vibration	MIL-STD 810F method 514.5, category 5, 8 and 20
Drop	MIL-STD 810 F method 516.5, procedure I
Operating altitude	Up to 4000 m [13,000 ft] without power loss
Surface temperature	below limits according to MIL-STD 1472F table XXI for prolonged contact
Noise	< 37 dB[A] at 1 m
Inclination along the lateral / roll axis	Permanent max +/- 95 °



SFC
SMART FUEL CELL

Delivery content
JENNY 600S fuel cell
User Manual
Service fluid, 20 ml
Transport box

Service accessories	Item number
Service fluid, 20 ml	303 903 001
Air filter	303 090 011
Slide-on battery, sand	303 079 006
Battery charger	303 906 021

Auxiliary equipment	Item number
Transport case	303 902 009
Summer pouch	303 903 005
Winter pouch	303 906 013
Communication adapter	303 906 022
Communication software	303 906 011

Optional cables	Item number
Li-145 Y-cable	905 906 072
LI-145 charging-cable	905 906 073
BB-2590 Y-cable	905 906 074
BB-2590 charging cable	905 906 075
MicroSun Y cable	905 906 078
Fuel cell IN cable	905 906 079

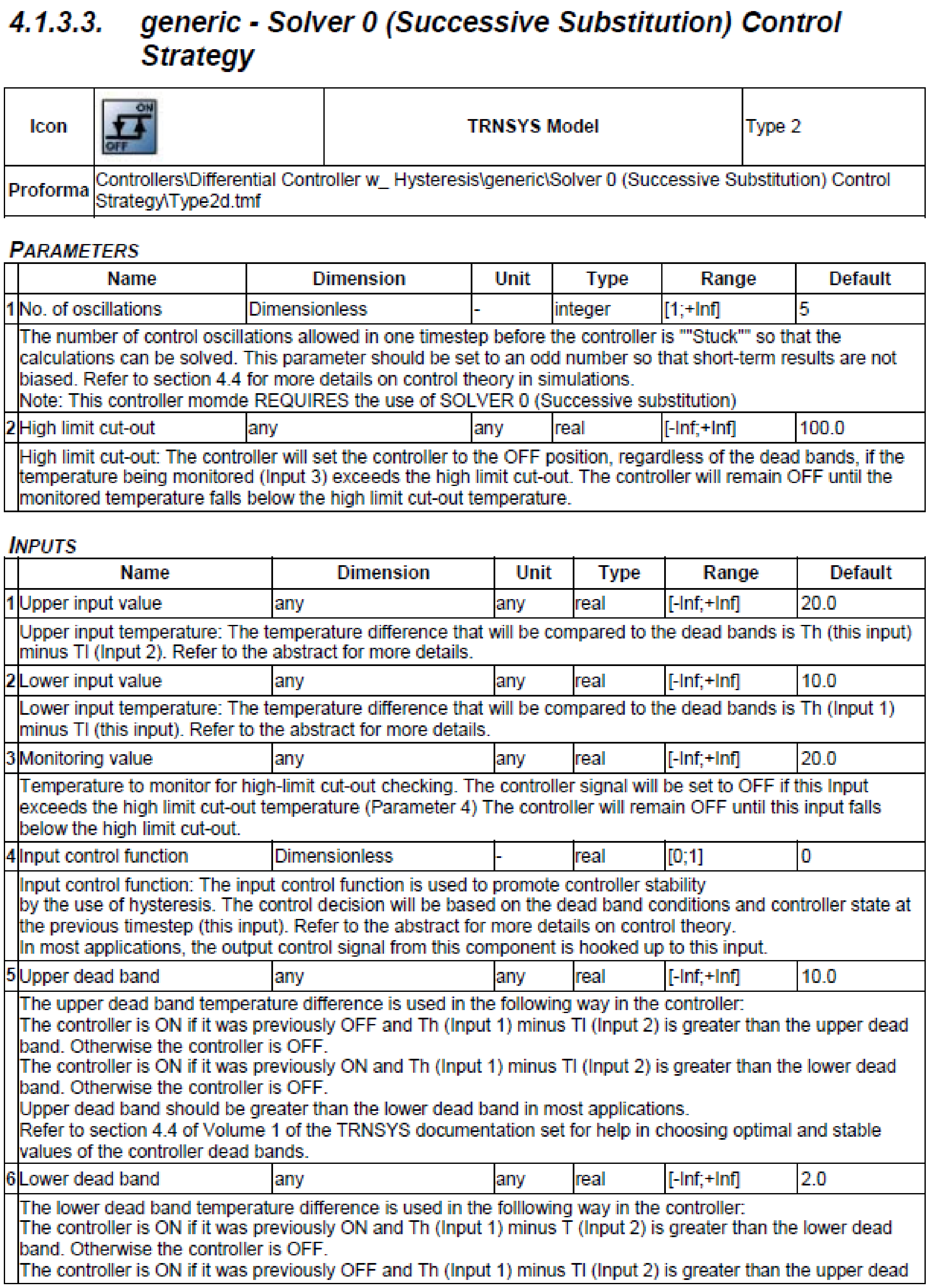
Fuel cartridges	M0.35 Regular	M0.35 Desert
Item number	303 905 024	303 905 041
Volume	350 m [11.8 oz]	350 ml [11.8 oz]
Content	100 % Methanol	60 % Methanol, 40 % Water
Weight	371 g [0.82 lbs]	410 g [0.90 lbs]
Nominal capacity	400 Wh	285 Wh
Operating temperature	-20 °C to +35 °C [-4 °F to +95 °F]	+10 °C to +55 °C [+50 °F to +122 °F]
Dimensions L x W x D	165 x 60 x 60 mm [6.50 x 2.36 x 2.36 in]	165 x 60 x 60 mm [6.50 x 2.36 x 2.36 in]

[1] Voltage is self adjusting via SMBus communication
[2] Factory Setting - can be modified for specific application through customer
[3] Effective consumption depends on operating conditions
[4] At temperatures from + 50 °C ... + 55 °C operation is possible for limited time only
[5] Start-up is possible down to -20 °C with optional Heat Pouch
[6] Frost Protection Mode needs to be activated manually when putting the Fuel Cell in the Off state
[7] A routine service check is required after 750 operating hours
[8] Fuel Cell does not produce power when being submersed, operation with power generation is possible in heavy rainfall

Appendix B TRNSYS Components

The component’s input – output – parameter given in this appendix is a copy of the TRNSYS 16 documentation volume 4. Below each component’s description the parameters and input values/data from in the simulated are listed.

