EUDP

PROJECT PARTNERS

NORDIC FIREFLY

living energy

NERVE
SMART SYSTEMS

FORCE
TECHNOLOGY

DTU Fotonik
Institut for Fotonik

DTU Elektro
Institut for Elektroteknologi

Title:
Development of intelligent solar-powered lighting system

EUDP Project number
64019-0589

Project Partners
Living Energy Lighting (project coordinator)
DTU Fotonik
Nordic Firefly
DTU Elektro
Nerve Smart Systems
Force Technologies

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March 2022

Front page
Photos of SolarDesign and SolarGlow installed respectively on Risø Campus and Vordingborg Municipality

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1. Project details

Project title	Udvikling af intelligent soldrevet belysningssystem
File no.	64019-0589
Name of the funding scheme	EUDP
Project managing company / institution	Living Energy Lighting ApS
CVR number (central business register)	39796422
Project partners	Nordic Firefly A/S, Nerve Smart Systems ApS, DTU Fotonik, DTU Elektro, Force Technologies
Submission date	31. March 2022

2. Summary

2.1 English summary

I the project a variety of technologies have been developed.

- 2 SolarDesign lamps and 1 SolarGlow lamp has been designed, developed and installed at DTU Risø campus with high resolution data monitoring implemented for performance monitoring. In the end of the project 2 SolarGlow lamps was installed at potential customers at Vordingborg Municipality.
- Photovoltaic panels have been developed for the two lamp systems based on a 24V architecture optimized for energy harvesting with high efficiency also at low-light conditions.
- A specialized 3-port converter incorporating the learnings from several prototypes was developed and realized. Now with one single high power MPPT harvesting channel that can fit into both SolarGlow and SolarDesign (with paralleled PV-panels). The converter has ultra heigh efficiency of energy conversion from solar panels to battery (above 96% in general, and 87-95% at low light conditions) and also above 96% conversion efficiency converting energy from battery to LED at night.
- Research was conducted at DTU Elektro Electronics Group in the design of a switched capacitor converter (SC) topology for MPPT harvesting and a prototype was demonstrated with a very high efficiency (>98%) and it was shown that SC novel SC converter topologies can be usable for building a switched mode converter for MPPT harvesting.
- A communication system (FFctrl) was developed on top of Nordic Firefly's 3-port converter unit to enable interfacing with both the multiport power converter (i2c), the smart battery (RS485) and external communication devices (i2c). In addition, FFctrl was designed to be able to communicate with an eSave proprietary zigbee based lighting management system, which was successfully demonstrated in the project.
- A battery solution was developed by Nerve Smart Systems for the lamp system which required the battery voltage to be switchable between 14V DC and 26V DC. This was also a requirement to achieve the optimal efficiency of the NFF MPPT. Prototypes of battery modules based on 26 LiFePo4 cells providing approximately 2000 Wh of storage capacity was realized.
- A software solution was developed (RoadBoy) for both dimensioning the lamp systems for it given installation point with respect to ensuring the solar cell system is properly dimensioned for delivering sufficient lighting, but also for ensuring compliance of the lighting to the relevant street lighting standards.

The 2 solar powered lamp systems can be seen to the right. The lamps are undergoing certification and SolarGlow is inside tenders for 30.000 lamps in Africa (Benin and Sierra Leone) and smaller sales are in process in the Nordic Countries.

2.2 Danish summary

I projektet er der udviklet en række forskellige teknologier.

- 2 SolarDesign-lamper og 1 SolarGlow-lampe er blevet udviklet installeret på DTU Risø campus med højopløsningsdataovervågning implementeret til performancemåling af systemet. Som afslutning på projektet blev der installeret 2 SolarGlow lamper hos potentielle kunder i Vordingborg Kommune.
- Der er udviklet solcellepaneler til de to lampesystemer baseret på en 24V-arkitektur optimeret til energihøst med høj effektivitet også ved svage sollysforhold.
- En specialiseret 3-ports konverter, der inkorporerer erfaringerne fra flere prototyper, blev udviklet og realiseret. Nu med én enkelt højeffekt MPPT-kanal, der kan passe ind i både SolarGlow og SolarDesign (med parallelle PV-paneler). Konverteren har en ultrahøj effektivitet af energikonvertering fra solpaneler til batteri (over 96% generelt og 87-95% ved svage lysforhold) og også over 96% konverteringseffektivitet ved konvertering af energi fra batteri til LED om natten.
- Der blev forsket på DTU Elektro Electronics Group i design af en switched capacitor converter (SC) topologi til MPPT solcelleladeoptimering og en prototype blev demonstreret med en meget høj effektivitet (>98%), og det blev vist, at SC-konvertertopologier kan være anvendelige til at bygge en switched mode konverter til MPPT optimering af indladning fra solcellepaneler.
- Et kommunikationssystem (FFctrl) blev udviklet oven på Nordic Fireflys 3-ports konverterenhed for at muliggøre interface med både multiport strømkonverteren (i2c), smartbatteriet (RS485) og eksterne kommunikationsenheder (i2c). Derudover blev FFctrl designet til at kunne kommunikere med et eSave proprietært ZigBee-baseret lysstyringssystem, som blev demonstreret med succes i projektet.
- En batteriløsning blev udviklet af Nerve Smart Systems til lampesystemet, som krævede, at batterispændingen kunne skiftes mellem 14V DC og 26V DC. Dette var også et krav for at opnå den optimale effektivitet af NFF MPPT. Der blev realiseret prototyper af batterimoduler baseret på 26 LiFePO4-celler, der giver ca. 2000 Wh lagerkapacitet.
- Der er udviklet en softwareløsning (RoadBoy) til både at dimensionere lampesystemerne til det givne monteringspunkt med hensyn til at sikre, at solcelleanlægget er korrekt dimensioneret til at levere tilstrækkelig belysning, men også for at sikre, at belysningen overholder de relevante gadebelysningsstandarder.

De 2 solcelledrevne lampesystemer kan ses til højre. Lamperne er under certificering og SolarGlow er skrevet ind i udbud af 30.000 lamper i Afrika (Benin og Sierra Leone), og mindre salg er i gang i de nordiske lande.

3. Project objectives

In the project has been dedicated to the following objectives:

- Development of a new PV-panel with an extended dynamic range increasing energy harvesting capabilities under all weather conditions, especially low light conditions.
- Development of a 7-port charge controller able to provide MPPT (Maximum Power Point Tracking) on five different surfaces increasing the per surface energy harvesting capabilities. Also, further optimising its dynamic range to enable DC/DC conversion as soon as there is any light vs. existing solutions that need more power before the conversion can begin.
- Creating a state-of-the art LED luminaire able to output min. 220lm/w by developing a proprietary PCB design with the highest performing LED chips and optics.
- Developing a state-of-the-art energy storage unit, likely by hybridising traditional chemical batteries with pseudo- or supercapacitors and integrating a state-of-the-art Battery Management System (BMS) developed and patented by project partner Nerve Smart Systems, thereby extending safe operating temperatures of the storage unit to all climatic conditions and increasing operational life beyond 10 years.
- Developing a real-time monitoring platform and intelligent machine learning algorithms able to continuously optimise the performance of the lamp, to only provide necessary illumination when a human or human operated vehicle passes by. This will conserve much needed energy. Moreover, a Machine Learning (ML) algorithm will be developed that precisely can predict any component degradation or failure, which will ensure predictive maintenance vs. preventive maintenance can be achieved, thereby lowering TCO.
- Prototyping, integration and testing all components to ensure perfect synergy and that the performance goal for low light weather conditions will be met.

The following 2 solar powered street lighting systems has been developed and demonstrated in the project:

Figure 1 - Left: SolarGlow, a low-cost solar powered lighting solution for medium to high traffic roads. Right: SolarDesign, highly aesthetic solar powered street lighting solution.

Photos of the in project installed SolarDesign solution on Risø Campus is shown below:

Figure 2 - Left: SolarDesign version 1 for baseline. Right: SolarDesign, version 2 with upgraded electronics, IoT and battery system.

Both systems have been equipped with high resolution data logging for measuring the energy flow onto the solar panels, through the controller electronics to the battery during the day on, and from the battery to the LEDs during night-time. Furthermore, irradiance sensors is mounted on all 5 surfaces with solar panels on, as shown on the figure below:

Figure 3 - Left: Irradiance sensors on sides. Right: Irradiance sensors on top.

The electrical system composed of solar panels, electronics controller unit, battery and LEDs are connected to a by DTU Fotonik developed logger board which is sniffing current and voltage values between all units to be able to measure the power. The logger board also has input for the irradiance sensors. The solar panels are furthermore equipped with temperature sensors. The logger unit is connected to a NI-9205 data acquisition system installed in the lamp head for the version lamps and in a ground-based closet for easy maintenance in version 2. The logging system can be seen below:

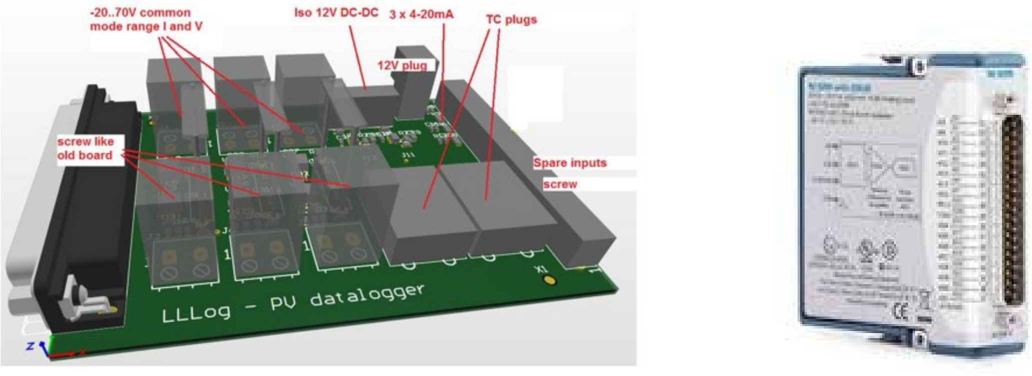
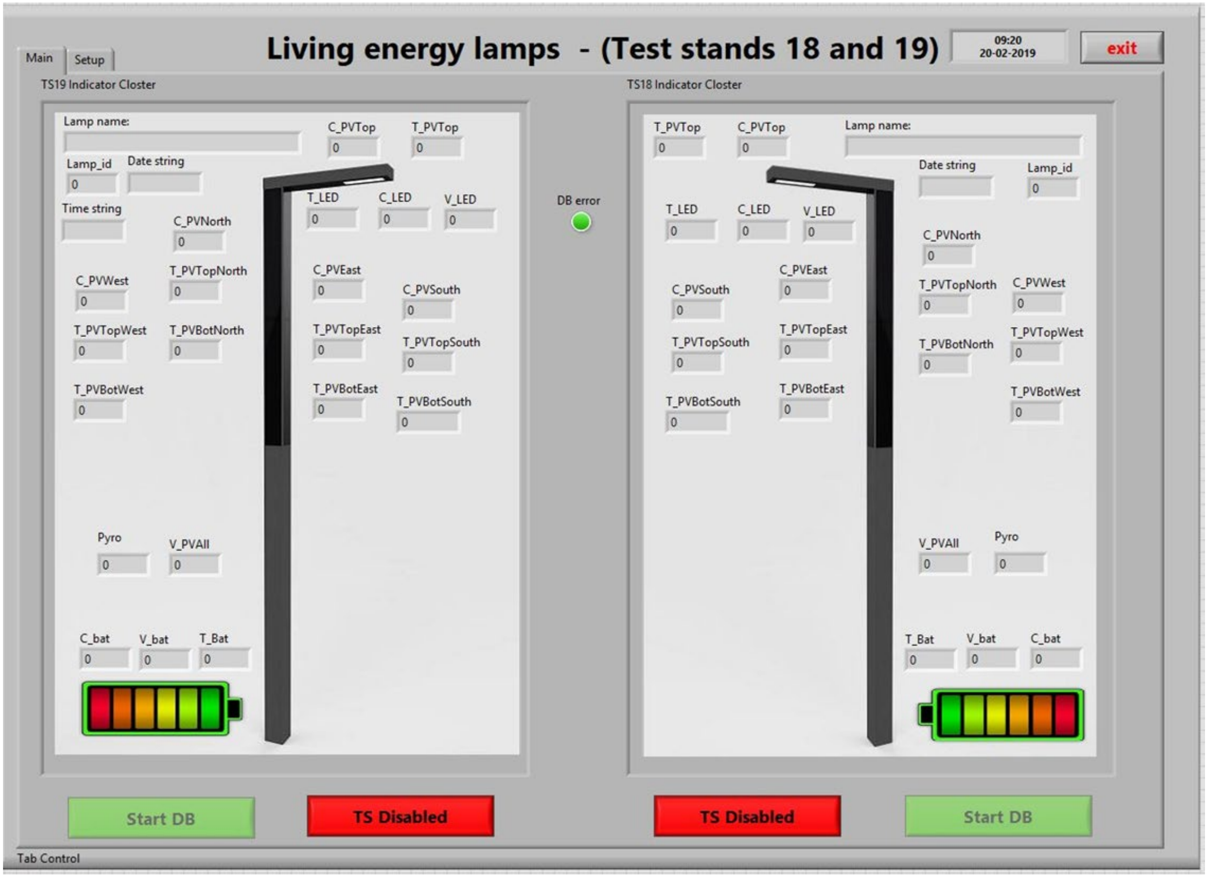


Figure 4 - Left: Datalogger board. Right: NI-9205 Data acquisition system.

The data acquisition is controlled remotely by LabVIEW feeding data to an SQL database. A view of the interface is shown below:



09:20
20-02-2019

TS19 Indicator Closter

Lamp name:
C_PVTop: 0
T_PVTop: 0
Lamp_id: 0
Date string:
Time string:
T_LED: 0
C_LED: 0
V_LED: 0
C_PVNorth: 0
C_PVWest: 0
T_PVTopNorth: 0
C_PVEast: 0
C_PVSouth: 0
T_PVTopWest: 0
T_PVBotNorth: 0
T_PVTopEast: 0
T_PVTopSouth: 0
T_PVBotWest: 0
T_PVBotEast: 0
T_PVBotSouth: 0
Pyro: 0
V_PVAll: 0
C_bat: 0
V_bat: 0
T_Bat: 0

TS18 Indicator Closter

T_PVTop: 0
C_PVTop: 0
Lamp name:
Date string:
Lamp_id: 0
T_LED: 0
C_LED: 0
V_LED: 0
C_PVNorth: 0
C_PVEast: 0
C_PVSouth: 0
T_PVTopNorth: 0
C_PVWest: 0
T_PVTopEast: 0
T_PVTopSouth: 0
T_PVBotNorth: 0
T_PVTopWest: 0
T_PVBotEast: 0
T_PVBotSouth: 0
T_PVBotWest: 0
V_PVAll: 0
Pyro: 0
T_Bat: 0
V_bat: 0
C_bat: 0

Figure 5 - LabVIEW interface of data logging system on SolarDesign lamps

This high-resolution test infrastructure was installed at 5 lamp fixture points at DTU Risø campus and has worked as test and demonstration platforms for developments in the project.

4. Project implementation

The project evolved very well especially since all the partners were already very well acquainted with each other from prior work together. The project had some goals that all project participants were highly interested in working with, and the collaboration has therefore proceeded smoothly.

With hardware developments and tests undertaken during this EUDP project Living Energy is confident that the technical solution is good. To verify this test is undertaken in Vordingborg municipality, Risø/Roskilde municipality, New Zealand as well as in Benin. Data is being collected to validate product performance.

A major risk of the project was that solar powered street lighting cannot hold enough surface area for solar cells to be able to be fully operational all year under Danish conditions. Even with upgraded technology it is not all road classes that can be powered by solar powered street lighting due to the many bad solar days during the Danish winter. Therefore, the main road classes relevant in Denmark are E2 and E3 where some dimming and intelligence energy use is possible. There is a trend in the lighting market towards Dark Sky Friendly lighting with minimum negative impact on animals and plants whose wellbeing is impacted negatively by light at night. This might be a game changer since new rules are starting to spread where even streetlight should be delivering an absolute minimum amount of light triggered by the presence of humans or cars. The solar powered lighting systems developed in this project will immediately be able to fulfil such requirement for many more road classes if the lamp placement is minimally shaded providing solar lighting conditions during the day for proper energy harvesting. Therefore, time is working positively towards the solution. Furthermore, risk is mitigated by developing markets close to the equator as a starting point and moving slowly northwards.

