Final report

1. Project details

Project title	Skalerbar elektronik til plastsolceller
File no.	64018-0167
Name of the funding scheme	EUDP
Project managing company / institution	infinityPV ApS
CVR number (central business register)	36420367
Project partners	infinityPV ApS
Submission date	23 May 2022

2. Summary

2.1 Summary (English)

Plastic solar cells are manufactured and marketed today on Danish soil as a result of many years of public investment in research and development. The plastic solar cell has some unique characteristics that make, especially the electronics that are necessary for conversion to mains power unique. The way power is built up in a plastic solar cell is in voltage rather than current and this opens up new opportunities in manufacture and use of the technology. With this project, infinityPV ApS wanted to fully mature the electronics so that the technology becomes widely applicable. Panels in arbitrary size are today manufactured on thermoplates and can be used for carports, bicycle sheds, conservatories, covered areas, greenhouses, noise barriers along roads, etc. and can easily meet varying requirements for shading / light penetration. The purpose of the project was to achieve the same degree of scalability in the electronics that is necessary for the energy to be harvested and used in the system and to obtain the necessary approvals. We have developed an approach for scalable electronics based on a master-slave matrix concept. As proof of concept for this approach we designed and built two scalable power converters for plastic solar panels: 1) a stand-alone 60W battery charger and 2) a grid-tie 150W inverter. The converters are based in master-slave modules that can be configured, within its maximum power rate, to accept different number of panels with different levels of power (arbitrary size and number of panels). We designed and also built a common enclosure for our new line of converters based on scalable electronics “infinityPV POWER LINE”. Units from both converters has been sent to external certification laboratory to ensure and demonstrate the designs are compliant with the safety and quality standards. The POWERLINE was planned to be launched as commercial products in Spring 2021. COVID-19 led to very large delays on the certifications while the project developments of the electronics had been completed before the effects of COVID-19 took effect. Everything has been prepared for marketing and the certification according

to IEC 62109-1 and 62109-2 has been obtained after some modifications to the original design. We are awaiting the final certifications on electromagnetic interferences and have had to make a number of modifications to reduce the noise levels sufficiently to meet the standard.

2.2 Summary (Danish)

Plastsolceller bliver i dag fremstillet og markedsført på Dansk jord takket være en langsigtet offentlig investering I forskning og udvikling. Plastsolcellen har nogle unikke egenskaber der kræver ligeledes unikke egenskaber af den elektronik der skal omdanne den høstede solenergi til elektrisk energi in el-nettet. Den made hvorpå effekt opbygges i en plastsolcelle er gennem øget spænding snarere en strøm. Dette åbner op for nye muligheder indenfor fremstilling og anvendelse af teknologien. Med dette projekt ønskede infinityPV ApS at modne elektronikken således at teknologien kunne udbredes. Solcellepaneler med en vilkårlig størrelse fremstilles i dag på termoplader der anvendes I carporte, cykelskure, udestuer, overdækkede arealer, drivhuse, støjværn langs veje osv. Det er også muligt at opnå variable skygge for lyset. Projektets formal bestod i at opnå det same mål af skalerbarhed for elektronikken som vi i dag har for solcellen samt at opnå de godkendelser der er påkrævet for markedsføring. Vi har udviklet en skalerbar elektronik tilgang baseret på et master-slave matrice koncept. For at vise anvendeligheden af denne udvikling har vi designet og bygget to skalerbare konvertere: 1) en ”stand-alone” 60W batteri lader samt, 2) en net-tilsluttet 150W inverter. De to konvertere er baseret på master-slave matrice konceptet og kan konfigureres alt efter den ønskede effekt til at være tilsluttet et forskelligt antal solcellepaneler med (arbitrært i størrelse og antal). Vi designede og byggede et kabinet der er fælles for begge typer af systemer og har givet dem navnet ”POWERLINE”. Flere enheder af begge typer er blevet sendt til et eksternt certificeringslaboratorium for at opnå de nødvendige godkendelser og sikre at de er i overensstemmelse med de nødvendige krav. Vi planlagte at markedsføre POWERLINE umiddelbart efter afslutningen af projektet og påregnede at dette ville finde sted i foråret 2021. COVID-19 gav dog anledning til store forsinkelser med certificering til trods for at vi havde afsluttet vores aktiviteter førend effekten af COVID-19 oplevedes. Vi har i løbet af 2021 opnået certificering i overensstemmelse med standarderne IEC 62109-1 and 62109-2. Vi har måttet lave få ændringer for at opnå disse. Her ved projektets afslutning afventer vi stadig certificeringerne der er knyttet til elektromagnetisk interferens og har måttet gennemføre en del ændringer for at prøve at reducere støjen.