Controller component



4.1.3.3. *generic - Solver 0 (Successive Substitution) Control Strategy*

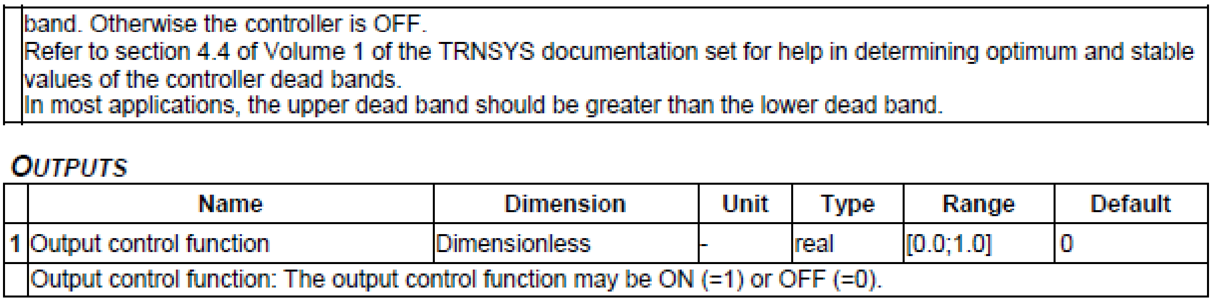
Icon		**TRNSYS Model**	Type 2
Proforma	Controllers\Differential Controller w_ Hysteresis\generic\Solver 0 (Successive Substitution) Control Strategy\Type2d.tmf		

PARAMETERS

	Name	Dimension	Unit	Type	Range	Default
1	No. of oscillations	Dimensionless	-	integer	[1;+Inf]	5
	The number of control oscillations allowed in one timestep before the controller is ""Stuck"" so that the calculations can be solved. This parameter should be set to an odd number so that short-term results are not biased. Refer to section 4.4 for more details on control theory in simulations. Note: This controller momde REQUIRES the use of SOLVER 0 (Successive substitution)					
2	High limit cut-out	any	any	real	[-Inf;+Inf]	100.0
	High limit cut-out: The controller will set the controller to the OFF position, regardless of the dead bands, if the temperature being monitored (Input 3) exceeds the high limit cut-out. The controller will remain OFF until the monitored temperature falls below the high limit cut-out temperature.					

INPUTS

	Name	Dimension	Unit	Type	Range	Default
1	Upper input value	any	any	real	[-Inf;+Inf]	20.0
	Upper input temperature: The temperature difference that will be compared to the dead bands is Th (this input) minus Tl (Input 2). Refer to the abstract for more details.					
2	Lower input value	any	any	real	[-Inf;+Inf]	10.0
	Lower input temperature: The temperature difference that will be compared to the dead bands is Th (Input 1) minus Tl (this input). Refer to the abstract for more details.					
3	Monitoring value	any	any	real	[-Inf;+Inf]	20.0
	Temperature to monitor for high-limit cut-out checking. The controller signal will be set to OFF if this Input exceeds the high limit cut-out temperature (Parameter 4) The controller will remain OFF until this input falls below the high limit cut-out.					
4	Input control function	Dimensionless	-	real	[0;1]	0
	Input control function: The input control function is used to promote controller stability by the use of hysteresis. The control decision will be based on the dead band conditions and controller state at the previous timestep (this input). Refer to the abstract for more details on control theory. In most applications, the output control signal from this component is hooked up to this input.					
5	Upper dead band	any	any	real	[-Inf;+Inf]	10.0
	The upper dead band temperature difference is used in the following way in the controller: The controller is ON if it was previously OFF and Th (Input 1) minus Tl (Input 2) is greater than the upper dead band. Otherwise the controller is OFF. The controller is ON if it was previously ON and Th (Input 1) minus Tl (Input 2) is greater than the lower dead band. Otherwise the controller is OFF. Upper dead band should be greater than the lower dead band in most applications. Refer to section 4.4 of Volume 1 of the TRNSYS documentation set for help in choosing optimal and stable values of the controller dead bands.					
6	Lower dead band	any	any	real	[-Inf;+Inf]	2.0
	The lower dead band temperature difference is used in the folllowing way in the controller: The controller is ON if it was previously ON and Th (Input 1) minus T (Input 2) is greater than the lower dead band. Otherwise the controller is OFF. The controller is ON if it was previously OFF and Th (Input 1) minus Tl (Input 2) is greater than the upper dead					



band. Otherwise the controller is OFF.
Refer to section 4.4 of Volume 1 of the TRNSYS documentation set for help in determining optimum and stable values of the controller dead bands.
In most applications, the upper dead band should be greater than the lower dead band.

OUTPUTS

	Name	Dimension	Unit	Type	Range	Default
1	Output control function	Dimensionless	-	real	[0.0;1.0]	0
	Output control function: The output control function may be ON (=1) or OFF (=0).					

Controller, TYPE 2d	
Parameter number	Simulation value(s)
1	5
2	1
Input number	Simulation value(s)
1	1
2	0
3	FSOC from battery
4	Output control function
5	0.8 to 0.6
6	0

Battery component

4.2.1.5. Power as an input - Shepherd modified Hyman Equation

Icon		**TRNSYS Model**	Type 47
Proforma	Electrical\Batteries\Power as an input\Shepherd modified Hyman Equation\Type47c.tmf		