Another risk to the project was the COVID-19 pandemic which though had close to no impact to the project since most of the partners could work normally during the project period. Furthermore, tasks could be shifted around so work that didn't require access to laboratory and workshops could be done during lockdowns. The project suffered only 3 months delay compared to the original plan.

5. Project results

The project has been dedicated to the following work tasks

- Development of 7 port Firefly converter electronics
- Development of Battery solution
- Development of Solar panel solution
- Development of LED light solution
- Development of Communication and SMART light platform
- Development, test and demonstration of prototype in Danish labs
- Development, test and demonstration of 0-series in DK
- Quality, cost and certification

All the listed topics have been addressed within this project and are described in detail below.

5.1. Development of 7 port Firefly converter electronics

Cost benefit analysis early in the project showed that a 7 port (5 MPPT inputs) converter was too expensive according to the expected added efficiency as long as the solar panels in the product was the same types and voltage. Cost estimations showed nearly a doubling in price only with an expected efficiency increasement in the area of 0-7 percentage points. A much higher benefit pr cost could for instance be found by increasing the PV area with a minor amount at a much cheaper price tag. Therefore, it was decided to cut the number of MPPT input ports to 2 for the prototypes to develop and demonstrate the technology effectively making a converter with a total of 4 ports.

First prototypes

The core of the existing platform from Nordic Firefly is a digital controlled switch mode power converter based on a patented topology effectively making a three-port converter with shared components. An additional MPPT harvesting buck-type channel was then added to this architecture. The main challenges in this regard were to:

1. Expand the digital controller to control 2 simultaneous power conversions (instead of 1). Ensuring proper dead time digitally and/or by analog circuits.
2. Prepare AUX power circuits for comms and other peripherals (3.3V and 12V).
3. Extend the voltage capabilities for higher voltages used in this project (battery voltage of up to 28V, LED voltages of up to 40V).
4. Define and implement a digital interface for the power converter to be controlled by and to deliver readouts of system voltages and currents.

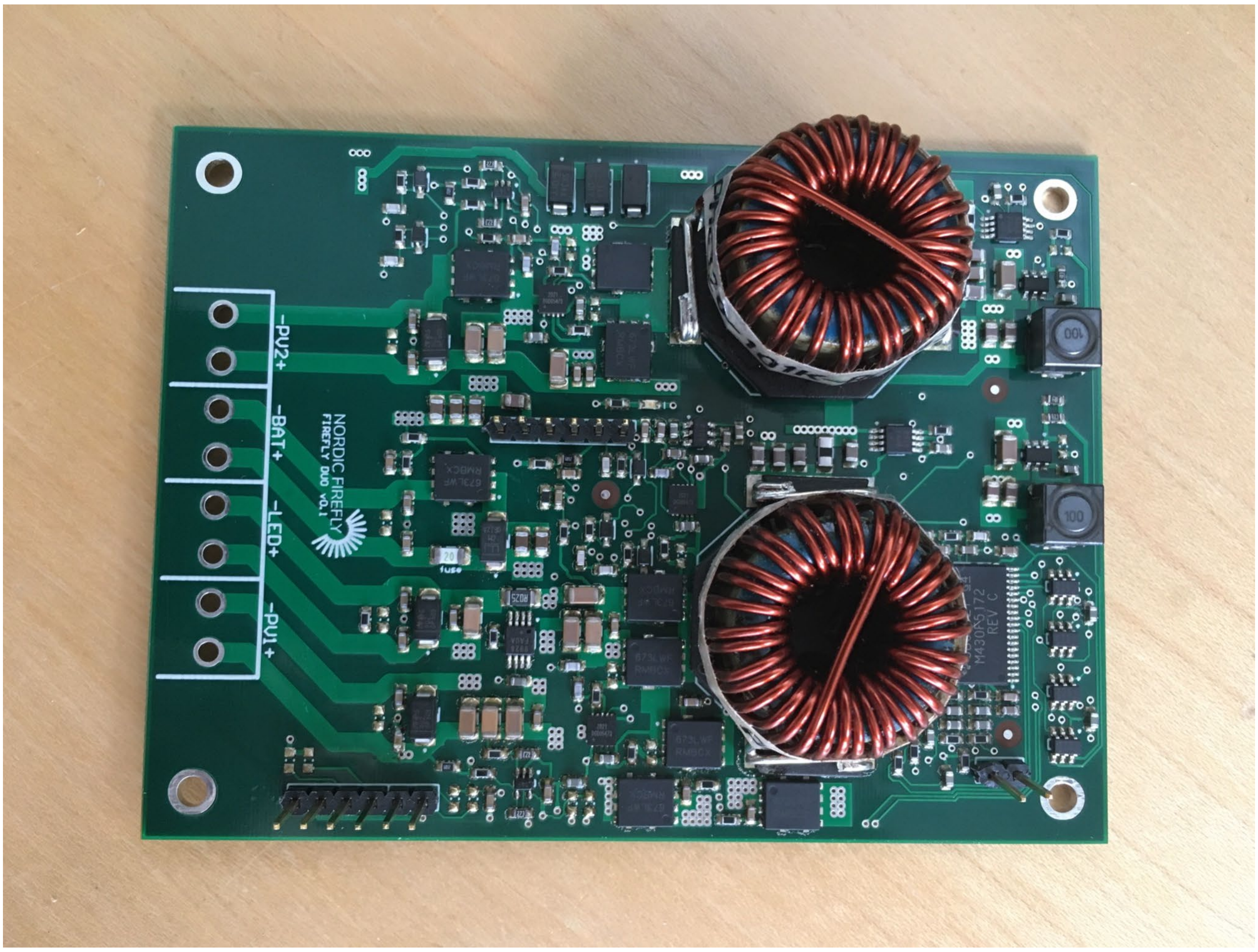


Figure 6 - First prototype. 4 port converter

Second prototype

The second prototype was developed as the next iteration of the design. Learnings from bench- and field testing the first prototype was incorporated and the design features an on-board integration of FFctrl-comms module as described in section 5.5

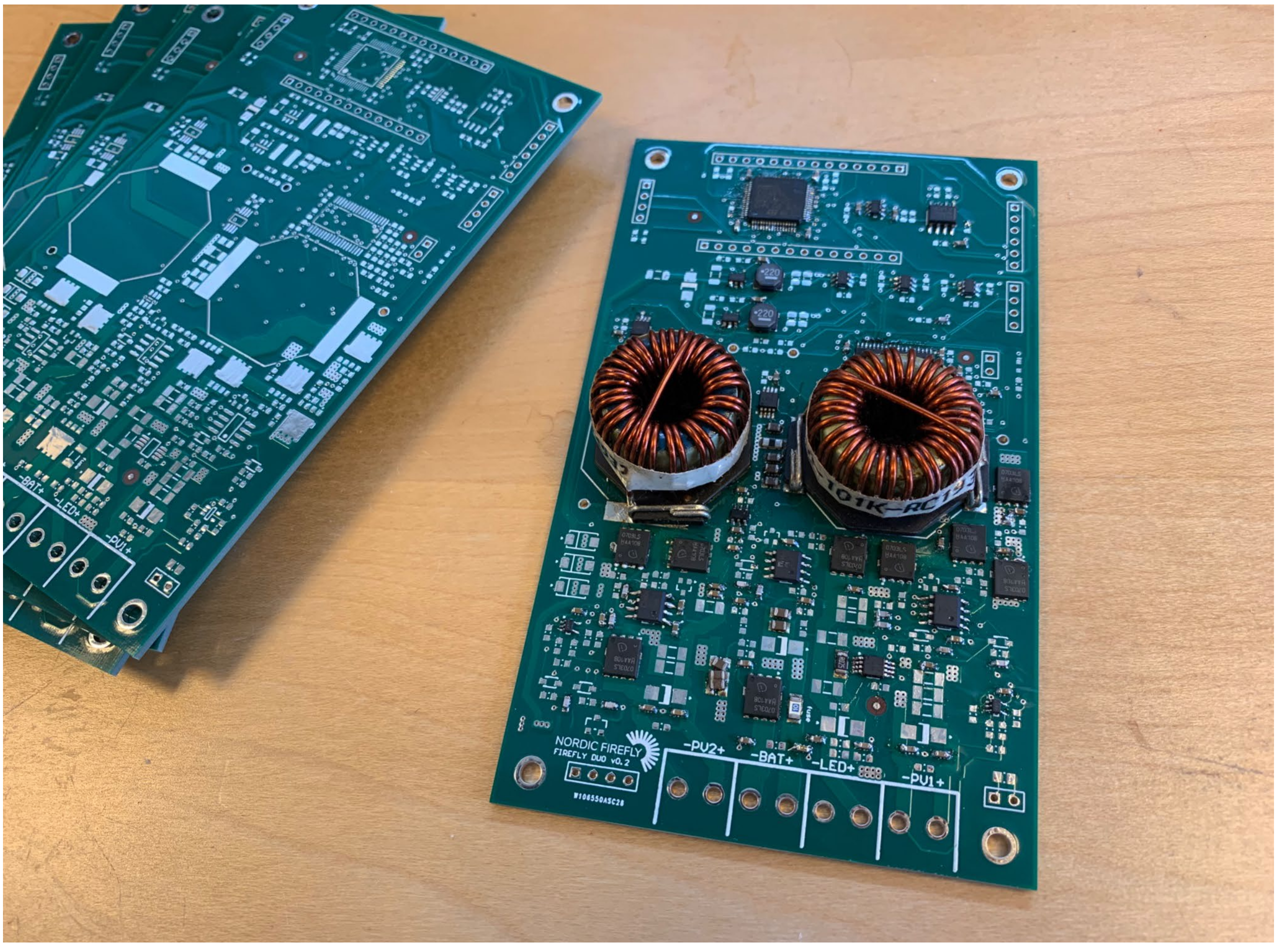


Figure 7 - Second prototype incorporating learnings from first prototype as well as on board comms module

Changes a part of on-board comms module includes

1. More robust AUX power circuit
2. Changed gate driver circuit capable of withstanding higher switching voltages.
3. Removal of logic IC’s for PWM control signal, as a programmed solution was developed

Performance

Power efficiency of prototype was measured to approximately 95 % for a single channel in a broad area of the functional window. More importantly the low power segment (< 10W) of above 87-94% which is satisfying for low irradiance conditions in Denmark.

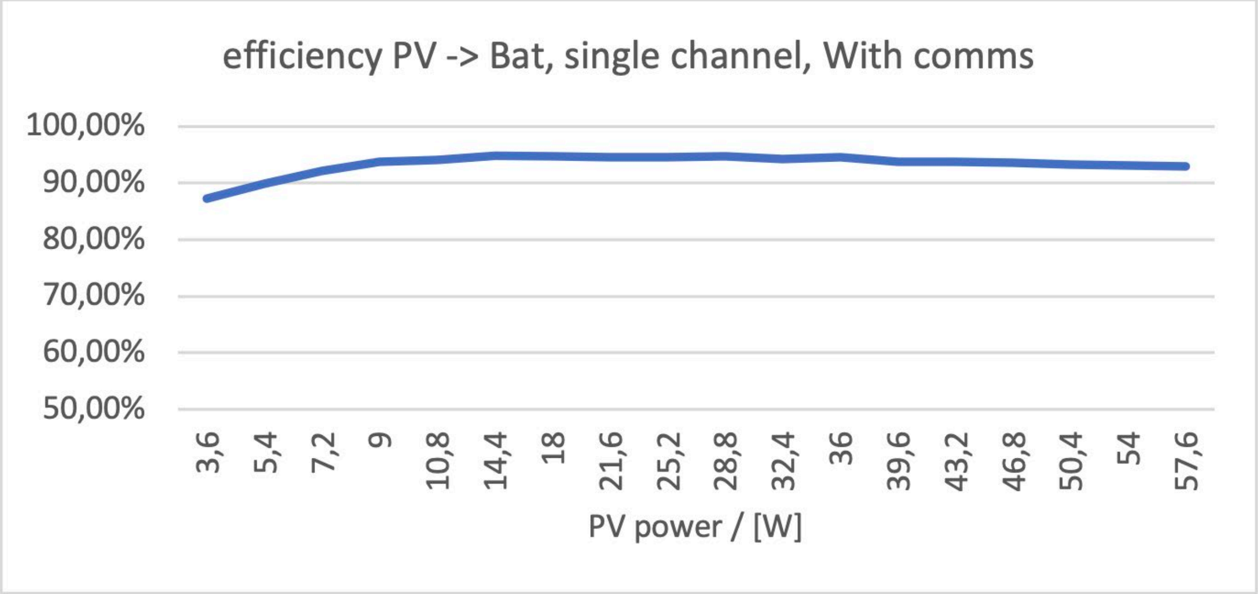


Figure 8 - Power efficiency from PV to battery, single channel. PV = 18 V, battery set to 13 V)

To illustrate the benefit from having a battery with controllable voltage a power efficiency measurement was performed with the Nerve Smart Systems battery set at respectively 14 V and 26 V. It is clearly seen that when the battery is working at 26 V the efficiency is approximately 4 percentage points higher than when the battery is working at 14 V as a result of a closer matching between the battery voltage and the LED voltage

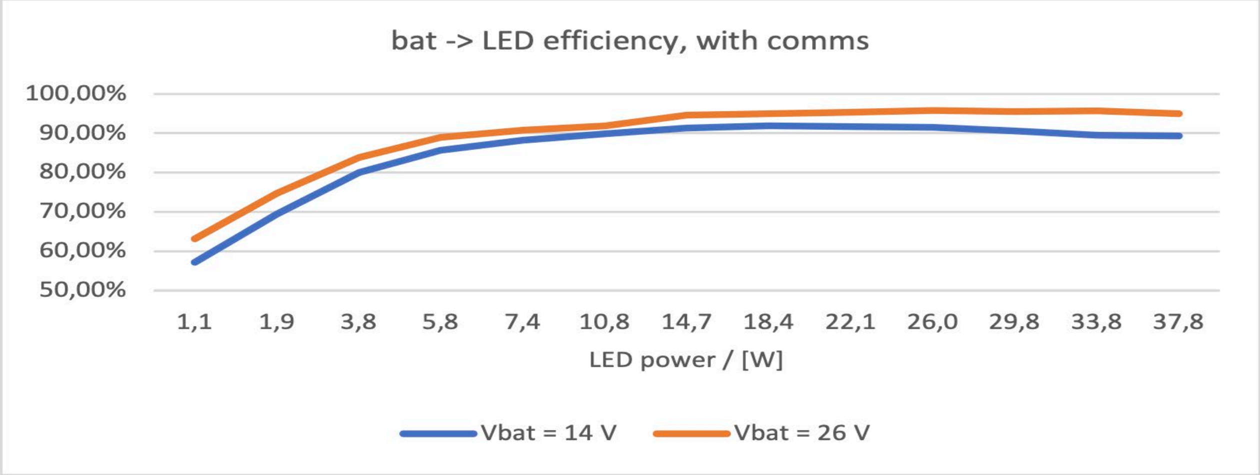


Figure 9 - Efficiency of power conversion from battery to LED module. Battery configured to respectively 14V and 26V.

Final 3 port converter edition

A converter with multiple MPPT input ports can be beneficial for lamps with multiple PV panels exposed differently to the sun or with varying design/sizes. However, usage of these for SolarGlow, that has only 1 large PV panel, would be very inefficient as only 1 harvesting channel could be used (too low power). In addition, the multiple MPPT channels was not designed to be used in parallel configuration.

Therefore, to conclude the project, a 3-port converter incorporating the learnings from the first 2 prototypes was developed and realized. Now with one single high power MPPT harvesting channel that can fit into both SolarGlow and SolarDesign (with paralleled PV-panels).