3. Project objectives

The objective of the project was to to achieve the same degree of scalability in the electronics that the present in plastic solar cell production. For achieving this main goal, we have based our designs in a modular approach.

The modular design approach is already applied to other areas of power electronics, specially where redundancy is needed because they are part of a critical application or where a very high voltage or high current is shared between the different modules. However, it has been never applied before to field of plastic solar cells.

Both the battery charger and the grid-tie inverter are developed under this modular concept in this project. We have demonstrated the use of this design approach allows to solve the two main challenges in power electronics for plastic solar cells: 1) high ratio voltage/current and 2) high degree of scalability.

We developed a generic modular implementation of the modular concept based on a matrix of modules that work coordinately. In that matrix some modules act as slaves and other as masters. Masters oversee

more complex tasks, as control/safety strategies or user interactions. While slaves just act as power converters “bricks” which, under the master supervision, share part of the total power. The modular concept is shown in Figure 1.

An important and key aspect of this modular implementation is the possibility of voltage sharing among the different modules of the matrix. The voltage sharing allows the converter to bear a high input voltage using components rated to lower voltages and therefore cheaper and more common in the market.

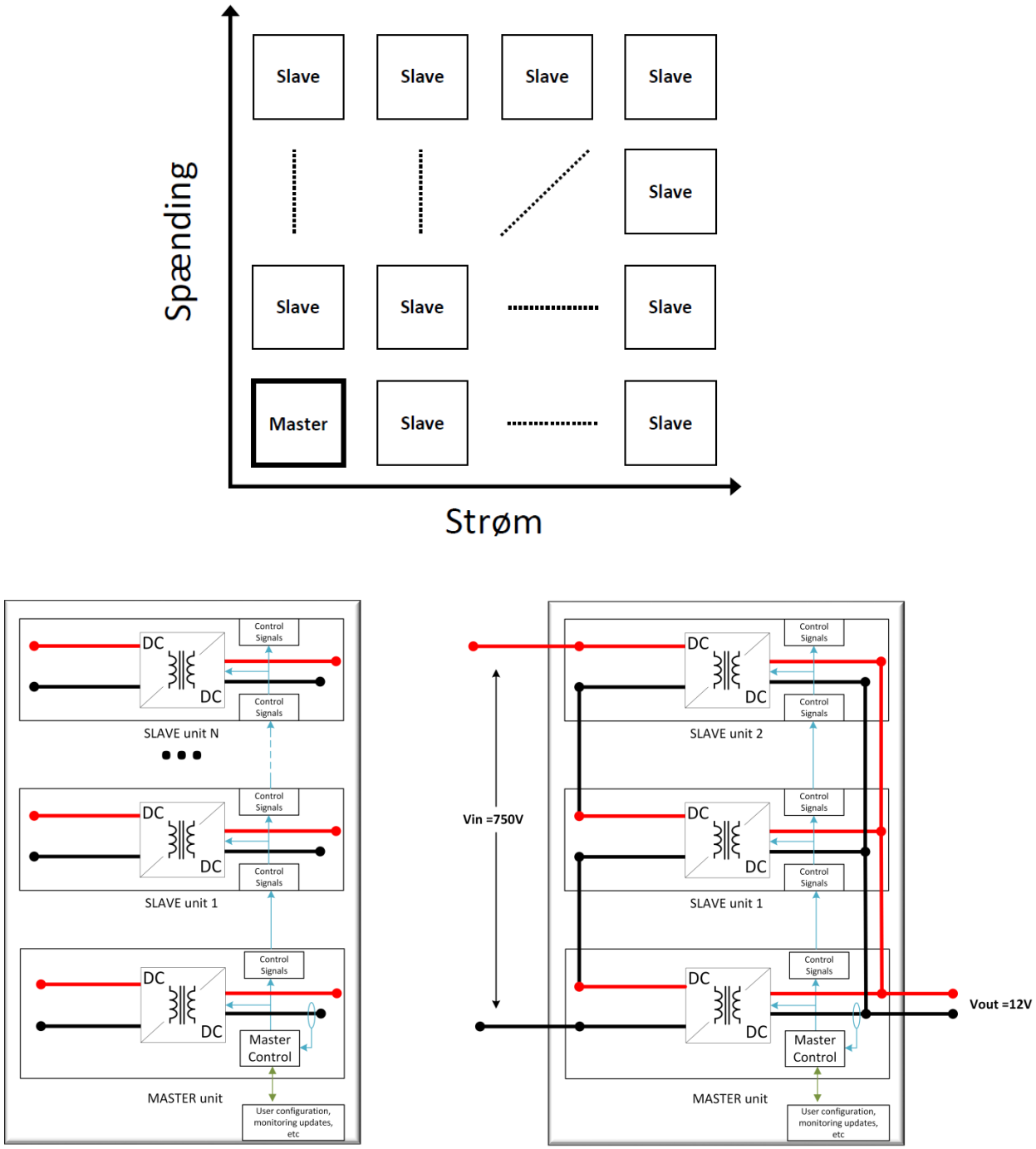