PARAMETERS

	Name	Dimension	Unit	Type	Range	Default
1	Mode	Dimensionless	-	integer	[3;3]	0
	Specify 3. Mode 3 corresponds to Hyman (modified Shepherd) equations, power given as input.					
2	Cell Energy Capacity	Electric Charge	Ah	real	[0;+Inf]	0
	Rated cell energy capacity. The battery capacity is obtained by multiplying the cell capacity by the number of cells in series and by the number of cells in parallel.					
3	Cells in parallel	Dimensionless	-	integer	[1;+Inf]	0
	Number of cells connected in parallel in the battery.					
4	Cells in series	Dimensionless	-	integer	[1;+Inf]	0
	Number of cells in series in the battery. A lead-acid battery cell has a rated voltage of 2V. So a 12V battery includes 6 cells in series, and a 24V battery includes 12 cells in series.					
5	Charging efficiency	Dimensionless	-	real	[0;1.0]	0
	The charging efficiency is typically high for low State of Charge (>=85%) but can drop below 50% for high State Of Charge (SOC higher than 90%). This model assumes a constant value.					
6	Max. current per cell charging	Electric current	amperes	real	[0;+Inf]	0
	Maximum allowed for cell charge current. This current should be set approximately to charge the battery in 5 hours ("C5"), i.e. 3.3 A if the cell capacity is 16.7 Ah. Too high values may lead to erroneous results. Use "C1" (i.e. 16.7 A for a 16.7 Ah cell) at most.					
7	Max. current per cell discharge	Electric current	amperes	real	[-Inf;0]	0
	Maximum allowed for cell discharge current (negative value). This current should be set approximately to discharge the battery in 5 hours ("C5"), i.e. 3.3 A if the cell capacity is 16.7 Ah. Too high values may lead to erroneous results. Use "C1" (i.e. 16.7 A for a 16.7 Ah cell) at most.					
8	Max. charge voltage per cell	Voltage	V	real	[1.8;2.8]	0
	The maximum allowed for each cell voltage in charge mode. Do no use values greater than 2.8V.					
9	Calculate discharge cutoff voltage	Dimensionless	-	real	[-1;2.5]	0
	Use -1 for automatic calculation of discharge cutoff voltage, or give a positive value. If the discharge cutoff voltage is given, it should be larger than 1.5V.					
10	Tolerance for iterative calculations	Electric current	amperes	real	[0;+Inf]	0
	Ic (charge)and Id (discharge) are calculated through an iterative process. This parameter gives the absolute tolerance on convergence check. The equation calculating V from P also requires iterations and the same value is used for the tolerance.					

INPUTS

	Name	Dimension	Unit	Type	Range	Default
1	Power to or from battery	Power	kJ/hr	real	[-Inf;+Inf]	0
	The power injected to the battery has a positive sign, while the power going from the battery to the load is negative.					

OUTPUTS

	Name	Dimension	Unit	Type	Range	Default
1	State of charge	Electric Charge	Ah	real	[-Inf;+Inf]	0

	The State Of Charge is expressed in the same units as the rated cell capacity (Ah). This value is given for one cell (all cells are assumed to be identical).					
2	Fractional state of charge	Dimensionless	-	real	[-Inf;+Inf]	0
	This is the ratio between the State Of Charge and the rated energy capacity.					
3	Power	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power to (>0) or from (					
4	Power lost during charge	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power loss. This is equal to (1-Efficiency)*Power when charging (0 else).					
5	Total current	Electric current	amperes	real	[-Inf;+Inf]	0
	Total current to (>0) or from the battery (					
6	Total voltage	Voltage	V	real	[-Inf;+Inf]	0
	Total voltage of the battery (Cell voltage * Nb of cells in series).					
7	Max. Power for charge	Power	kJ/hr	real	[-Inf;+Inf]	0
	Maximum power for battery charge (i.e. power corresponding to maximum charge current).					
8	Max. Power for discharge	Power	kJ/hr	real	[-Inf;+Inf]	0
	Maximum power for battery discharge (i.e. power corresponding to maximum discharge current) - Negative value.					
9	Discharge cutoff voltage (DCV)	Voltage	V	real	[-Inf;+Inf]	0
	Discharge cutoff voltage (computed if PAR(9)<0).					
10	Power corresponding to DCV	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power corresponding to Discharge cutoff voltage.					
11	Charge cutoff voltage (CCV)	Voltage	V	real	[-Inf;+Inf]	0
	Charge cutoff voltage.					
12	Power corresponding to CCV	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power corresponding to Charge cutoff voltage.					

DERIVATIVES

	Name	Dimension	Unit	Type	Range	Default
1	State of charge1	Electric Charge	Ah	real	[0;+Inf]	0
	Initial State Of Charge of one cell of the battery. This value should use the same units as parameter 2. The value is given for one cell. The SOC of the battery is obtained by multiplying this value by the number of cells.					

Battery, TYPE 47d

Parameter number	Simulation value(s)
1	3
2	31 to 120
3	1 to 10
4	12
5	0.8 to 1
6	10 to 40
7	10 to 40
8	2,5
9	Default: -1
10	Default:0.001
Input number	Simulation value(s)
1	Power from regulator

Dynamo and FC component

4.2.3.2. Generic Model

Icon	G	**TRNSYS Model**	Type 120
Proforma	Electrical\Diesel Engine (DEGS)\Generic Model\Type120a.tmf		

PARAMETERS

	Name	Dimension	Unit	Type	Range	Default
1	MODE	dimensionless	-	integer	[1;1]	0
	1 = Generic Model, 2 = Specific DEGS					
2	FUELTYPE	dimensionless	-	integer	[1;6]	0
	1 = Diesel, 2 = LPG, 3 = Propane, 4 = Methane, 5 = Natural gas, 6 = Hydrogen					
3	PMAX	Power	kW	real	[0;+Inf]	0
	Maximum allowable power. Usually 20% above rated power.					
4	PMIN	Power	kW	real	[0;+Inf]	0
	Minimum allowable power. For a single DEGS placed in parallel with many DEGSs, this value is usually about 40% of rated power					
5	PRATED	Power	kW	real	[0;+Inf]	0
	Rated power in kW. Usually, 20% lower than rated power in kW and 20% lower than maximum allowable power (PMAX).					