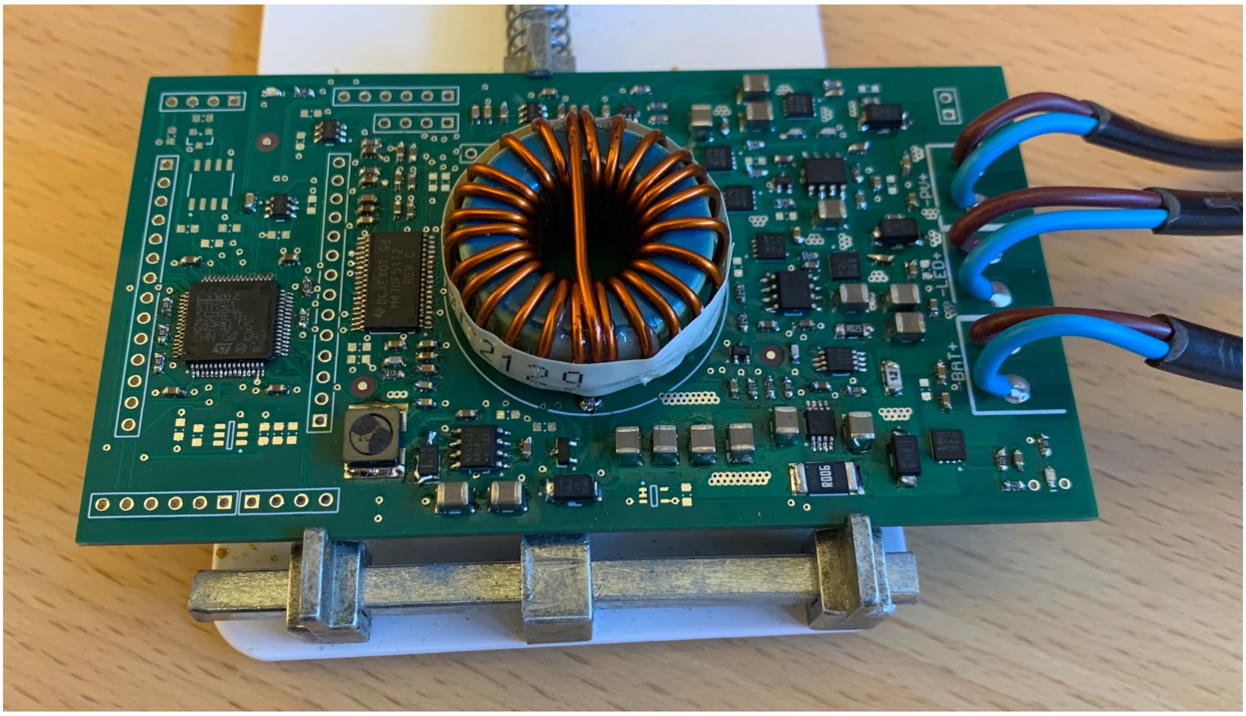


Figure 10 - FF200: 200 W MPPT 3 port converter. Can be fitted both into SolarGlow and SolarDesign.

This edition was designed to be able to handle up to +200W of harvesting power and +60W LED power. Both with very high efficiencies of above 96 %. Ready for marked and regulations testing.

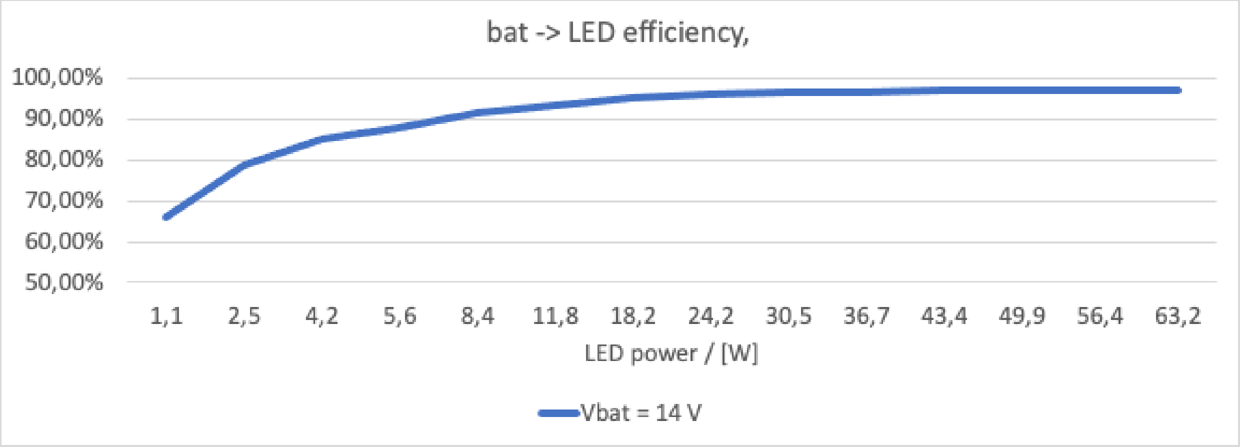


Figure 11 - FF200 Power efficiency, battery -> LEDs

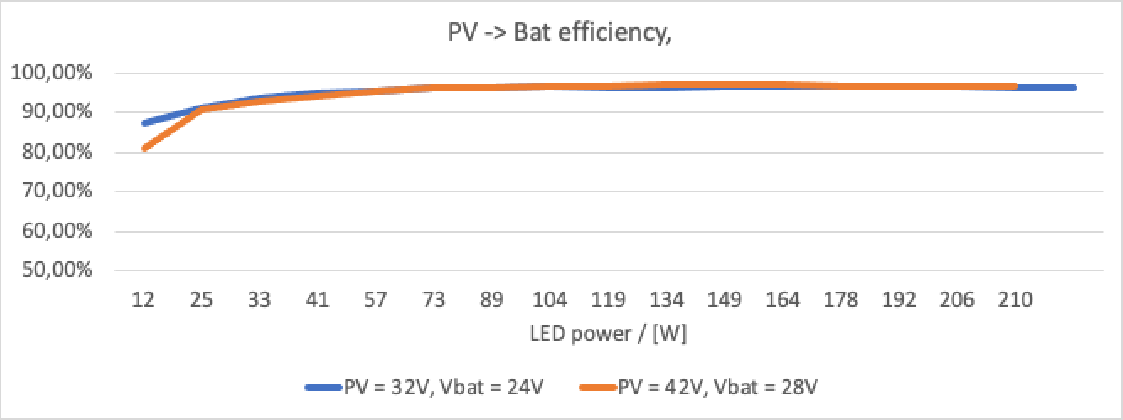


Figure 12 - FF200 Power efficiency, PV -> battery

Research in usage of a switched capacitor converter for MPPT harvesting

Parallel to the development of the multi-port converter research has been conducted at DTU Elektro Electronics Group in the design of a switched capacitor converter (SC) topology for MPPT harvesting. Switched capacitor converters are a well-known technology of which DTU Elektro is leading experts. The methodology can provide very high efficiency and an inductor less design, which can benefit cost and rare earth material usage. Furthermore, such a topology can be realized as an integrated circuit with external capacitors leaving a very small footprint. Drawback is that the topology has a finite amount of conversion ratios which can be challenging if high dynamic range with a large voltage operation window is desired.

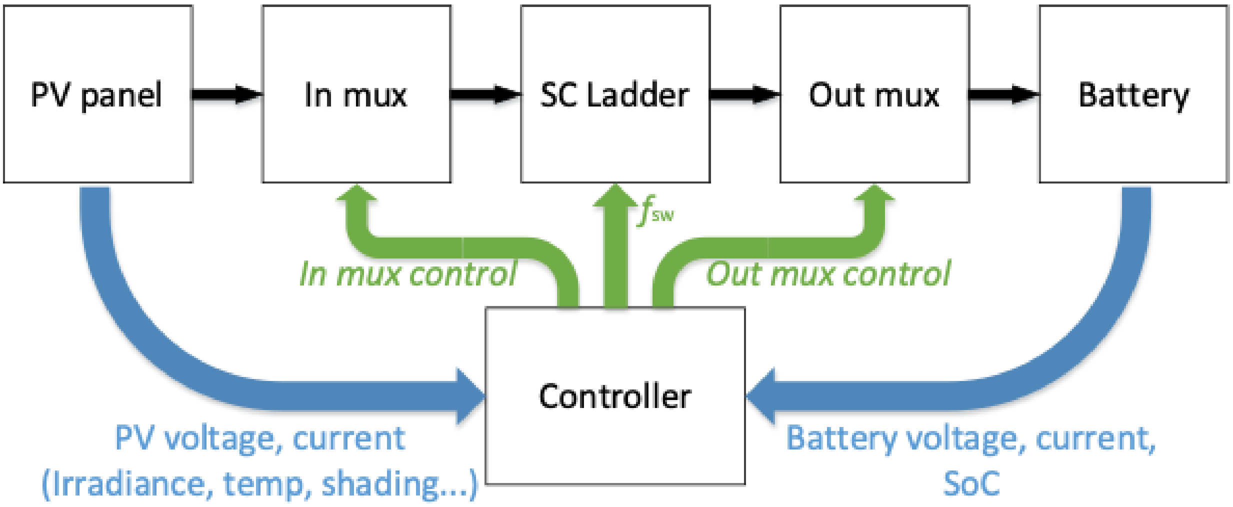


Figure 13 - Switched Capacitor (SC) Ladder with input- and output multiplexors. High amount of conversion ratios can be achieved

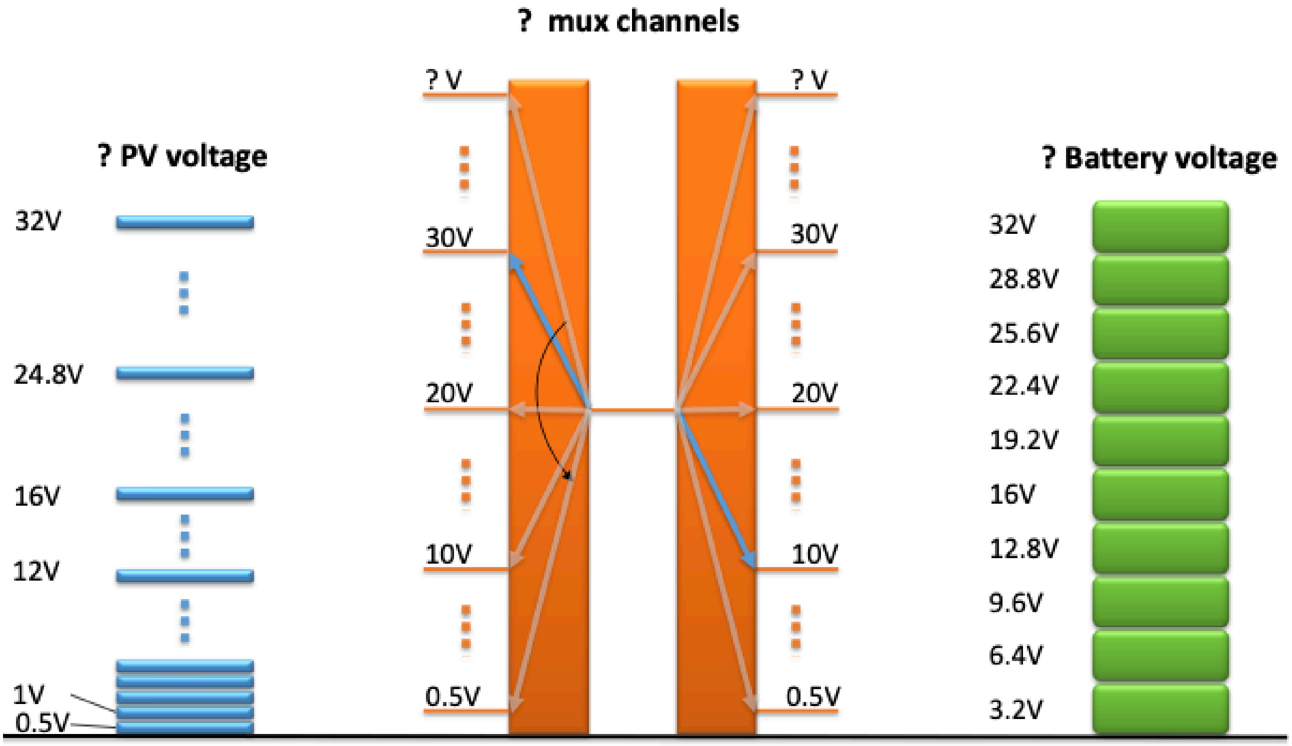


Figure 14 - Conceptual example of SC ladder network to be implemented using multiplexor channels to match input and output voltages

By combining input- and output multiplexors a desired conversion ratio can be used with the switched capacitor ladder. In the following figure a distribution of the conversion ratios *k* of an SC converter is shown. It is seen that in this example highest dynamic range Is achieved around *k* = 1, so this distribution would be preferred if battery and PV voltage is in close vicinity.

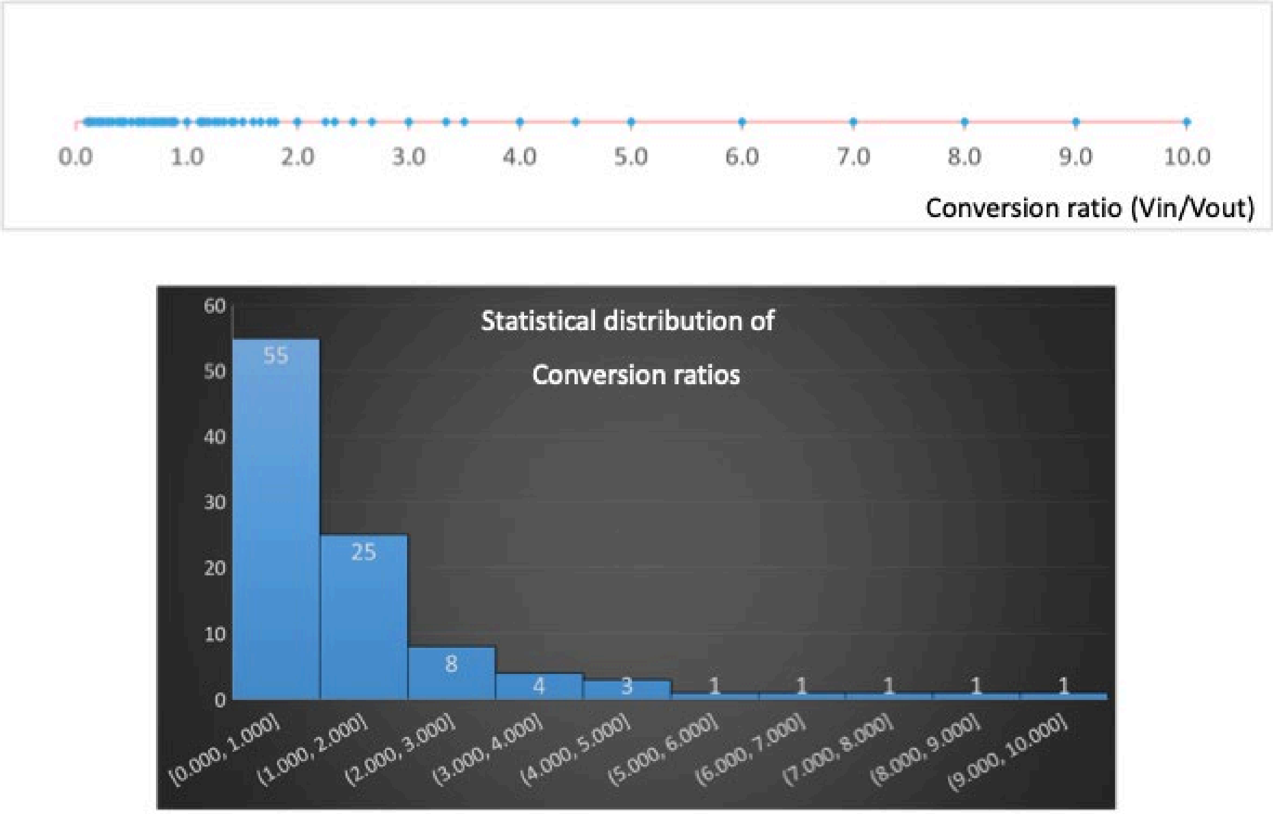


Figure 15 - Example of distribution of conversion ratios (Vin/Vout) for SC converter

By cascading multiple stages a very high dynamic range both in size and number of *k* was achieved and prototyped in this project. Very high efficiency (>98%) was achieved and it was shown that SC novel SC converter topologies can be usable for building a switched mode converter for MPPT harvesting.