Figure1. Top: illustration of the matrix concept with one "master" and an arbitrary number of slaves. Left: The modular DC / DC converter concept, a “master” constitutes the basic unit and other units can be connected in series or parallel as “slaves”. Right: An example where 3 units (à each 250 V / 15W) are connected in series on the input side and in parallel on the output side.

This implementation has demonstrated to offer a high grade of scalability. For example, in the battery charger the final customer can order different sizes and different number of plastic solar modules. The modular implementation of the charger allows to plug only the number of needed slaves for the customer

selection. The charger still has the same functionalities, i.e., battery charge optimization, safety, and user interaction, but internally it only contains the strictly needed power modules for the application.

Figure 2 shows an internal view of the battery charger. The battery charger can place up to 5 slave modules of 12W and up to 180V each one. Each slave module (vertical boards in the picture) can be configured to accept a maximum different voltage in the input, up to 180V, and it can be plugged or not according to the customer needs. Independently of the number of plugged slave board the master (red PCB in the left corner) will offer same control/safety and interaction functionalities.

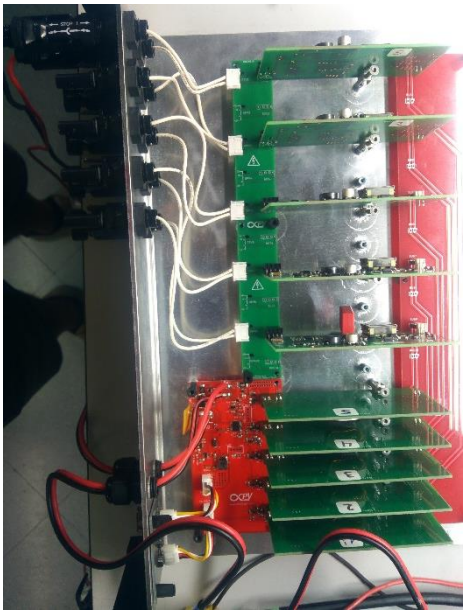

Figure 2. Internal view of the battery charger developed in the project

Another important energy technology we have implemented and demonstrated is the use of LLC converters as topology used for slave power modules. The LLC topology offers a high efficiency with minimum components, and because it uses a transformer as core of the topology, it offers galvanic isolation between input and output. The galvanic isolation is needed for safety reasons but also key for the slaves to be able to share the total input voltage having their secondaries connected in parallel.