INPUTS

	Name	Dimension	Unit	Type	Range	Default
1	SWITCH	dimensionless	-	real	[0;1]	0
	ON/OFF-switch for the DEGS (1 = ON, 0 = OFF)					
2	P_SET	Power	W	real	[0;500000]	0
	Power set point for one single DEGS (signal from DEGS controller)					
3	NUNITS	dimensionless	-	integer	[0;100]	0
	Number of identical units in operation (needs to be decided by the DEGS controller)					

OUTPUTS

	Name	Dimension	Unit	Type	Range	Default
1	PTOTAL	Power	W	real	[0;+Inf]	0
	Total power output					
2	V_LIQ	Volumetric Flow Rate	l/hr	real	[0;+Inf]	0
	Total liquid fuel consumption rate					
3	V_GAS	any	Nm3/h	real	[0;+Inf]	0
	Total gas fuel consumption rate					
4	ETA_FUEL	any	kWh/L	real	[0;+Inf]	0
	Fuel efficiency					
5	ETA_EL	dimensionless	-	real	[0;+Inf]	0
	Electrical efficiency					
6	Q_WASTE	Power	W	real	[0;+Inf]	0
	Total waste heat					

Diesel Engine (FC), TYPE 120	
Parameter number	Simulation value(s)
1	2
2	1
3	25-700
4	24.99 to 700.1
5	1
Input number	Simulation value(s)
1	0 or 1 depend on the signal from forcing forcing function or output from controller (Equa 5,SWin)
2	25 to 700
3	1

PV thin film component

4.2.4.11. *Thin Film Modules*

Icon		**TRNSYS Model**	Type 94
Proforma	Electrical\Photovoltaic Panels\Thin Film Modules\Type94b.tmf		

Parameters

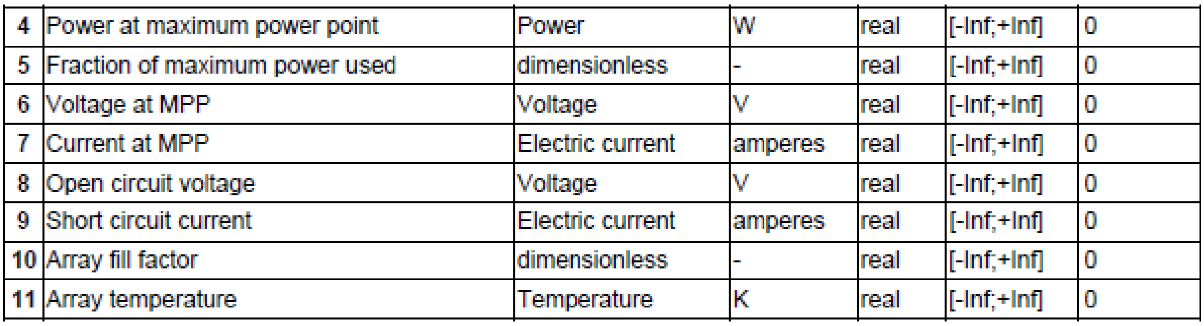
	Name	Dimension	Unit	Type	Range	Default
1	Module short-circuit current at reference conditions	Electric current	amperes	real	[0;+Inf]	0
2	Module open-circuit voltage at reference conditions	Voltage	V	real	[0;+Inf]	0
3	Reference temperature	Temperature	K	real	[0;+Inf]	0
4	Reference insolation	Flux	W/m^2	real	[0;+Inf]	0
5	Module voltage at max power point and reference conditions	Voltage	V	real	[0;+Inf]	0
6	Module current at max power point and reference conditions	Electric current	amperes	real	[0;+Inf]	0
7	Temperature coeficient of Isc at (ref. cond))	any	any	real	[-Inf;+Inf]	0
8	Temperature coeficient of Voc (ref. cond.)	any	any	real	[-Inf;+Inf]	0
9	Number of cells wired in series	dimensionless	-	integer	[1;+Inf]	0
10	Number of modules in series	dimensionless	-	integer	[1;+Inf]	0
11	Number of modules in parallel	dimensionless	-	integer	[1;+Inf]	0
12	Module temperature at NOCT	Temperature	K	real	[0;+Inf]	0
13	Ambient temperature at NOCT	Temperature	K	real	[0;+Inf]	0
14	Insolation at NOCT	Flux	W/m^2	real	[0;+Inf]	0
15	Module area	Area	m^2	real	[0;+Inf]	0
16	tau-alpha product for normal incidence	dimensionless	-	real	[0;1]	0
17	Semiconductor bandgap	any	any	real	[-Inf;+Inf]	0
18	Slope of IV curve at Isc	any	any	real	[-Inf;0]	0
19	Module series resistance	any	any	real	[-Inf;+Inf]	0

Inputs

	Name	Dimension	Unit	Type	Range	Default
1	Total incident radiation	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
2	Ambient temperature	Temperature	K	real	[-Inf;+Inf]	0
3	Load voltage	Voltage	V	real	[-Inf;+Inf]	0
4	Flag for convergence promotion	dimensionless	-	integer	[0;1]	0
5	Array slope	Direction (Angle)	degrees	real	[-Inf;+Inf]	0
6	Beam radiation	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
7	Diffuse radiation	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
8	Incidence angle of beam radiation	Direction (Angle)	degrees	real	[-Inf;+Inf]	0

Outputs

	Name	Dimension	Unit	Type	Range	Default
1	Array voltage	Voltage	V	real	[-Inf;+Inf]	0
2	Array current	Electric current	amperes	real	[-Inf;+Inf]	0
3	Array power	Power	W	real	[-Inf;+Inf]	0



4	Power at maximum power point	Power	W	real	[-Inf;+Inf]	0
5	Fraction of maximum power used	dimensionless	-	real	[-Inf;+Inf]	0
6	Voltage at MPP	Voltage	V	real	[-Inf;+Inf]	0
7	Current at MPP	Electric current	amperes	real	[-Inf;+Inf]	0
8	Open circuit voltage	Voltage	V	real	[-Inf;+Inf]	0
9	Short circuit current	Electric current	amperes	real	[-Inf;+Inf]	0
10	Array fill factor	dimensionless	-	real	[-Inf;+Inf]	0
11	Array temperature	Temperature	K	real	[-Inf;+Inf]	0

Thin film module, TYPE 94

Parameter number	Simulation value(s)
1	5.5 to 8
2	21.6 to 32
3	Default: 298
4	Default: 1000
5	Default: 17
6	Default: 5.9
7	Default: 0.02
8	Default: -0.079
9	Default: 36
10	Default: 1
11	1 to 3
12	Default: 313
13	Default: 293
14	Default: 800
15	1
16	Default: 0.95
17	Default: 1.12
18	Default: -0.003
19	Default: -1

Input number	Simulation value(s)
1	AvailRad from weather calc.
2	298
3	Default: 12