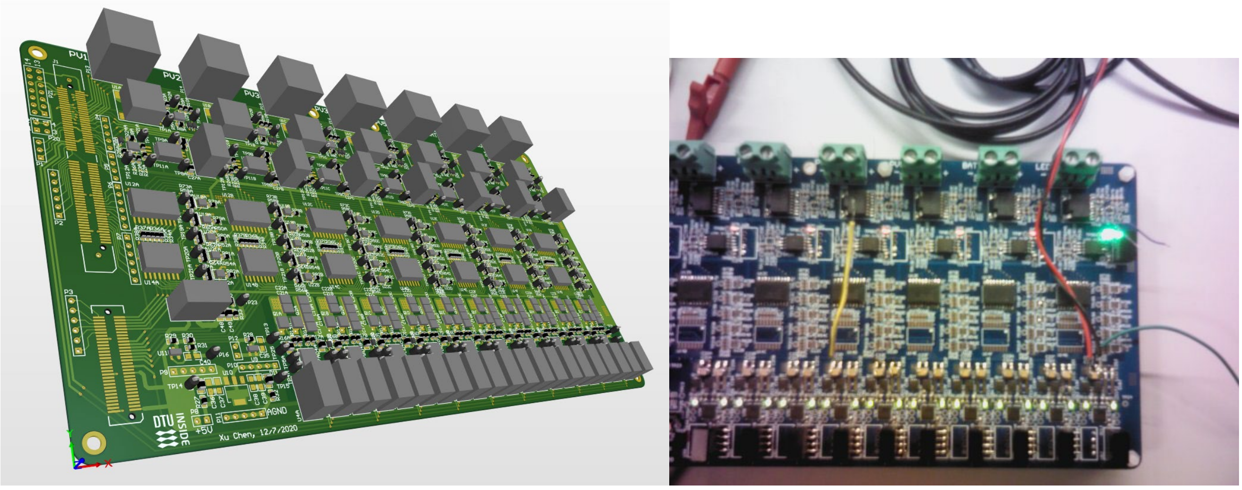


Figure 16 - SC converter prototype built by DTU Elektro for proof of concept

5.2. Development of Battery solution

The battery solution for the system requires the battery voltage to be switchable between 14V DC and 26V DC. This is a requirement to achieve the optimal efficiency of the NFF MPPT.

Nerve Smart Systems contribution to the project is the Variable Battery Topology battery pack shown in the below high-level diagram of the system.

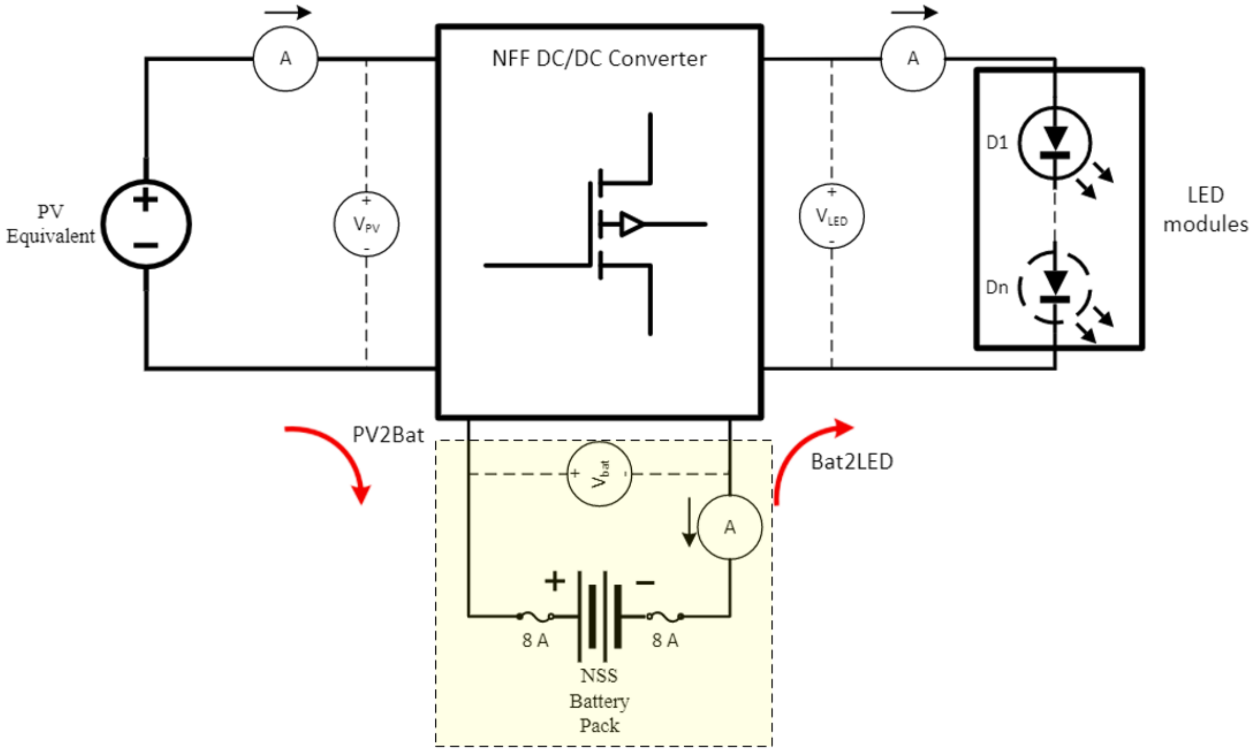


Figure 16 - System architecture with NSS Battery solution highlighted in Yellow

The Battery system is based on the patented Nerve Switch Technology which allows single Battery cells to be actively Engaged or Bypassed in the battery strings. This system differs significantly from conventional Battery Systems where all cells are connected in series HW wise. Conventional battery systems rely on all cells to be in perfect balance using BMS system to ensure the balance. If a single cell malfunctions, the entire Battery String becomes useless and must be repaired. Furthermore, the terminal voltage of conventional battery systems is generally fixed and varies only as the SoC of the system changes. This often requires expensive and powerful DC-DC converters to be used for obtaining the desired working DC voltage.

The Nerve Switch® offers a flexible and reliable control solution of the battery cells, where the terminal voltage can be varied, by digital control, in steps of the individual cell voltage. In the case of LiFePo4 battery technology, this voltage step is approximately 3.2 V DC.

This allows for any terminal voltage, in steps of 3.2V, to be obtained by engaging the desired number of cells in the battery string.

This principle is shown in the below simplified picture:

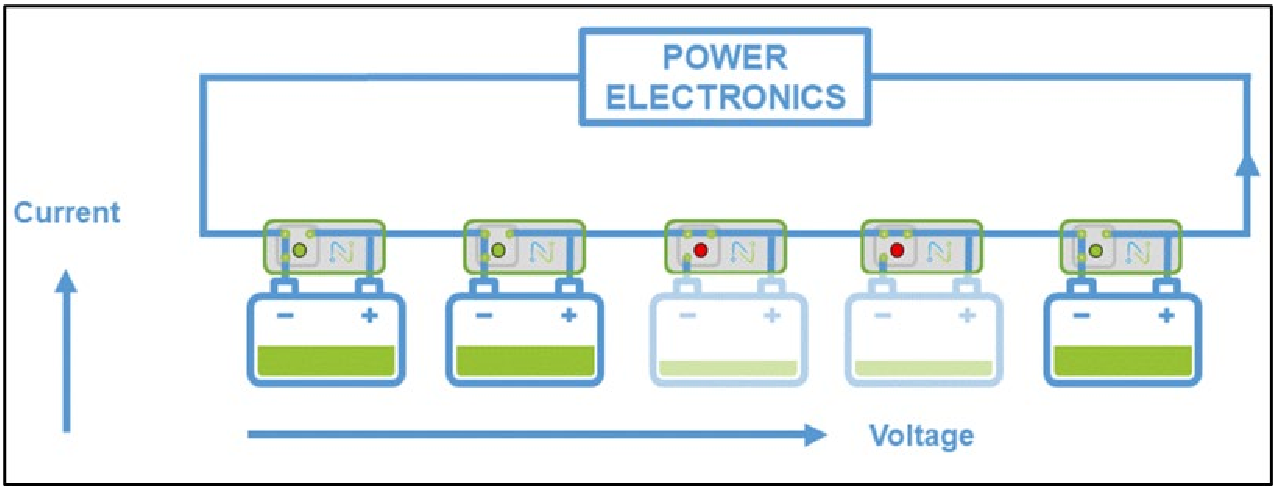


Figure 17 - Nerve Switch® principle.

Cells with relatively low SoC can be actively bypassed in favour of cells with higher SoC to ensure that the most capable cells are used to provide the needed current. By actively rotating the engaged cells, the cell loading can be shared to ensure that all cells are maintained at the same SoC level. In this way cells with low SoH (State of Health) will be used less in favour of cells with high SoH. Even if some cells malfunction completely, they will be permanently bypassed by the BMS SW. This way, the system can continue to function, even with a number of malfunctioning cells. In practice, the system shall be designed to contain a certain amount of battery cells in excess of the maximum required voltage to maintain this principle.

It is important to point out that all cells will actively be used on a rotating basis to provide the needed terminal voltage, and that no cells are left unused in this system. The duty-cycle of each cell is however <100%.

The main benefit of this Variable Battery Topology is that any desired terminal voltage can be achieved while still actively using all cells at their capability.

NSS has developed and optimised the Nerve Switch® solution HW and SW to provide an efficient and reliable solution. This has resulted in the Nerve Switch® tailored for the selected LiFePO4 battery cell.

To support the complete system testing, NSS has developed a prototype battery module based on 26 LiFePO4 cells providing approximately 2000 Wh of storage capacity.

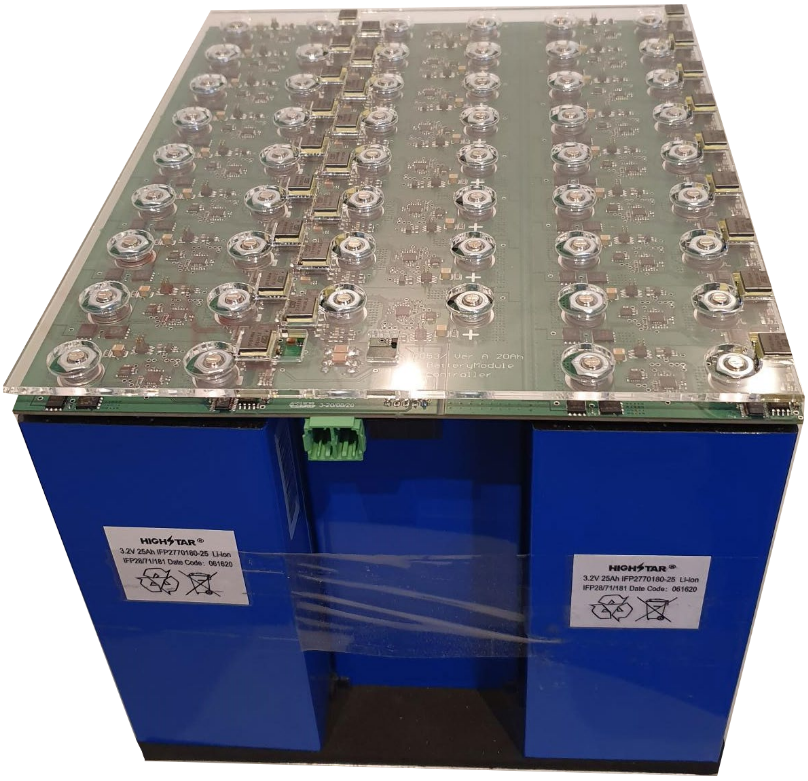


Figure 18 - NSS Prototype battery module

The selected cell is the HighStar 25Ah IFP2770180-25.

No.	Items（项目）	Specifications（规格）
1	Charge voltage 充电电压	3.65V
2	Nominal voltage 标称电压	3.2V
3	Rated Capacity 额定容量(discharge at 0.33C to voltage of 2.5V at 23°C±5°C)	25Ah
4	Standard Charging Current 充电电流	0.33C
5	Standard Charging method 标准充电方法	Under the conditions of 25° C ± 5 ° C，0.33C Constant current charge to 3.65V, then Constant voltage3.65V charge till charge current decline to ≤0.05C. 在25°C±5 °C的条件下，0.33C恒流充电至3.65V,转为3.65V 恒压充电，直至充电电流小于0.05C.
6	Max. charge current 允许最大充电电流	1C
7	Max. Discharge current 允许最大放电电流	3C
8	Discharge cut-off voltage 放电截止电压	2.5V
9	Operating temperature Relative humidity % 工作温度、湿度	Charging : 0°C-45°C, 65%±20%RH 充电: 0°C-45°C，65%±20%RH discharging : -20°C-60°C, 65%±20%RH 放电: -20°C-60°C，65%±20%RH
10	Recommended Storage temperature 推荐存储温度	15°C-35°C
11	Cell Weight 电芯重量	Approx. 600g
12	Impedance 内阻	≤2mΩ
13	Cell dimension 电芯尺寸(包胶)	厚度 thick : 27.5mm±0.3mm 宽度 Width : 70.2mm±0.2mm 长度 Length : 138.0mm±1.0mm

Figure 19 - Highstar LiFePO4 cell datasheet

Since the solution developed is to be regarded as an active battery, provision has been made to “Boot” the battery by using the voltage provided by the NFF converter. This is done using a DC-DC converter from the NFF converter to the control logic of the NSS battery.

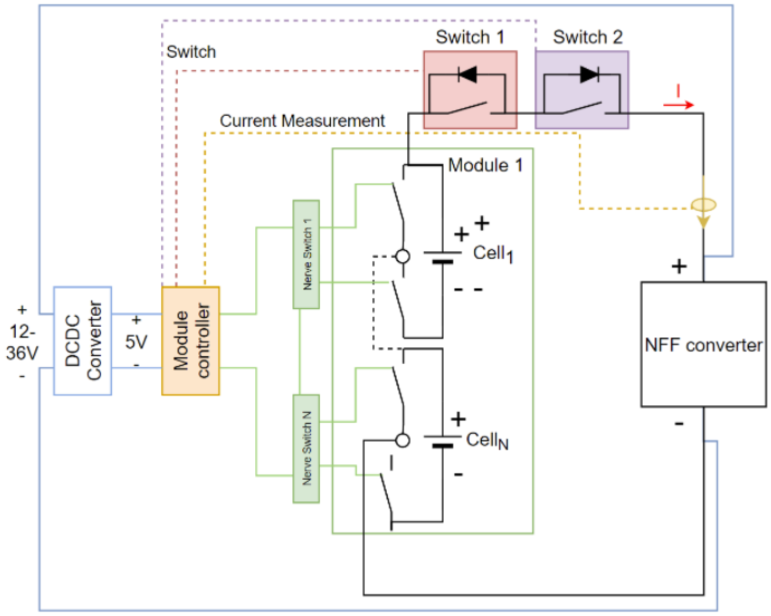


Figure 20 - Power Supply system for the Battery

Switch 1 ensures that the battery cannot be discharged below a safe threshold, whereas Switch 2 ensures that the battery cannot be charged above a safe threshold. Both switches are controlled by the EMS / Module controller.

The EMS is shown below along with the full battery system integrated in a box.

Figure 21 – EMS and battery system integrated in a box.

5.3. Development of Solar panel solution

One of the major improvements made to the solar panels on both the SolarDesign solution and SolarGlow solution was to move from a system architecture of 12V to 24V thereby necessitating the solar PV panel to operate at above 32V to have a good balance in the DC to DC conversion between PV power and battery power. By moving the system architecture to 24V and therefore increasing the voltage on the PV panels, the internal resistance in the PV panel was reduced leading to better power harvesting in all instances including low-light instances.

One of the main technical challenges encountered in creating a vertical mounted PV panel for SolarDesign with a voltage of above 32V was in ensuring it could still be achieved within a panel length of no more than approx. 180cm and a width of no more than 19cm. The rationale for fulfilling these dimensions lies in both ensuring the aesthetics of the panel dimensions would work with our mechanical design and also to ensure the length of the panel did not introduce mechanical instability in the panel leading to increased breakage potential.

To achieve this the cells had to be cut quite small and connected in series to achieve approx 34V. When cells are cut as tightly as we had to do, to achieve the desired voltage, they can shunt. Only a handful of manufacturers in the world are able to perform this task of cutting the cells as small as we required without creating process induced shunts. Therefore, to also verify the quality of our PV panels and ensure no defects arise during the manufacturing process we have ensured our panels go through an Electro Luminescence test (EL-Test) when manufacturing is completed.

Further improvements to the panels were achieved by increasing the cable diameter of the parallel connection cables on the back of each panel, as well as creating an optimised parallel wire connection scheme that can accommodate even further cable diameter increases to reduce losses in critical choke points. Lastly two bypass diodes have also been implemented enabling each panel to still produce power even though half of the panel may be soiled.

The outcome is a higher performing panel in all instances including low light instances, with even greater soiling resistance and that is further not challenged in its mechanical strength, as the length of the panel is kept relatively short, thereby ensuring the cells inside do not crack during handling.

5.4. Development of LED light solution

The successful implementation of a PV-based light-as-a-service business model, requires not only pre-installation quality-control of the product itself, but pre-installation-quality control of the lighting conditions at the installation sites. For a lighting pole to have sufficient uptime, the battery and PV-panels have to be dimensioned and measured against the local environment. This includes the local shading characteristics, typical weather conditions, and irradiance levels.

Road-lighting in particular, is not just a matter of power-in light-out. The quality and relative utility of the light is dependent on standards and models all of its own. Therefore, in addition to the lighting and performance models, a road-lighting simulation and optimization environment has also been developed.

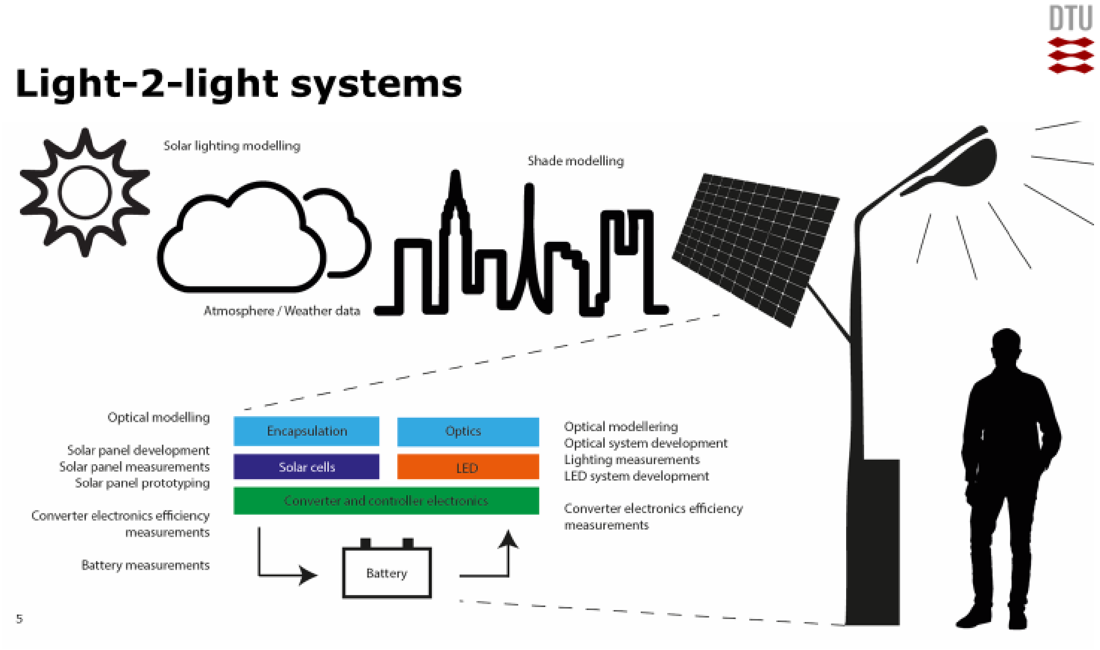


Figure 22 - Modelling the performance of a light-to-light system involves the interplay between many individual simulation models. The battery charge is dependent on power usage, temperature, and power input. Power input is dependent on solar irradiance, weather, temperature and shading. Power output is dependent on state-of-charge of the battery, etc.

Therefore, a lot of time has been focused on developing and validating a number of software packages that can model and predict not only the product performance itself, but the product performance as a function of environment at the installation site. This includes modelling the solar irradiance, the shading environment, the power-consumption and battery performance, as well as the optical performance at a given site.

The modules are currently available as separate software packages written in either Matlab, Python or C#, that can eventually be combined to form a full-fledged irradiance- and finance-forcasting, as well as lighting-simulation and -optimization suite. One of the packages has been hooked up to a Visual Programming Language that could be leveraged for swift aggregation of the modules into a full-fledged simulation suite.

5.4.1 Development of Irradiance Model

In order to predict typical irradiance at an installation site, an irradiance simulation model has been developed that relies on yearly, hour-based weather data to create minute-by-minute irradiance data for use in performance simulation.

The method relies on training a Discrete-Time Markov-Chain model against actual weather data to create Transition Probability Matrices (TPM) that mimic the irradiance patterns of different types of weather. Most specifically overcast, cloudless, and broke-cloud conditions. After training, the model can simulate weather conditions by using yearly weather data from the installation location. As input, the model only needs the simplest, locally measured data, the Global Horizontal Irradiance and cloud coverage class, in 1 hour resolution, which is typically readily available. Using a clear-sky model, the algorithm can calculate the direct and diffuse components and use the appropriate TPM to simulate the local irradiance condition at a much higher resolution.

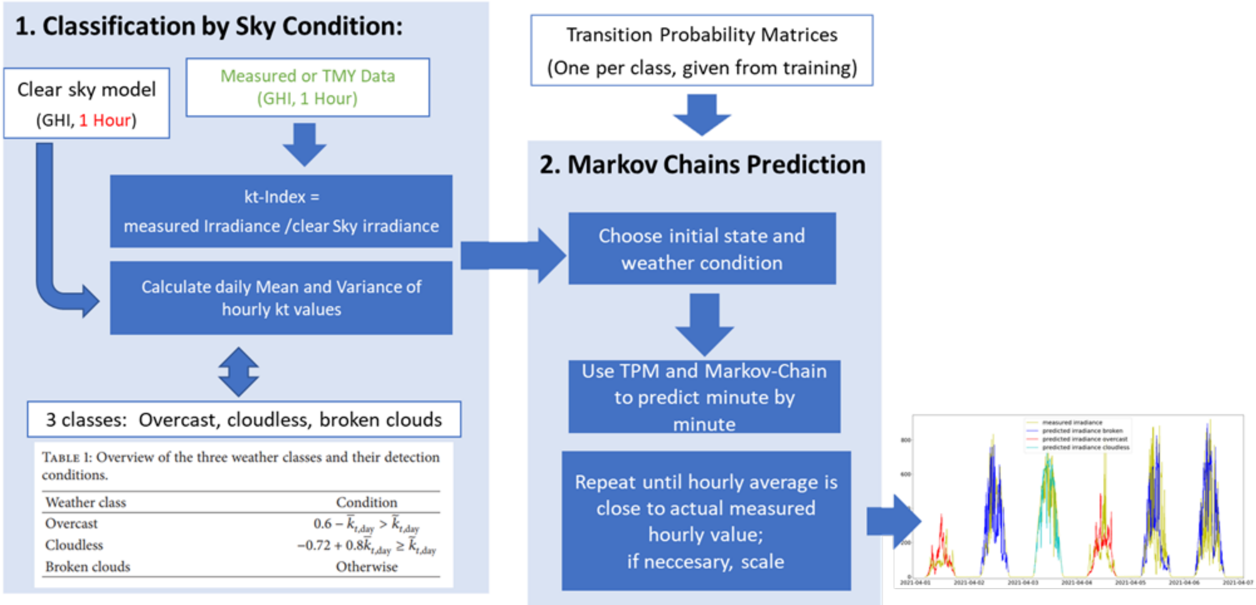


TABLE 1: Overview of the three weather classes and their detection conditions.

Weather class	Condition
Overcast	$0.6 - \bar{k}_{t,\mathrm{day}} > \tilde{k}_{t,\mathrm{day}}$
Cloudless	$-0.72 + 0.8\bar{k}_{t,\mathrm{day}} \geq \tilde{k}_{t,\mathrm{day}}$
Broken clouds	Otherwise

Figure 23 - An overview of the basic irradiance-modelling algorithm. Minute-by-minute data is generated by a Markov-Chain model using pre-trained Transition Probability Matrices.

The model has been trained and validated against actual measured data using metrics such as hourly maximum and minimum, hourly mean, and hourly variance. Sample data showing the hourly means of a simulated forecast alongside actual measured data can be seen in the following image.

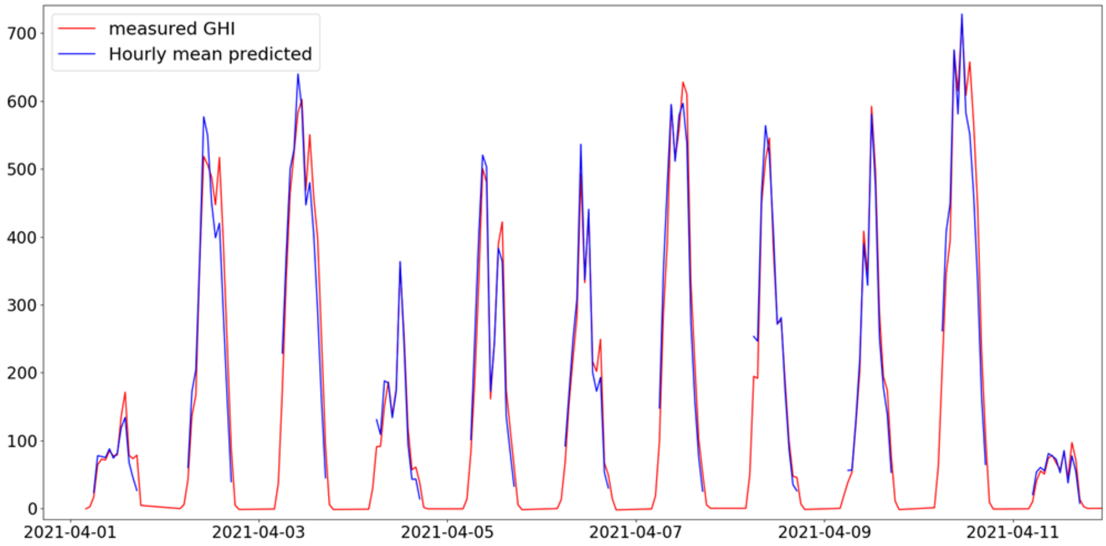
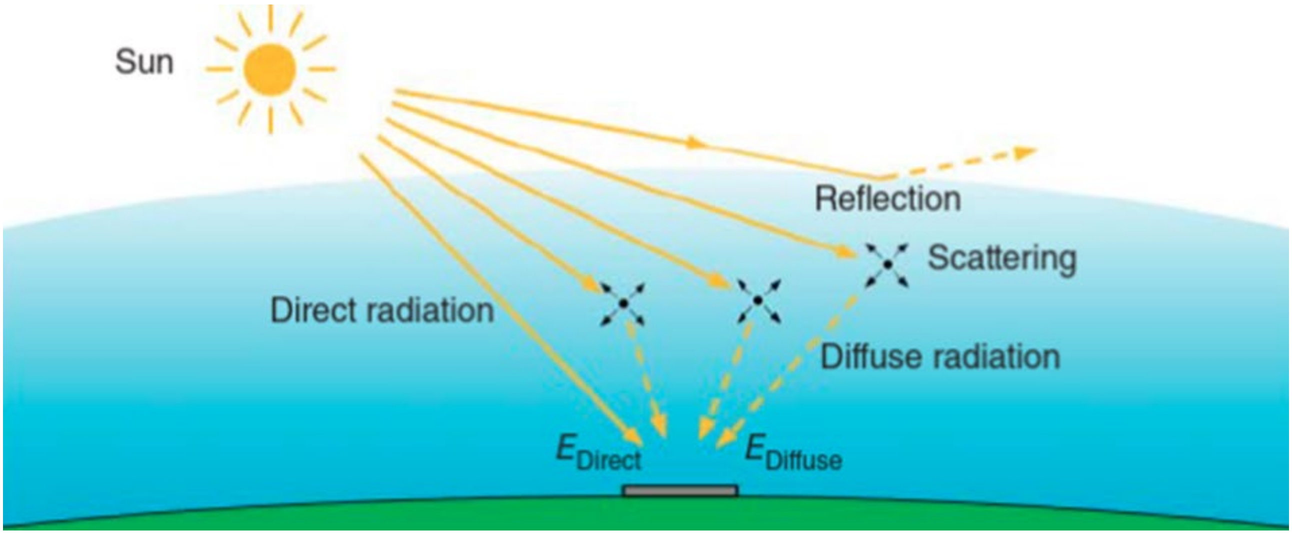


Figure 24 - Hourly means of the 1-minute resolution irradiance simulation, shows full adherence to the actual, measured irradiance.

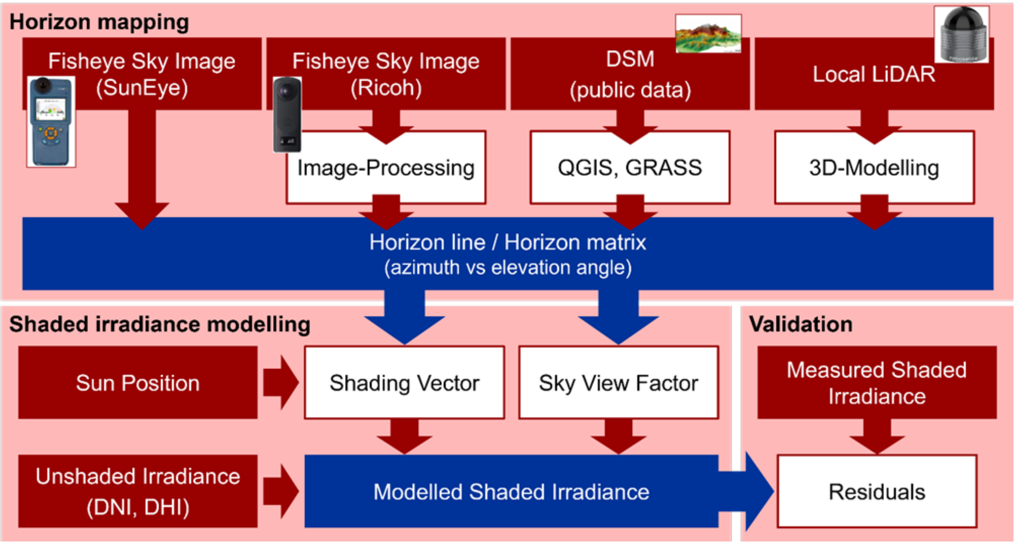
- ### 5.4.2 Development of Shading Model

PV-powered road-lighting is highly susceptible to the surrounding shading characteristics. Whether the site be urban or arboreal, the placement of a lighting pole can severely impact performance. The irradiance incident on a panel is a combination of direct and diffuse (scattered) radiation (shown in the following image) and shading can impact both of these components, as well as any ground-reflected components.

Predicting typical irradiance conditions in a shaded environment requires combining a local horizon-line or shading-matrix with an irradiance model that takes this shading into account and estimates the amount of direct and diffuse radiation hitting the PV panels. A horizon line is simply a 360-degree map of the highest elevations in the surrounding area, while a shading-matrix can represent gaps below e.g. balconies, canopies, and trees.



A shading modelling software package was developed, capable of accepting multiple forms of input to output a shading model of a particular location as shown in the image below. The shading model can be combined with the weather- and irradiance models, to more accurately predict product performance.



- ### 5.4.2.1. Fish-eye imaging

Fish-eye images can provide a full hemispherical view from any given location that can be processed and turned into horizon-lines. It requires on-site measurements that must sometimes be performed at the same height as the PV-panels to be of use, and the tilt and orientation of the measurements must be accurate.

The software package accepts:

1. Ready-made horizon lines from existing shading estimation products, such as the SunEye from Solmetric. These can be used directly from the source and only requires import and data compliance/conversion to match the irradiance model.

2. Fish-eye images from commercial 360-degree cameras – such as the Ricoh Theta line. These images are turned into horizon-lines using custom-made image-processing that can differentiate between sky and obstructing objects like trees, mountains and buildings.

Fish-eye imaging can also produce shading matrices, but without complex computer vision algorithms, windows and other bright objects can easily be mistaken for clear sky, which complicates the process of producing a reliable shading model and increases the amount of manual intervention required.