Regulator component

4.2.6.2. System w_ battery storage - MPP Tracking - SOC and SOV monitoring

Icon		**TRNSYS Model**	Type 48
Proforma	Electrical\Regulators and Inverters\System w_ battery storage\MPP Tracking\SOC and SOV monitoring\Type48c.tmf		

PARAMETERS

	Name	Dimension	Unit	Type	Range	Default
1	Mode	Dimensionless	-	integer	[2;2]	0
	Specify 2: Peak-power tracking collector, battery, monitoring of battery state of charge and voltage.					
2	Regulator efficiency	Dimensionless	-	real	[0;1]	0
	Regulator efficiency (e.g. use this for non-perfect max-power tracker efficiency).					
3	Inverter efficiency (DC to AC)	Dimensionless	-	real	[0;1]	0
	Inverter efficiency, DC to AC.					
4	High limit on fractional state of charge (FSOC)	Dimensionless	-	real	[0;1]	0
	High limit on fractional state of charge (FSOC). If FSOC is higher than this value, charging with the PV array is not allowed.					
5	Low limit on FSOC	Dimensionless	-	real	[0;1]	0
	Low limit on fractional state of charge (FSOC). If FSOC is lower than this value, discharging is not allowed.					
6	charge to discharge limit on FSOC	Dimensionless	-	real	[0;1]	0
	FB: Charge to discharge limit on fractional state of charge (FSOC). If FSOC < FB and the battery has been charging, then the battery must be on "total charge." On "total charge," first priority is given to recharging the battery with any array output, rather than sending the output to the load until FSOC > FB. Use FB					
7	Power output limit	Power	kJ/hr	real	[-Inf;+Inf]	0
	Output power capacity of inverter.					
8	Inverter efficiency (AC to DC)	Dimensionless	-	real	[0;1]	0
	Inverter efficiency, AC to DC.					
9	Current for grid charging of battery	Electric current	amperes	real	[-Inf;+Inf]	0
	Battery charge current when grid power is used for charging.					
10	Upper limit on FSOC for grid charging	Dimensionless	-	real	[0;1]	0
	High limit on fractional state of charge (FSOC). If FSOC is higher than this value, charging with the grid is not allowed.					

INPUTS

	Name	Dimension	Unit	Type	Range	Default
1	Input power	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power from solar PV array.					
2	Load power	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power demanded by load.					
3	Battery fractional state of charge	Dimensionless	-	real	[-Inf;+Inf]	0
	Battery fractional State Of Charge (FSOC).					
4	Battery voltage (BV)	Voltage	V	real	[-Inf;+Inf]	0
	Battery voltage (BV).					
5	Max battery input	Power	kJ/hr	real	[-Inf;+Inf]	0

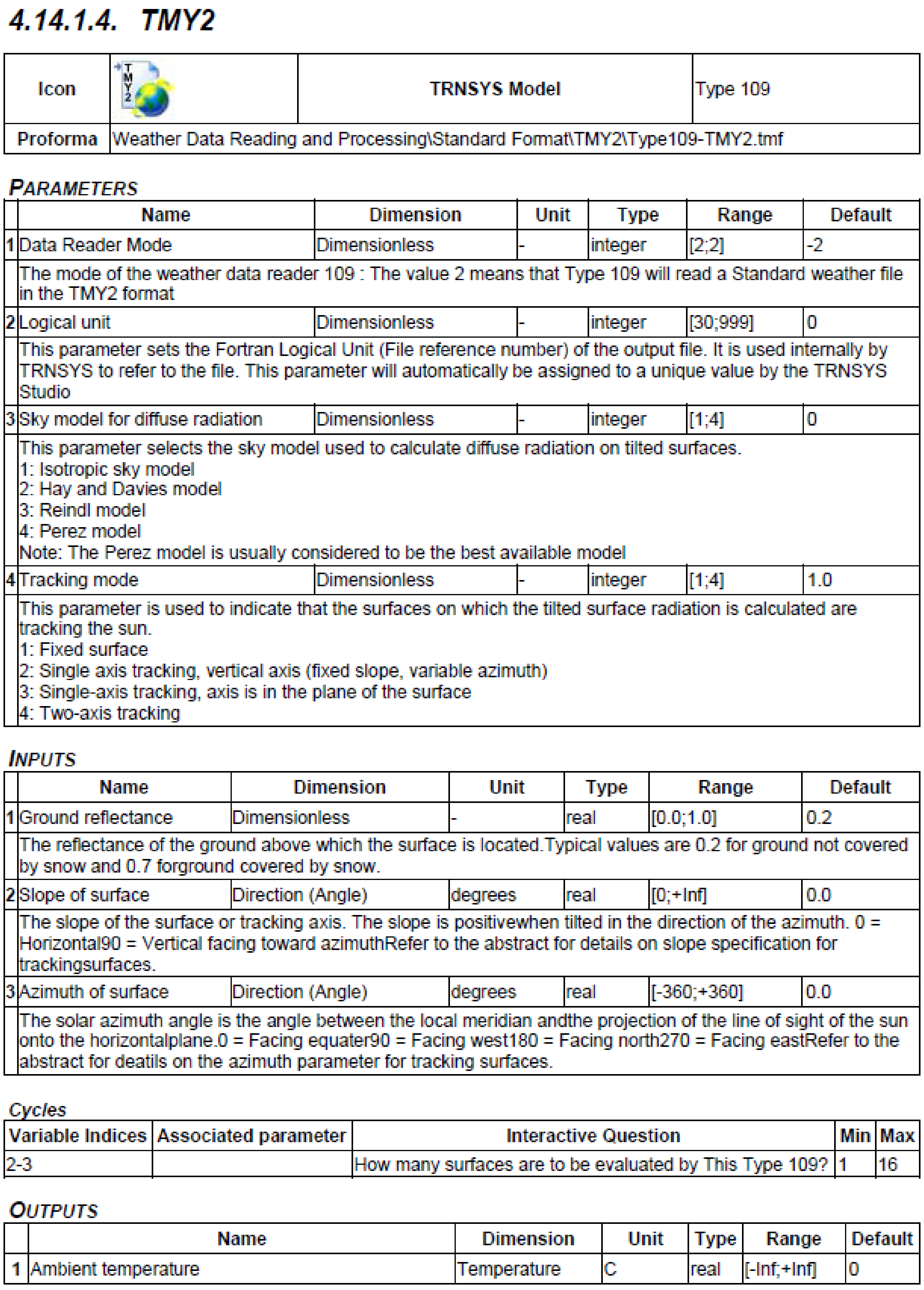
	Maximum power for battery charge (i.e. power corresponding to maximum charge current) - Use battery output.					
6	Min. battery output	Power	kJ/hr	real	[-Inf;+Inf]	0
	Maximum power for battery discharge (i.e. power corresponding to maximum discharge current) - Negative value - Use battery output.					
7	lower limit on battery voltage	Voltage	V	real	[-Inf;+Inf]	0
	Lower limit on battery voltage during discharge - Use battery output.					
8	Power corresponding to BV	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power corresponding to lower limit on battery voltage during discharge - Use battery output.					
9	High limit on BV	Voltage	V	real	[-Inf;+Inf]	0
	Higher limit on battery voltage during charge - Use battery output.					
10	Power corresponding to high limit on BV	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power corresponding to higher limit on battery voltage during charge - Use battery output.					
11	Start time for grid battery charging	Time	hr	real	[-Inf;+Inf]	0
	t1: Time of the day at which battery charging with the grid can start (this assumes TIME=0 in the simulation is midnight). Use t1=t2 to allow charging at all times					
12	Stop time for grid battery charging	Time	hr	real	[-Inf;+Inf]	0
	t2: Time of the day at which battery charging with the grid should stop (this assumes TIME=0 in the simulation is midnight) t2 < t1 is allowed (e.g. night charging from 22 to 7)					