- ### 5.4.2.2. DSM LiDAR Data

In some countries, Digital Surface Models (DSM's) are publicly available, at a varying degree of resolution. They are essentially a recording of the topology of a region, including buildings and trees, using Drone-propelled LiDAR equipment.

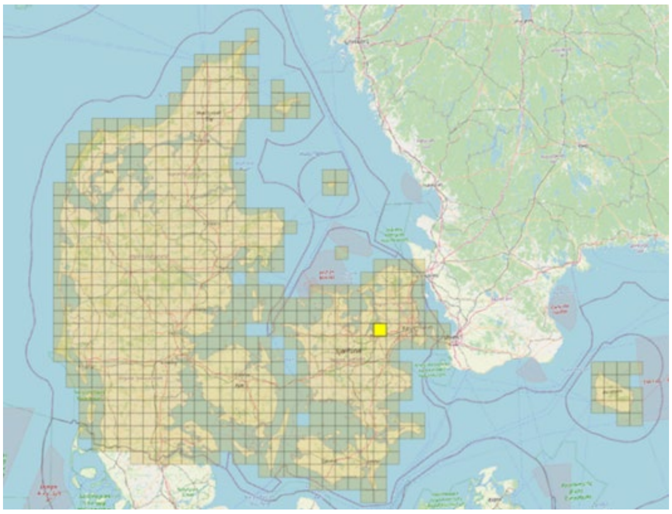


Figure 25 - The entire topology of Denmark is scanned regularly (last scan was performed in 2020) by drones.

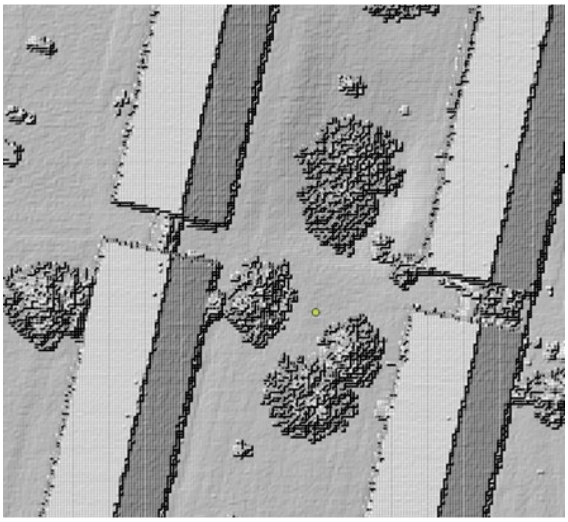


Figure 26 - A DSM can provide a high-detail topological map, which can be used to estimate shading.

When available and up to date, they provide an opportunity to assess shading conditions at any desired point in the map, without needing to go to the actual site – except for validating that the elevation data is up to date.

Not only does a DSM allow the remote creation of horizon lines at any coordinate on the map, the installation height of the PV-panels can also be taken into account, since a DSM is inherently 3D-information.

A software module to support DSM-based shading models was developed and validated against conventional shading models based on fish-eye imaging. Since the entirety of Denmark has been scanned by LiDAR drones, and high resolution maps are readily available from KortForsyningen (soon available at DataForsyningen instead), it was possible to validate the DSM-approach at multiple locations with different types and degrees of shading.The results show, that a DSM-based shading model is just as accurate as a fish-eye image, without requiring any manual on-site labour, and can therefore be used for validation of light-as-a-service installations in combination with an irradiance and performance model.

- ### 5.4.2.3. Local LiDAR Data

The software package includes the possibility of enhancing DSM data, in case the DSM is of relatively low quality, or in case that the site contains “overhung” objects such as balconies or trees. Since the DSM only captures the highest point of elevation, it cannot detect large gaps that could be crucial to the dimensioning and performance of an installation.

The local LiDAR data must be measured locally but has the benefit of being a 3D representation of the surroundings, so that the installation height and multiple positions can be considered without having to position the measurement equipment exactly at the PV-panel installation location. A number of LiDAR measurements can be taken at different locations and be combined and matched to the DSM model for a much more high-detail model.

Below is shown an example of a location, where the horizon lines do not fully capture the amount of direct sunlight on the site, because they only measure the top of the tree canopies. The shading matrix in such cases provide a more realistic input for the irradiance simulations.

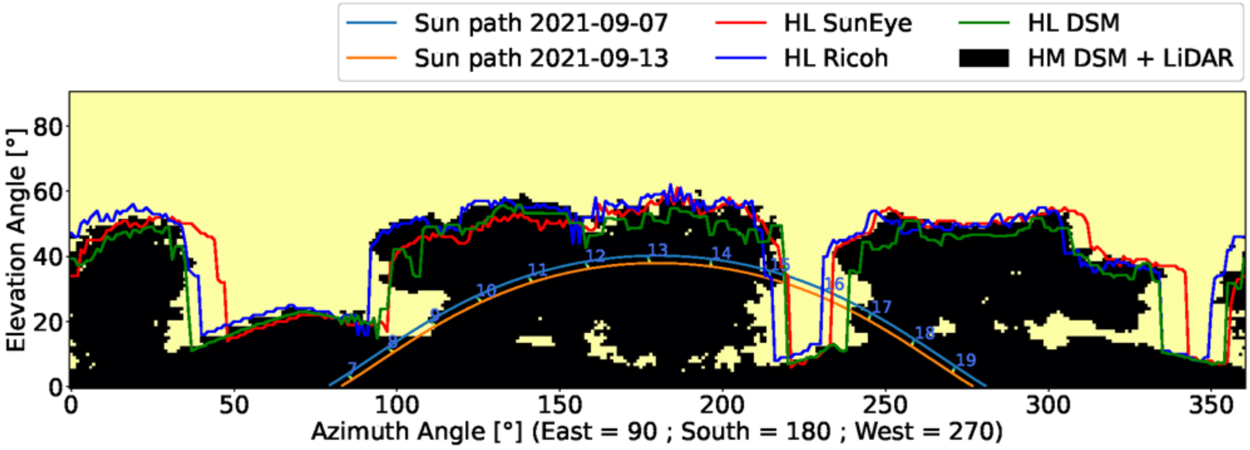


Figure 27- Horizon lines from on-site measurements and from publicly available DSM data for one of the shading locations (Location A), juxtaposed on a shading matrix created by enhancing the DSM with locally measured LiDAR data. Two sun paths from September are also shown.

The following tables show error metrics for the irradiance simulations based on the horizon lines and the shading matrix (LiDAR), compared with actual measured irradiance. The tables show both absolute and relative errors. They are for this scene divided into errors for summer and winter, since the scene contained deciduous trees that lose their leaves during winter.

Error metrics for Location A in summer

	SunEye	Ricoh	DSM	LiDAR
MBE [W/m²]	-35.13	-37.42	-23.44	1.54
MBPE [%]	-21.99	-23.53	-12.61	8.29
MAE [W/m²]	36.18	40.23	27.13	28.43
RMSE [W/m²]	67.85	74.45	59.87	52.63

Error metrics for Location A in winter

	SunEye	Ricoh	DSM	LiDAR
MBE [W/m²]	-14.01	-17.58	-20.24	-7.76
MBPE [%]	-13.01	-18.47	-24.03	-1.83
MAE [W/m²]	18.57	20.3	20.47	14.39
RMSE [W/m²]	36.49	38.39	38.43	31.13

Figure 28 - Development of Power Performance Model

A lot of time was spent on developing a model that could simulate the performance of a multi-panel PV-powered lighting system with potentially multiple MPPT's and a non-continuous voltage battery such as the Nerve Smart Systems battery technology.

The development required extensive work in both characterization, modelling and validation of the individual components and their combined performance characteristics in the field. The components were characterized independently and field performance was validated through extensive analysis of measurements from the on-site test-poles, as well as by auxiliary field test devices.

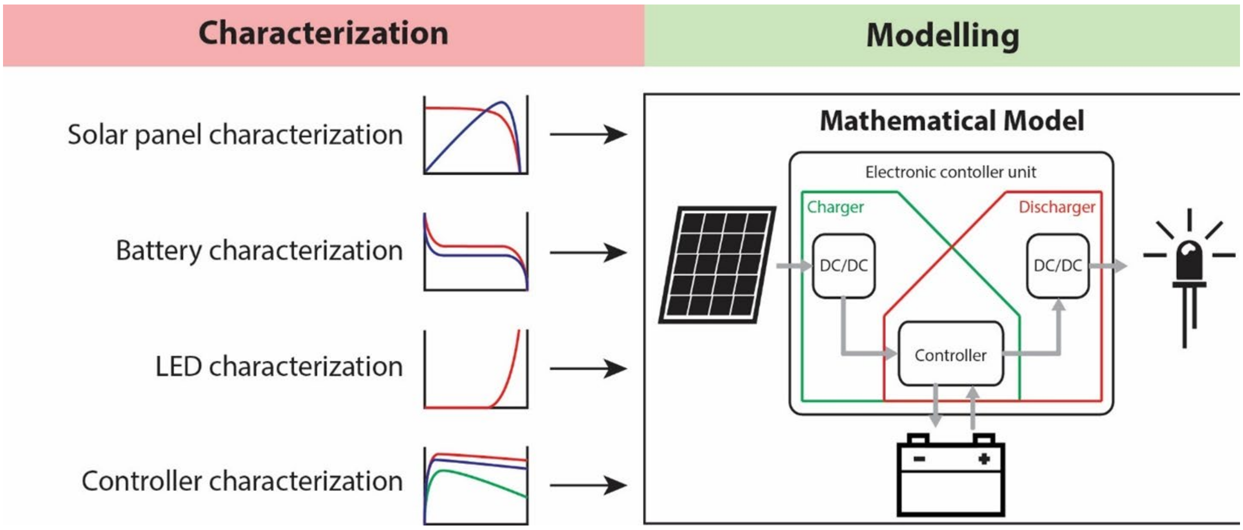


Figure 29 - Modelling a light-to-light system requires both accurate characterization of the individual components, as well as subsequent simulation of these components. Aside from irradiance simulation, environmental factors such as wind, temperature, and even soiling, also affect the components' performance.

Characterization and simulation of the NSS battery was a research topic in itself, due to the fact that the technology can switch subunits on and off to optimize load-bearing and adapt its voltage.

The model includes component-level temperature simulation capabilities, which depends on wind, irradiance and ambient temperature, due to the fact that the efficiency of several components - battery and solar panel in particular - are dependent on internal temperature.

As input, the model currently takes yearly local solar insolation, wind speed and ambient temperature - all based on measured data. Eventually, the model can be coupled up to the shading model so that urban and arboreal environments can be modelled, as well as to the road-lighting configurator, so that light quality is also taken into account.

The output is the result of a full-year simulation in terms of energy delivered and down-time hours due to insufficient battery levels. Multiple typical years can be processed for either average- or worst-case scenario estimation, which can in turn be used for financial calculations. In addition, soiling can be taken into account.

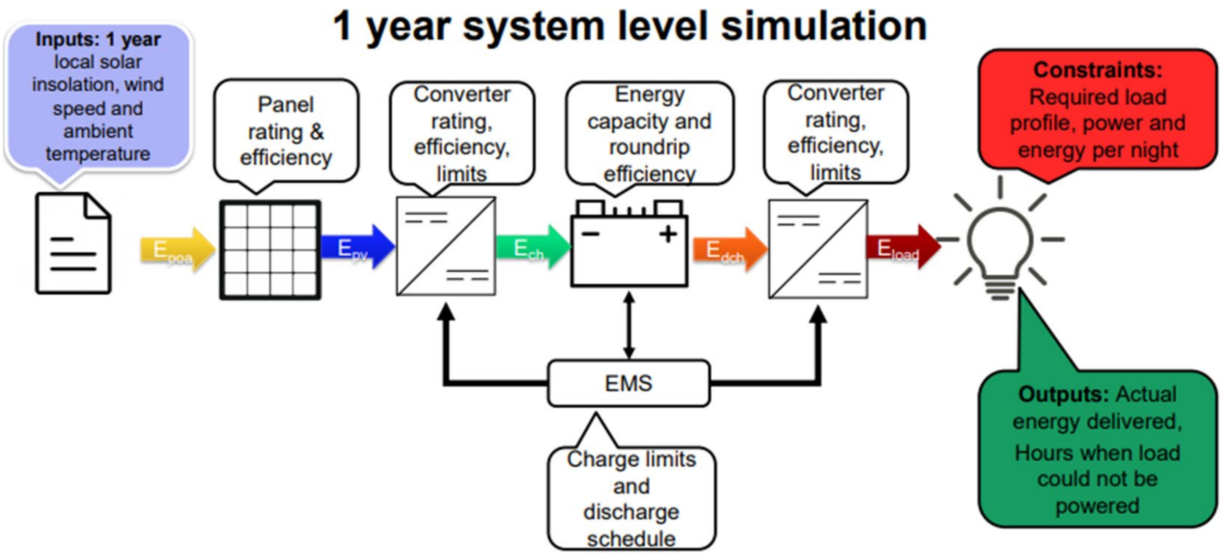


Figure 30 - A very simplified overview of the product performance simulation.

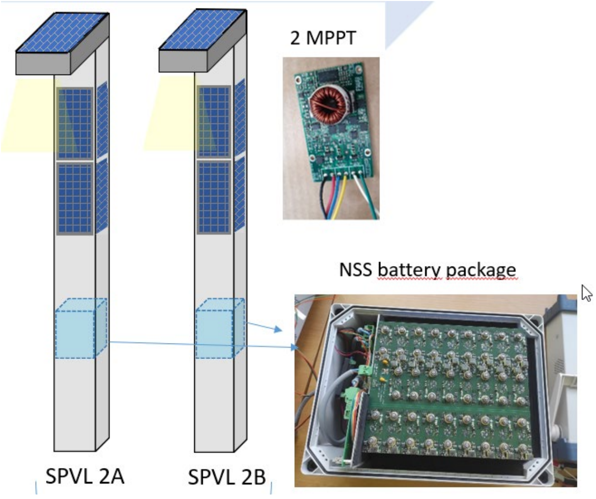


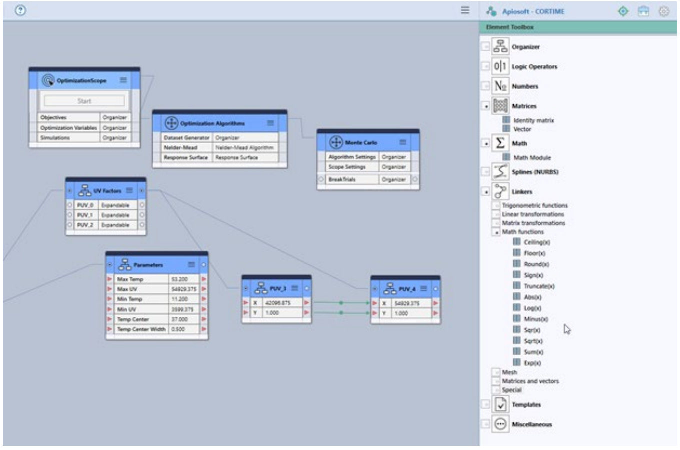
Figure 31 - For validation of the performance model, two light poles with 2 MPPTs and NSS batteries were installed in a local, shade-free environment. Along with sentinel installations with additional monitoring instruments, they will provide validation data for improving and expanding the model in the future.

5.4.3 Development of Road-Lighting Configurator

In many countries it is necessary to comply with standards for road lighting. Some proprietary software exists for this, namely the software DIALux, which has a built in plugin that can estimate whether or not a light source complies with the given road standards for a particular road geometry.

However, the process of testing compliance in DIALux is highly manual, but it offers limited capability to test an optical arrangement on multiple road geometries, and even less for optimizing the performance. There is no API available, meaning that the calculations cannot be easily coupled to external optimizers. In general it is difficult to find readily available optimization software with the capability to optimize toward the many different metrics required to satisfy road-lighting standards. Since there is a noticeable cost related to buying and installing a multitude of optical components, it is desirable to be able to optimize toward being able to supply a broad range of road-geometries satisfactory with as few different components as possible. This increases the number of objective an optimization algorithm must be able to handle at once.

Therefore, a different approach was taken than developing a road-lighting simulation from scratch. Instead, it was decided to build upon **RayBoy**, an in-development software package for ray-tracing simulation from the Danish company ApioSoft. The reason being, that the software contains a module for road-lighting simulation, **RoadBoy**, and because it was in the development pipeline to be connected to ApioSoft's massively multi-objective optimization engine and Visual Programming Language, CORTIME. CORTIME is similar to e.g. Dynamo from AutoDesk and Grasshopper for Rhino in terms of interactivity, but CORTIME has additionally the capability of optimizing highly difficult optimization problems, with a large number of objectives and variables, as well as mixed integer/category and floating point operation. This will allow the road-lighting configurator to optimize multiple road-scenarios at once through a combination of optics selection (integer/category) and pole configuration (floating point).



OptimizationScope
Objectives: Organizer
Optimization Variables: Organizer
Simulations: Organizer

Optimization Algorithms
Dataset Generator: Organizer
Nelder-Mead: Nelder-Mead Algorithm
Response Surface: Response Surface

Monte Carlo
Algorithm Settings: Organizer
Scope Settings: Organizer
BreakTrials: Organizer

UV Factors
PUV_0: Expandable
PUV_1: Expandable
PUV_2: Expandable

Parameters
Max Temp: 53.200
Max UV: 54929.375
Min Temp: 11.200
Min UV: 3599.375
Temp Center: 37.000
Temp Center Width: 0.500

PUV_3
X: 42096.875
Y: 1.000

PUV_4
X: 54929.375
Y: 1.000

Figure 32 - CORTIME's main interface is a Visual Programming Language that functions as both a data-hub to connect diverse software modules, and as a data-manipulation- and -creation sandbox.

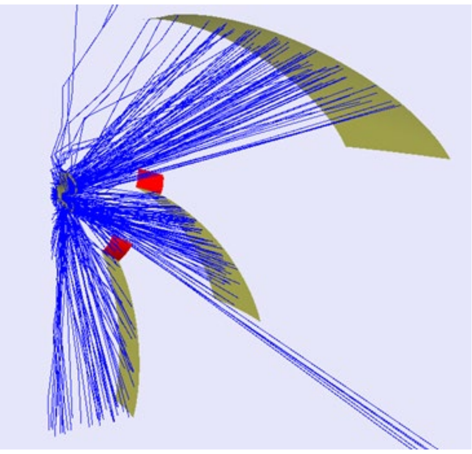


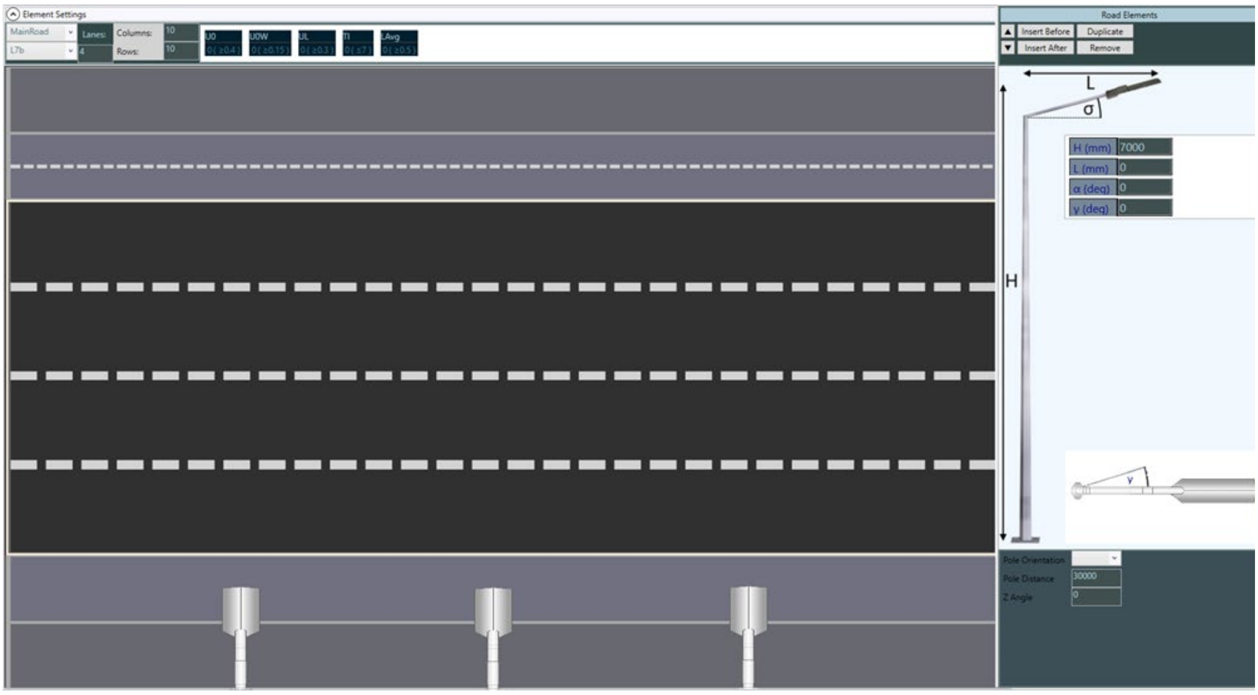
Figure 33 - Some of the modules implemented for the CORTIME sandbox are a geometry engine, as well as a ray-tracing engine.

RoadBoy was at the initiation of development based on CIE road standard calculations from 2000 and road classes from 1995. These standards had to be upgraded to the current standards, from 2019 and 2010 respectively. In addition, the road-lighting module did not have neither an API, nor was it hooked up to the CORTIME VPL and API yet. Setting up a full road geometry could only be done in code, in rather tedious, brute-force fashion. Therefore, substantial time was required to both define the API requirements and develop it along with ApioSoft, who were in the process of developing their own extension API. This caused both road-blocks but also opportunities to fine-tune the API for the integration toward RayBoy and most specifically the road-lighting module.

Once the RoadBoy API was functional and provided rudimentary interfaces for creating and modifying road-geometries and lighting pole configurations, development of the road configurator could commence in parallel with the further API development. The configurator was developed as a plugin for a container-application developed at DTU Fotonik. This allowed for the creation of an independent interface, coupled to the CORTIME API.

The independent interface hosts wrappers that make the translation from a visual road geometry to RoadBoy objects, while all modifiable objects and values at the same time have a matching representation in the VLP sandbox. Depending on the future development strategy, the VPL can be used as a hub for all the different software modules of this project to interface directly with each-other without requiring enterprise-level development. This would increase the potential for automated product configuration, using e.g. the shading and performance simulations as inputs for pole positioning- and dimensioning.

A snapshot of the independent interface can be seen in the following image.



MainRoad
L7b
Lanes: 4
Columns: 10
Rows: 10
U0 0(≥0.4)
U0W 0(≥0.15)
UL 0(≥0.3)
TI 0(≤7)
LAvg 0(≥0.5)
H (mm) 7000
L (mm) 0
α (deq) 0
γ (deq) 0
Pole Orientation
Pole Distance 30000
Z Angle 0

Figure 34 - Snapshot of the road-configurator application in its current state. The CORTIME VPL and optimization settings can be reached through the container-application interface (not shown), which also supplies file-loading functionality.

The initial development goals were to:

- Define and develop the RoadBoy API.
- Create interop between the RoadBoy API and the CORTIME API, to allow dynamic creation and modification of road geometry in the VPL.
- Create RoadBoy data wrappers for the application UI.
- Create an application interface connecting with the RoadBoy wrappers (in WPF, using the MVVM paradigm).
- Implement the application interface as a plug-in for the DTU container-application.

The application interface goals were to be able to:

- Define basic road geometry (sections, number of lanes, road width, direction of travel).
- Define additional road-elements such as midsections, sidewalks and bike-lanes.
- Set road-classification of all road elements according to CIE standards.
- Define initial light pole configuration (position, distance, height, layout).
- Import trial optics for the optimization of the light distribution.
- Engage/halt optimization of the road lighting setup.
- Wrap UI controls from the CORTIME UI modules, for optimization and analysis.
- Define optimization objectives through the use of the road-standards.
- Define parameter constraints for the optimization of selected optics, pole position, height, distance, and possible layouts.
- Display results from simulation analysis in different ways.

- Output a report of the results and the most optimal choice of optics and pole configuration.

Out of the above objectives, only the last three have not yet been met, but they are expected to be either partially or fully completed by the end of March. The application should by then be able to perform basic optimization of pole-configuration and optics.

The road-lighting application has been validated by optimising a single set of optics to comply with the road standards of a number of fixed but highly different motor-road geometries. Because the interface and API was not fully completed, it was necessary to hardcode the geometries. The results, which have been validated in DIALux, can be seen in the table below. The ability of the CORTIME optimization algorithm to cope with the 70 objectives (all green cells, except the E2 Side Areas, which were always fulfilled) shows that there is ample potential for optimizing both the selection of optics and the geometric layout of light poles, in order to provide optimum usage of the available power.

🟫 Road geometry and requirements
🟩 Fulfilled requirements
🟦 Fulfilled optional requirements

Optic	Standard	Width [m]	Height [m]	Pole Distance [m]	Overhang [m]	Glare Class	Intensity Class	Flux [lm]	Uavg [cd/m^2]	U0	Ul	U0(wet)	TI [%]	E2 Side Areas?	Surround Ratio
DNSG6: G6 and D6 Compliant	DK L7b	7	8	32	-2	D6	G6	4000	0.54>0.50	0.46>0.40	0.46>0.30	0.20>0.15	4.4<7.0	Yes	-
	DK L7b	7	8	35	-2	D6	G6	4500	0.56>0.50	0.46>0.40	0.37>0.30	0.18>0.15	4.8<7.0	Yes	-
	DK L7b	8	9	40	-2.5	D6	G6	5500	0.53>0.50	0.43>0.40	0.38>0.30	0.17>0.15	4.7<7.0	Yes	-
	MEW4	7	8	37	-1	D6	G6	8000	0.78>0.75	0.46>0.40	0.28 -	0.16>0.15	7<15	Yes	0.73>0.50
	MEW4	7	10	48	-2.25	D6	G6	15000	0.79>0.75	0.42>0.40	0.40 -	0.17>0.15	7<15	Yes	0.84>0.50
DNSG4: G4 and D6 compliant	DK L7b	7	8	32	-2	D6	G4	4000	0.57>0.50	0.55>0.40	0.46>0.30	0.19>0.15	5.2<7.0	Yes	-
	DK L7b	7	8	35	-2	D6	G4	4500	0.58>0.50	0.52>0.40	0.38>0.30	0.18>0.15	5.8<7.0	Yes	-
	DK L7b	8	9	40	-2.5	D6	G4	5500	0.54>0.40	0.50>0.40	0.39>0.30	0.18>0.15	5.6<7.0	Yes	-
	MEW4	7	8	37	-1	D6	G4	8000	0.81>0.75	0.52>0.40	0.29 -	0.17>0.15	8<15	Yes	0.71>0.50
	MEW4	7	8	41	-2.25	D6	G4	11000	0.80>0.75	0.43>0.40	0.28 -	0.17>0.15	11<15	Yes	0.76>0.50
	MEW4	7	10	48	-2.25	D6	G4	15000	0.83>0.75	0.49>0.40	0.34 -	0.17>0.15	8<15	Yes	0.82>0.50

5.5. Development of Communication and SMART light platform

Extensive work was put into defining the system architecture. It was clear that the multiport power converter (denoted here as Intelligent Light Unit) needed a communication system (denoted as Komms in figure) to be able to interface with smart battery, external communication systems, and other possible peripherals (sensors alternative communication platforms etc.).

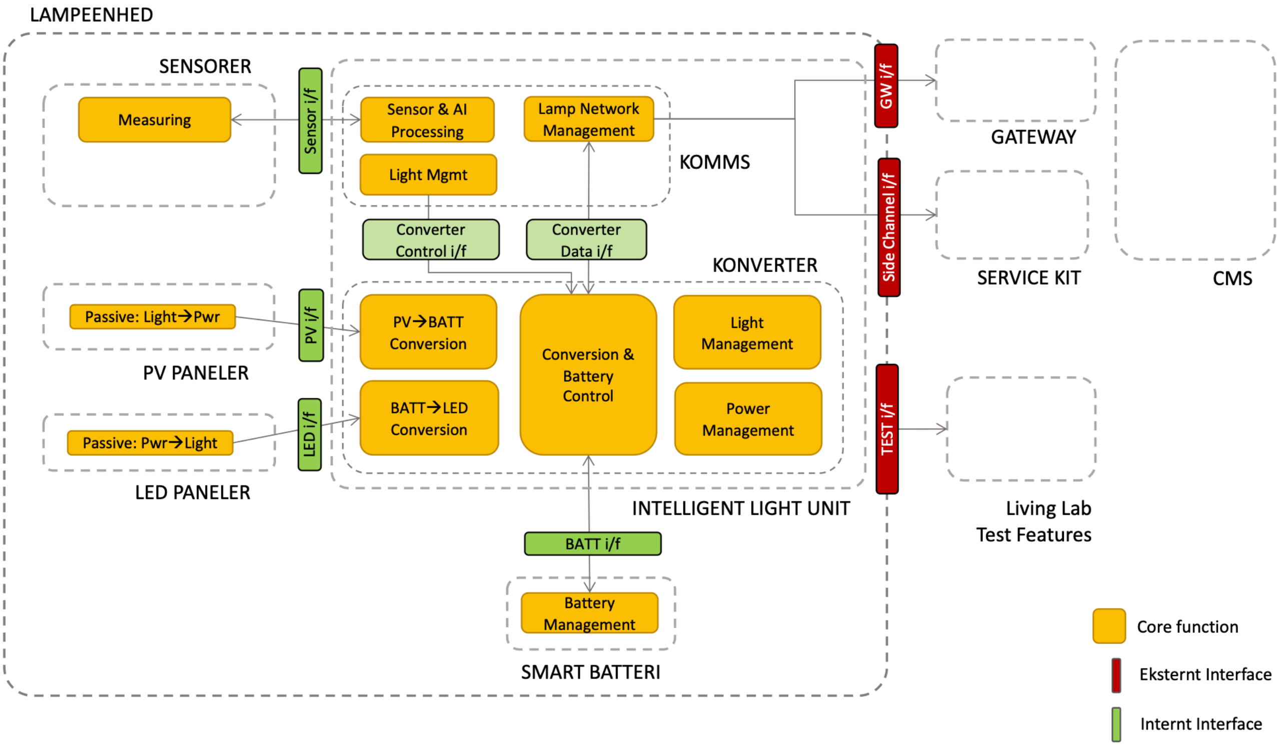


Figure 35 - Overall system architecture

Nordic Firefly designed this platform, FFctrl, that could be able to function as the communication link. It could interface with both the multiport power converter (i2c), the smart battery (RS485) and external communication devices (i2c).

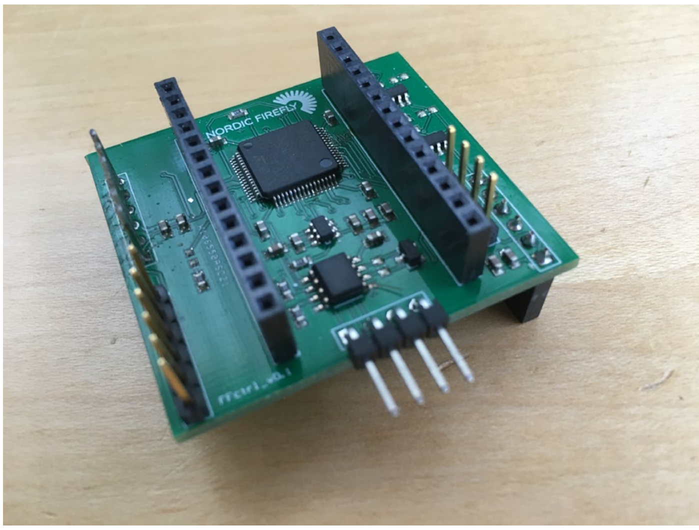


Figure 36 - FFctrl on separate PCB: interface between NFF multiport converter and external communication.

In addition, FFctrl was designed to be able to communicate with an eSave proprietary ZigBee based lighting management system. An interface protocol between Nordic Firefly and eSave was agreed upon so that system variables (Battery SoC, SoH, PV voltages and LED current/voltages etc.) was able to be transmitted though FFctrl to eSave SoC with wireless transmitting to the eSave backend system (see screenshot).