OUTPUTS

	Name	Dimension	Unit	Type	Range	Default
1	Power in from generation	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power from solar PV array.					
2	Power to or from battery	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power to (>0) or from (					
3	Power to load	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power to load.					
4	Dumped generated power	Power	kJ/hr	real	[-Inf;+Inf]	0
	PV Array power "dumped" or not collected due to full battery.					
5	Power from grid	Power	kJ/hr	real	[-Inf;+Inf]	0
	Power from electricity grid.					

Regulator, TYPE 48c	
Parameter number	Simulation value(s)
1	Default: 2
2	0.8 to 1
3	0.95 to 1
4	1
5	0 .05
6	0 .01
7	100 to 1000
8	1
9	0
10	Default: 1
Input number	Simulation value(s)
1	TotINPower from Power calculator
2	Data from load profile
3	Battery output nr 2
4	12
5	Battery output nr 7
6	Battery output nr 8
7	Default: 0
8	Default: 0
9	Battery output nr 11
10	Default: 0
11	Default: 0
12	Default: 0

Weather component



4.14.1.4. TMY2

Icon		TRNSYS Model	Type 109
Proforma	Weather Data Reading and Processing\Standard Format\TMY2\Type109-TMY2.tmf		

PARAMETERS

	Name	Dimension	Unit	Type	Range	Default
1	Data Reader Mode	Dimensionless	-	integer	[2;2]	-2
	The mode of the weather data reader 109 : The value 2 means that Type 109 will read a Standard weather file in the TMY2 format					
2	Logical unit	Dimensionless	-	integer	[30;999]	0
	This parameter sets the Fortran Logical Unit (File reference number) of the output file. It is used internally by TRNSYS to refer to the file. This parameter will automatically be assigned to a unique value by the TRNSYS Studio					
3	Sky model for diffuse radiation	Dimensionless	-	integer	[1;4]	0
	This parameter selects the sky model used to calculate diffuse radiation on tilted surfaces. 1: Isotropic sky model 2: Hay and Davies model 3: Reindl model 4: Perez model Note: The Perez model is usually considered to be the best available model					
4	Tracking mode	Dimensionless	-	integer	[1;4]	1.0
	This parameter is used to indicate that the surfaces on which the tilted surface radiation is calculated are tracking the sun. 1: Fixed surface 2: Single axis tracking, vertical axis (fixed slope, variable azimuth) 3: Single-axis tracking, axis is in the plane of the surface 4: Two-axis tracking					

INPUTS

	Name	Dimension	Unit	Type	Range	Default
1	Ground reflectance	Dimensionless	-	real	[0.0;1.0]	0.2
	The reflectance of the ground above which the surface is located.Typical values are 0.2 for ground not covered by snow and 0.7 forground covered by snow.					
2	Slope of surface	Direction (Angle)	degrees	real	[0;+Inf]	0.0
	The slope of the surface or tracking axis. The slope is positivewhen tilted in the direction of the azimuth. 0 = Horizontal90 = Vertical facing toward azimuthRefer to the abstract for details on slope specification for trackingsurfaces.					
3	Azimuth of surface	Direction (Angle)	degrees	real	[-360;+360]	0.0
	The solar azimuth angle is the angle between the local meridian andthe projection of the line of sight of the sun onto the horizontalplane.0 = Facing equater90 = Facing west180 = Facing north270 = Facing eastRefer to the abstract for deatils on the azimuth parameter for tracking surfaces.					

Cycles

Variable Indices	Associated parameter	Interactive Question	Min	Max
2-3		How many surfaces are to be evaluated by This Type 109?	1	16

OUTPUTS

	Name	Dimension	Unit	Type	Range	Default
1	Ambient temperature	Temperature	C	real	[-Inf;+Inf]	0