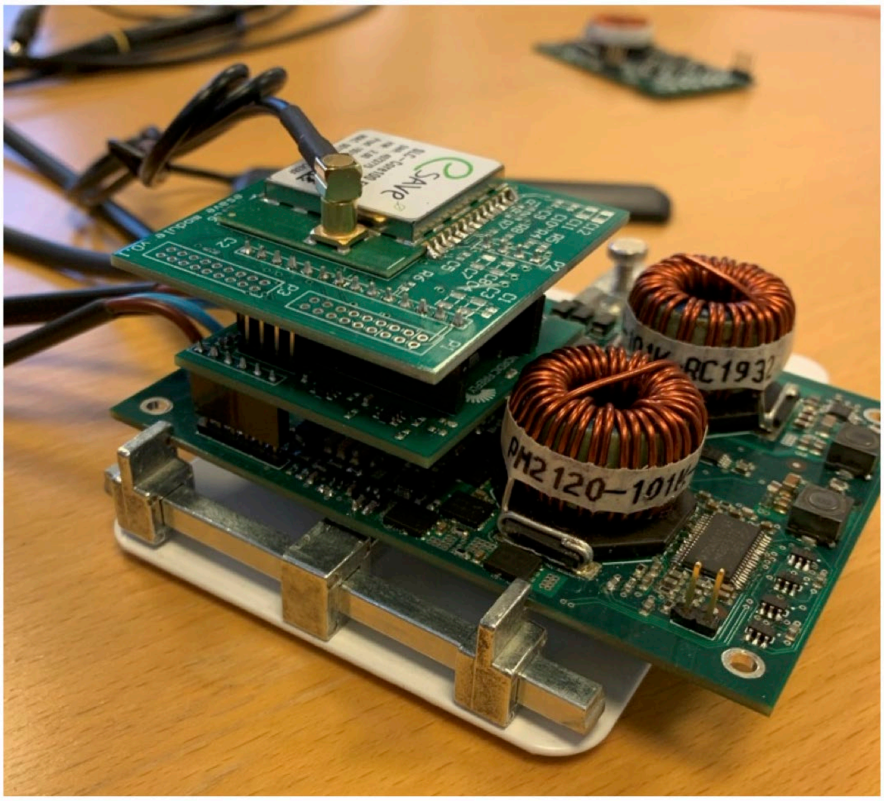
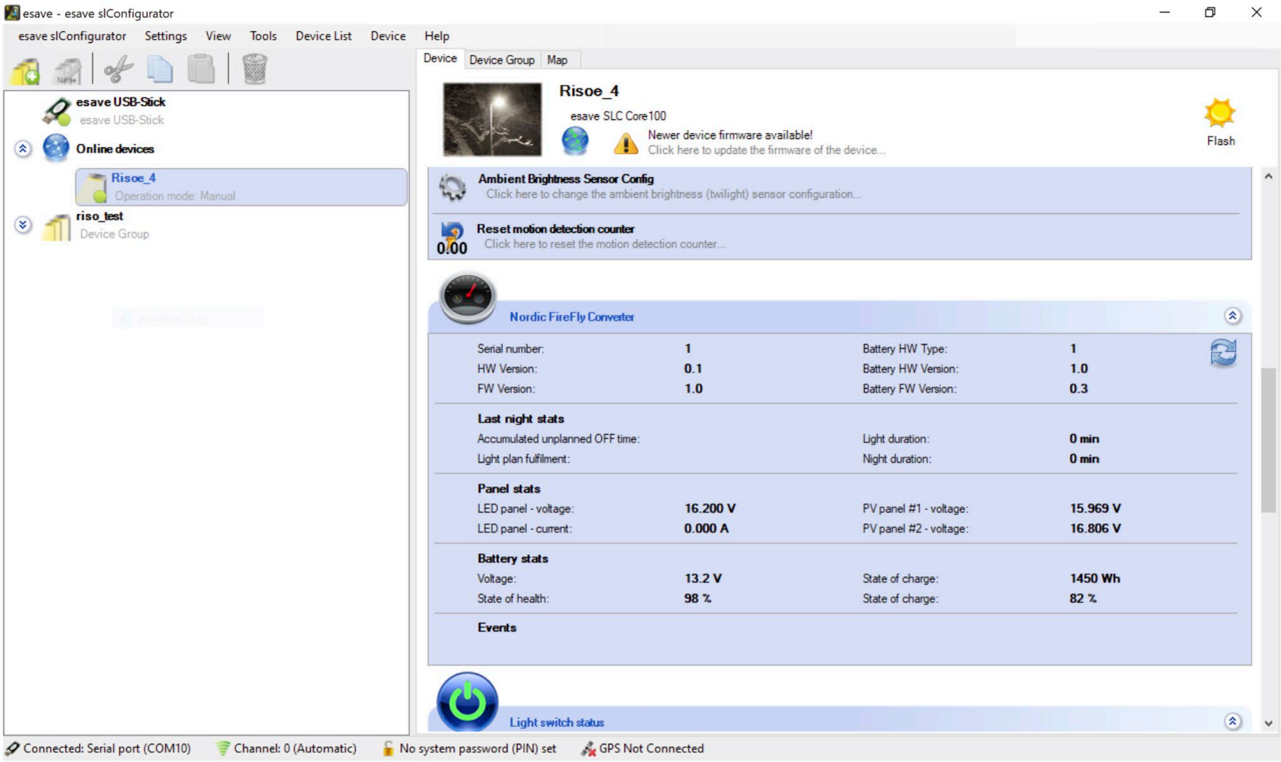


Figure 37 - 4 port converter prototype with FFctrl and PCB with eSave SoC for wireless communication



Risoe_4

esave SLC Core100

Newer device firmware available!
Click here to update the firmware of the device...

Ambient Brightness Sensor Config
Click here to change the ambient brightness (twilight) sensor configuration...

Reset motion detection counter
Click here to reset the motion detection counter...

Serial number:	1	Battery HW Type:	1
HW Version:	0.1	Battery HW Version:	1.0
FW Version:	1.0	Battery FW Version:	0.3
Last night stats			
Accumulated unplanned OFF time:		Light duration:	0 min
Light plan fulfilment:		Night duration:	0 min
Panel stats			
LED panel - voltage:	16.200 V	PV panel #1 - voltage:	15.969 V
LED panel - current:	0.000 A	PV panel #2 - voltage:	16.806 V
Battery stats			
Voltage:	13.2 V	State of charge:	1450 Wh
State of health:	98 %	State of charge:	82 %
Events			

Connected: Serial port (COM10)　Channel: 0 (Automatic)　No system password (PIN) set　GPS Not Connected

Figure 38 - eSave backend configuration software with integrated system variables for SolarDesign.

5.6. Development, test and demonstration of prototype in Danish labs

Figure 39 – SolarDesing lamps installed on Risø Campus for field test.

2 SolarDesign lamps was installed with the full system of NNS batteries and Nordic Firefly converters on Risø campus for testing.

5.7 Development, test and demonstration of 0-series in DK

Figure 40 – SolarGlow installed in Vordingborg Municipality

The Pictures above show the SolarGlow streetlight performing in Vordingborg Municipality. The new and improved system architecture is producing very high light output with excellent homogeneity in the light distribution on the road.

History Data

Sampling period:30Minutes

03-15 - 03-22

Statistical extremum

Max Voltage 45.0 V

Max Current 1.15 A

Max Power 52 W

Max Brightness 100 %

Figure 41 – SolarGlow lamp performance data from Vordingborg installation

The graphs above show the first 7 days of operation showing the first few days the charge in the battery was very low and as the battery charged the light output slow began to reach its full potential providing full illumination 50% of the night and then dimming down to 50% illumination the remaining part of the night.

History Data

Sampling period:30Minutes

03-15 - 03-22

Statistical extremum

Max Voltage 53.0 V

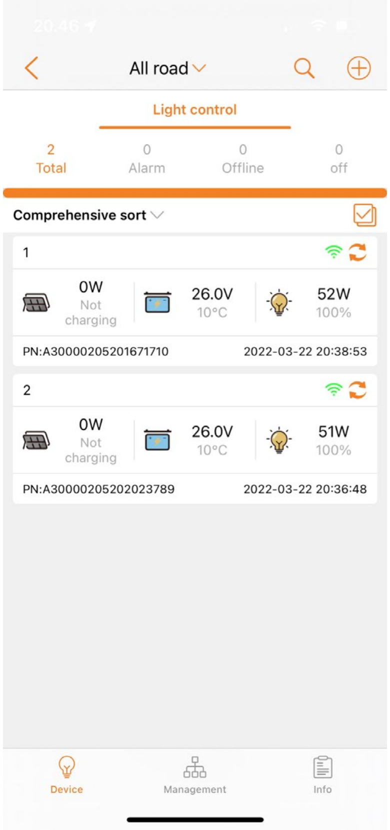
Max Current 4.88 A

Max Power 207 W

Figure 42 – SolarGlow solar panel performance data from Vordingborg installation

The graph above shows the solar panel was challenged the first few days where it was very overcast. In day 4 the panel was able to fully charge the battery. The remaining days the battery charges quickly and power from the panel is reduced as the battery is fully charged.

Both graphs are a direct feed from our monitoring system which is successfully implemented in the SolarGlow lamps and which is now running on an app on iPhone (see screenshot below).



2 Total
0 Alarm
0 Offline
0 off

1
0W Not charging
26.0V 10°C
52W 100%
PN:A30000205201671710
2022-03-22 20:38:53

2
0W Not charging
26.0V 10°C
51W 100%
PN:A30000205202023789
2022-03-22 20:36:48

Figure 43 – App of monitoring system

5.8. Quality, cost and certification

High quality, high reliability and low cost are key parameters for our commercial success with the product. All key components have been thoroughly tested to ensure stable performance.

Production has been set-up with a Chinese manufacturer in Shenzen. The overall cost targets have been achieved.

- the SolarGlow can be produced for 850 - 1000 USD pending upon volume
- the SolarDesign can be produced for 1400 - 1600 USD pending upon volume

We have performed an analysis of relevance of certification in different markets.

There are currently going through CE certification of the product as well as UL38.3 which will allow us to ship and sell the product in our initial target markets. To ensure both quality and cost requirements for the final product and ensure technical solutions that can be CE marked / certified for relevant markets.

5.9 Commercial outcome

Commercially, Living Energy Lighting has identified some sales opportunities, hereof two large potential projects one in Sierra Leone another in Benin, both for the sale of 30.000 SolarGlow streetlights (our low cost solution). The process is not concluded yet, but in Sierra Leone a feasibility study has been carried out and the project is now awaiting final approval from both the Ministry of Finance and Ministry of Energy. For the potential project in Benin 13 SolarGlow has been sold as a trial to verify the technical performance. We expect to sign a contract for at least one of the two projects in 2022. Simultaneously other smaller projects are also being developed in Africa.

In the Nordics our test installations have created interest from private street owners to Gate 21 a joint sourcing initiative among the municipalities in southern Sweden and eastern Denmark. We expect to close the first sales after ending a 6 month test period.

5.10 Dissemination

The project has had several scientific tasks which have been relevant to involve master students in. They have done dissemination in form of theses. The following theses has been made

1. Marina García Agúndez Blanco, Performance modelling and design optimization of a Solar Powered Street Lighting system for delivering light as a service in remote areas - July 2021.
2. Martin Sturdy, Modelling and performance assessment of a Solar Powered Street Lighting product for delivering light as a service - July 2021
3. Luca Morino, Performance and financial modelling of a Solar Powered Street Lighting system for delivering light as a service in remote areas - March 2022.
4. Accuracy Evaluation of Horizon Shading Estimation Based on Fisheye Sky Imaging, Alvarez Mira, D., Bartholomaus, M., Poulsen, P. B. & Spataru, S. V., 20 Jun 2021, Proceedings of IEEE 48th Photovoltaic Specialists Conference. IEEE, p. 2052-2059 (Conference Record of the IEEE Photovoltaic Specialists Conference).

Commercial project results are expected to be published after the project where sales are expected already to be created.

6. Utilisation of project results

The technical solutions developed in the project are all impressive with very high quality. The test results are also good, and the 2 developed lighting products are brought close to the market in the project with test installations in Vordingborg and 13 in Benin giving a small revenue in the order of 150KKR, mostly for export.

Living Energy Lighting will be selling the lamps and will incorporate technology from Nordic Firefly and Nerve Smart Systems to the extend it is commercially viable. The added benefits of the NSS battery in stability and lifetime are obvious, thought the price is also higher than many lower quality batteries with the same capacity. So the use of the components will be dependent of the business model use in the given case and what the costumer is willing to pay. For the light-as-a-service business model the NSS battery will give some advantages over cheaper solutions though on the upfront cost is expectedly too high when selling the luminaires.

The competitors on especially the African market are low-cost Chinese solutions which is also why the project in the end changed towards making both the SolarDesign and the SolarGlow solution, where the latter are a much more cost-efficient solution enabling participation in mass market tenders, where Living Energy Lighting is already participation in 2 about sales of 30.000 luminaires.

The luminaire solutions is also exploited sold in in the Nordics where the test installations have created interest from private street owners to Gate 21 a joint sourcing initiative among the municipalities in southern Sweden and eastern Denmark. We expect to close the first sales after ending a 6 month test period creating fully solar powered street lighting for the local market.

No PhD has been involved in the project, though 4 master students have worked on technical topics from the project where especially the energy modelling was highly geared by this effort. Also, post.doc. work was done at DTU Elektro to investigate the design of a switched capacitor converter (SC) topology for MPPT harvesting which looks very promising though more research is needed for commercialization of such a solution which will be exploited in other research projects in the future.

7.Project conclusion and perspective

I the project a variety of technologies have been developed.

Photovoltaic panels have been developed for the two lamp systems based on a 24V architecture optimized for energy harvesting with high efficiency also at low-light conditions.

A specialized 3-port converter incorporating the learnings from several prototypes was developed and realized. Now with one single high power MPPT harvesting channel that can fit into both SolarGlow and SolarDesign (with paralleled PV-panels). The converter has ultra heigh efficiency of energy conversion from solar panels to battery (above 96% in general, and 87-95% at low light conditions) and also above 96% conversion efficiency converting energy from battery to LED at night.

Research was conducted at DTU Elektro Electronics Group in the design of a switched capacitor converter (SC) topology for MPPT harvesting and a prototype was demonstrated with a very high efficiency (>98%) and it was shown that SC novel SC converter topologies can be usable for building a switched mode converter for MPPT harvesting.

A communication system (FFctrl) was developed on top of Nordic Firefly’s 3-port converter unit to enable interfacing with both the multiport power converter (i2c), the smart battery (RS485) and external communication devices (i2c). In addition, FFctrl was designed to be able to communicate with an eSave proprietary zigbee based lighting management system, which was successfully demonstrated in the project.

A battery solution was developed by Nerve Smart Systems for the lamp system which required the battery voltage to be switchable between 14V DC and 26V DC. This was also a requirement to achieve the optimal efficiency of the NFF MPPT. Prototypes of battery modules based on 26 LiFePo4 cells providing approximately 2000 Wh of storage capacity was realized.

2 SolarDesign lamps and 1 SolarGlow lamp was installed at DTU Risø campus with high resolution data monitoring implemented for performance monitoring. In the end of the project 2 SolarGlow lamps was installed at potential customers at Vordingborg Municipality.

A software solution was developed (RoadBoy) for both dimensioning the lamp systems for it given installation point with respect to ensuring the solar cell system is properly dimensioned for delivering sufficient lighting, but also for ensuring compliance of the lighting to the relevant street lighting standards.

The project was disseminated in 3 master project reports and 1 peer reviewed conference contribution for the IEEE 48th Photovoltaic Specialists Conference. Commercial communication will come after the project.

Commercially, Living Energy Lighting has identified some sales opportunities, hereof two large potential projects one in Sierra Leone another in Benin, both for the sale of 30.000 SolarGlow streetlights The process is not concluded yet, but in Sierra Leone a feasibility study has been carried out and the project is now awaiting final approval from both the Ministry of Finance and Ministry of Energy. For the potential project in Benin 13 SolarGlow has been sold as a trial to verify the technical performance. We expect to sign a contract for at least one of the two projects in 2022. Simultaneously other smaller projects are also being developed in Africa. In the Nordics our test installations have created interest from private street owners to Gate 21 a joint sourcing initiative among the municipalities in southern Sweden and eastern Denmark. We expect to close the first sales after ending a 6 month test period.