	ambient temperature					
2	relative humidity	any	any	real	[-Inf;+Inf]	0
	ambient relative humidity					
3	wind velocity	Velocity	m/s	real	[-Inf;+Inf]	0
	wind speed					
4	wind direction	Direction (Angle)	Degrees	real	[-Inf;+Inf]	0
	N=0°, E=90°, etc.					
5	Atmospheric pressure	Pressure	Pa	real	[-Inf;+Inf]	0
	Atmospheric pressure					
6	userdefined data 2	any	any	real	[-Inf;+Inf]	0
	Sixth value read from data file (if PAR 2 > 5).					
7	userdefined data 3	any	any	real	[-Inf;+Inf]	0
	Seventh value read from data file (if PAR 2 > 6).					
8	userdefined data 4	any	any	real	[-Inf;+Inf]	0
	Eigth value read from data file (if PAR 2 > 7)					
9	extraterrestrial radiation on horizontal	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
	Ninth value read from data file (if PAR 2 > 8).					
10	solar zenith angle	Direction (Angle)	degrees	real	[-360;+360]	0
	Tenth value read from data file (if PAR 2 > 9).					
11	solar azimuth angle	Direction (Angle)	degrees	real	[-360;+360]	0
	Eleventh value read from data file (if PAR 2 > 10).					
12	total radiation on horizontal	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
	Twelfth value read from data file (if PAR 2 > 11).					
13	beam radiation on horitonzal	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
	Thirteenth value read from data file (if PAR 2 > 12).					
14	sky diffuse radiation on horizontal	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
	Fourteenth value read from data file (if PAR 2 > 13).					
15	ground reflected diffuse radiation on horizontal	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
	Fifteenth value read from data file (if PAR 2 > 14).					
16	angle of incidence on horizontal surface	Direction (Angle)	degrees	real	[-Inf;+Inf]	0
	Sixteenth value read from data file (if PAR 2 > 15).					
17	slope of horizontal surface	Direction (Angle)	degrees	real	[-Inf;+Inf]	0
	Seventeenth value read from data file (if PAR 2 > 16).					
18	total radiation on tilted surface	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
	Eighteenth value read from data file (if PAR 2 = 18).					
19	beam radiation on tilted surface	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
20	sky diffuse radiation on tilted surface	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
21	ground reflected diffuse radiation on tilted surface	Flux	kJ/hr.m^2	real	[-Inf;+Inf]	0
22	angle of incidence for tilted surface	Direction (Angle)	degrees	real	[-Inf;+Inf]	0
23	slope of tilted surface	Direction (Angle)	degrees	real	[-Inf;+Inf]	0

Cycles

Variable Indices	Associated parameter	Interactive Question	Min	Max
18-23		How many surfaces are to be evaluated by This Type 109?	1	16

Weather component, TMY2	
Parameter number	Simulation value(s)
1	Default: 2
2	42
3	Default: 4
4	1
Input number	Simulation value(s)
1	Default: 0.2
2	0
3	0

Weather calculator

AvailRad=Weather output nr 12 * Value from forcing function

Power calculator

TotINPower=Pdyn+Ppv+Pfc

Weight calculator

Described by equation (4.9) in chapter 4.4

Equa 5

SWin=Controller output function + forcing function value

Appendix C Batteries

Li-SO$_2$ primary battery system

BA 5590 B/U

One battery for various military applications

10 LO 26 SX cells connected in 2 groups of 5 cells in series providing 2 nominal 12 V sections at connector. These sections can be connected in series (for 24 V) in parallel (for 12 V) or used as two separate 12 V units.

Key features

- A non-replaceable fuse is incorporated in the negative leg of each series group of cells.
- A normally closed high temperature switch or thermal fuse is incorporated into each series group of cells to protect against overheating.
- A diode is incorporated into the positive leg of each series group of cells to prevent charging or flow of current into the battery.
- A device consisting of a manually activated pull tab and resistors designed to discharge the battery to 0 V is built into the battery.

Typical applications

- AN/PRC-104 Radio
- AN/PRC-113 Radio
- AN/PRC-117 Radio
- AN/PRC-119 Singcars Radio
- KY-57, KY-65 Encryption Set
- REMBASS Remotely Monitored Battlefield Surveillance System
- PLRS Position Locator and Reporting System
- RT-991 Buoy Radio
- RT-1175 Buoy Radio
- AN/TAS-4A TOW Night Sight

Electrical characteristics

Typical OCV (V)	15.0 or 30.0
Nominal voltage (at 500 mA) (V)	13.5 or 27.0
Cut-off (V)	10.0 or 20.0
Typical capacity +21°C/+70°F (at 250 mA discharge current)	15 Ah at 12 V 7.5 Ah at 24 V
Operating temperature	-40°C to +71°C -40°F to +160°F
Storage Recommended max	+35°C / +95°F
Possible	-40°C to +71°C / -40°F to +160°F

Physical characteristics

Typical Weight (g/oz)	1000 / 35.3
Weight of Li metal content (g/oz)	24 / 0.85
Width (mm/in)	62.2 / 2.45
Height (mm/in)	111.8 / 4.40
Depth (mm/in)	127.0 / 5.00
Battery Case	Plastic

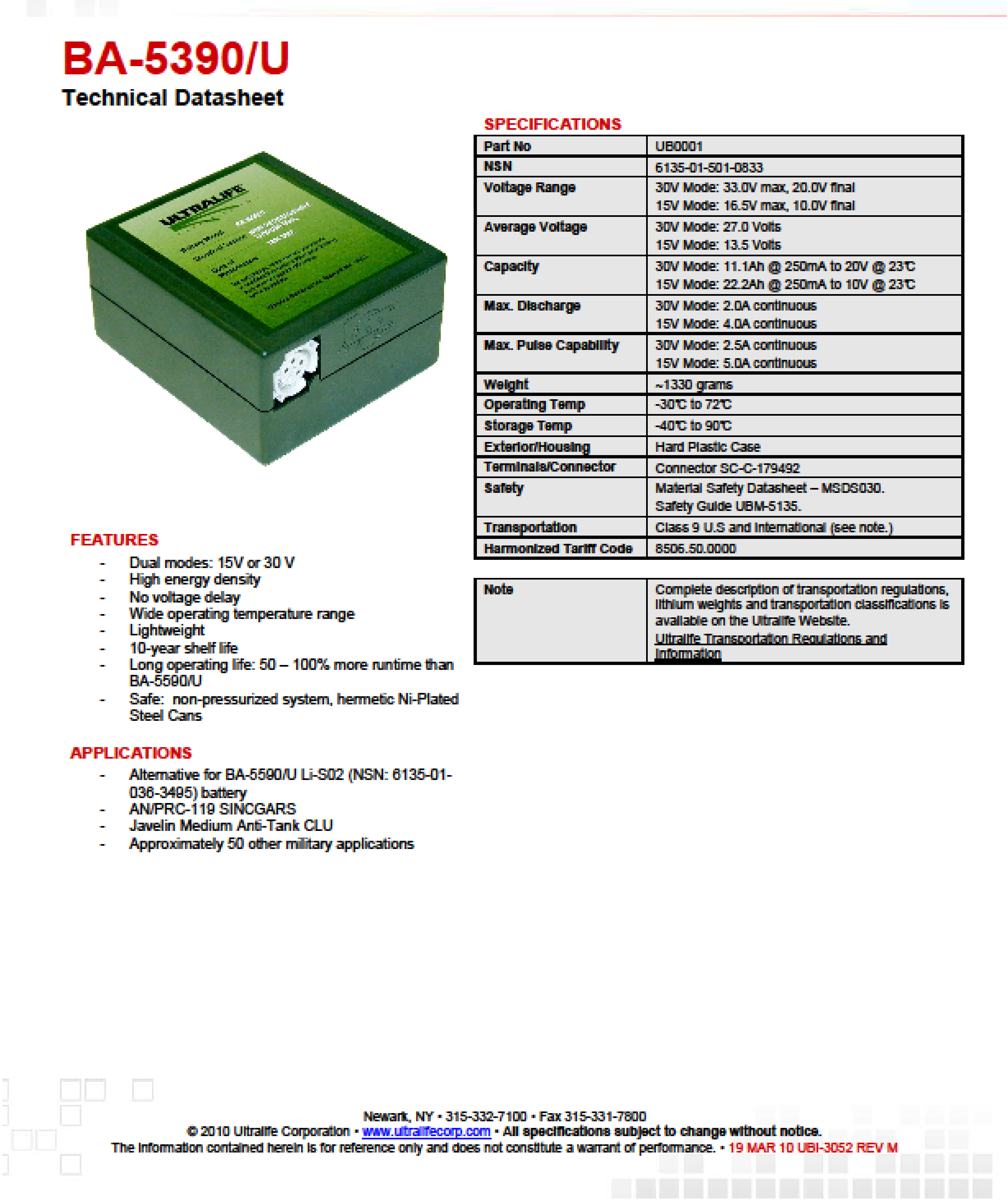
References

Mating connector	ITT Cannon CA 110821- 6
Reference specifications	MIL PRF 49471B or Saft Standard Specification
Nato Stock Number	6135-01-036-3495 6135-01-438-9450

December 2005

saft

Lithium/manganese dioxide, Li/MnO_2



ULTRALIFE

BA-5390/U

Technical Datasheet

SPECIFICATIONS

Part No	UB0001
NSN	6135-01-501-0833
Voltage Range	30V Mode: 33.0V max, 20.0V final 15V Mode: 16.5V max, 10.0V final
Average Voltage	30V Mode: 27.0 Volts 15V Mode: 13.5 Volts
Capacity	30V Mode: 11.1Ah @ 250mA to 20V @ 23°C 15V Mode: 22.2Ah @ 250mA to 10V @ 23°C
Max. Discharge	30V Mode: 2.0A continuous 15V Mode: 4.0A continuous
Max. Pulse Capability	30V Mode: 2.5A continuous 15V Mode: 5.0A continuous
Weight	~1330 grams
Operating Temp	-30°C to 72°C
Storage Temp	-40°C to 90°C
Exterior/Housing	Hard Plastic Case
Terminals/Connector	Connector SC-C-179492
Safety	Material Safety Datasheet – MSDS030. Safety Guide UBM-5135.
Transportation	Class 9 U.S and International (see note.)
Harmonized Tariff Code	8506.50.0000

Note	Complete description of transportation regulations, lithium weights and transportation classifications is available on the Ultralife Website. Ultralife Transportation Regulations and Information

FEATURES

- Dual modes: 15V or 30 V
- High energy density
- No voltage delay
- Wide operating temperature range
- Lightweight
- 10-year shelf life
- Long operating life: 50 – 100% more runtime than BA-5590/U
- Safe: non-pressurized system, hermetic Ni-Plated Steel Cans

APPLICATIONS

- Alternative for BA-5590/U Li-S02 (NSN: 6135-01-036-3495) battery
- AN/PRC-119 SINCGARS
- Javelin Medium Anti-Tank CLU
- Approximately 50 other military applications

Newark, NY • 315-332-7100 • Fax 315-331-7800
© 2010 Ultralife Corporation • www.ultralifecorp.com • All specifications subject to change without notice.
The information contained herein is for reference only and does not constitute a warrant of performance. • 19 MAR 10 UBI-3052 REV M

Appendix D Vehicle’s Fuel Consumption

Vehicle’s fuel consumption for electrical loads

	Engine 1			Engine 2			Engine 3			Average		Diesel	
	start	end		start	end		start	end				Kg/m3	840
Motor temp.	76	79		74	79		75	77				GJ/m3	36,2
Time	10,18	11,18		10,26	11,26		12,12	13,12				GJ/Kg	0,04309524
Ampere	0,8			2,1	2,1		2	2				MJ/Kg	43,0952381
Volt	28,3			28			28,1					kWh/kg	11,9708995
Kg	4,408	3,812		4,46	3,74		3,48	2,83				kWh/l	10,0555556
litre													
kg/t	0,596			0,72			0,65			0,66		1 kWh	3,6
Watt	22,64			58,8			56,2			45,88		kg/l	0,84
kWh	0,02			0,06			0,06			0,05			
litre/t	0,710			0,857			0,774			0,78			
Energy [kWh]	7,13			8,62			7,78			7,84			
Efficiency	0,32 %			0,68 %			0,72 %			0,57 %			
Motor temp.	77	79					76	78					
Tid	13,49	14,49					16,50	17,50					
Ampere	26	26					26,1	26					
Volt	28,3	28,09					28,1	28					
Kg	3,45	2,72					3,15	2,35					
litre	3,6	2,75					3,1	2,3					
kg/t	0,73						0,8			0,77			
Watt	735,8						733,41			734,61			
kWh	0,74						0,73			0,73			
liter/t	0,869						0,952			0,91			
Energy [kWh]	8,74						9,58			9,16			
Efficiency	8,42 %						7,66 %			8,04 %			
Motor temp.	ok	ok					74	80					
Tid	15,42	16,42					14,40	15,40					
Ampere	49,9	50					49,8	49,9					
Volt	26,5	26,1					26,2	26					
Kg	2,469	1,507					2,64	1,44					
litre	2,6	1,3					2,5	1,1					
kg/t	0,962						1,2			1,08			
Watt	1322,35	1305					1304,76	1297,4		1307,38			
kWh	1,32						1,30			1,31			
litre/t	1,145						1,429			1,29			
Energy [kWh]	11,52						14,37			12,94			
Efficiency	11,48 %						9,08 %			10 %			