We have designed and implemented different LLC converters for the project, all of them working as slaves power modules in the matrix. They have shown to be an excellent option for stepping down the high voltage present in plastic solar modules, which minimum components, size, and cost. Figure 3 shows the LLC converter developed to be used as slave module in the battery charger, the number of components is very low, the maximum height for the board is 8mm and it acts as DC transformer, converting the DC high voltage characteristic of a solar module to a low voltage DC characteristic at its output.

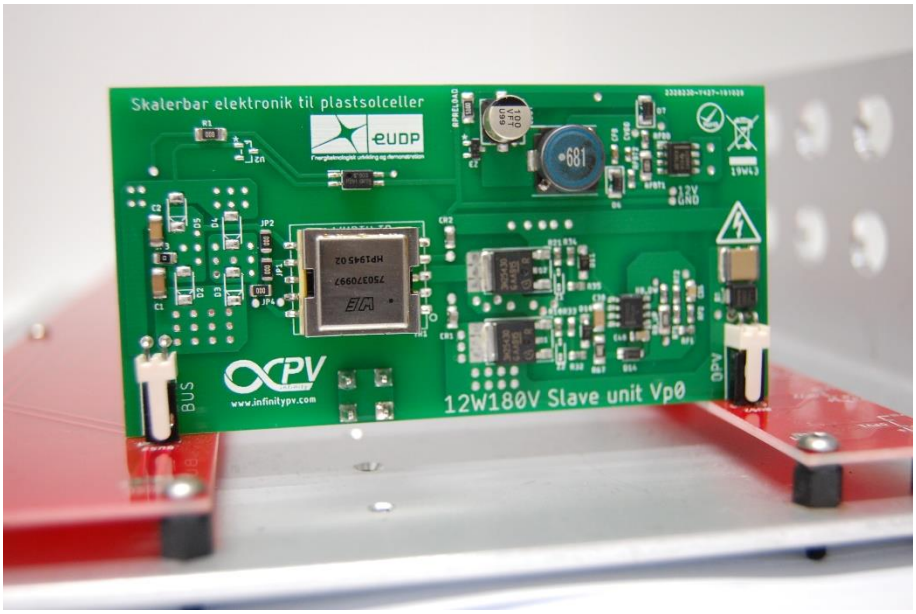

Figure 3 LLC converter used as slave module in the battery charger

We have found during the project that the use of the LLC topology offers another important advantage working with high input voltages, which require a high level of isolation, as it is the case with high voltage plastic solar modules. For getting a high level of isolation between primary and secondary the windings must be placed separately, e.g., in a split bobbin, but generally this separation leads to a very high leakage inductance of the transformer which is normally seen as a source of power losses. However, the LLC topology makes this leakage inductance part of the LLC circuit, taking advantage of it.

We have demonstrated this clear advantage during the design of the LLC transformer for the grid-tie inverter slave module. Figure 4 shows this module during one of the temperature tests, in the center of the picture the LLC transformer can be seen. The separation between the 2 windings (in yellow) can be appreciated. This LLC transformer of only 180W can work with input voltages up to 900V in the primary, offering a galvanic isolation between primary and secondary of 6kV, which was needed during the certification safety tests.

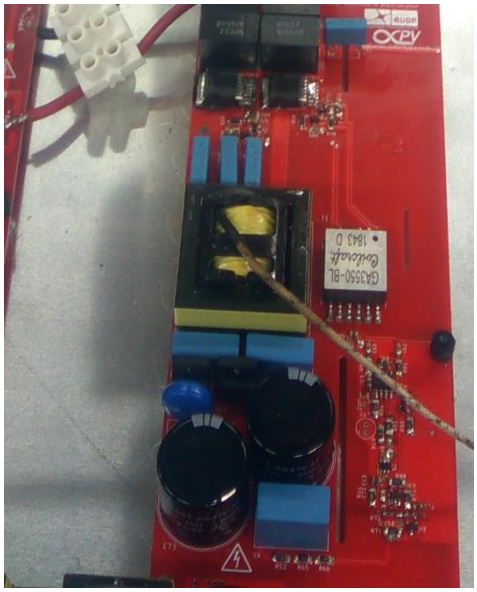

Figure 1. Picture of the LLC transfomer used as slave module in the grid-tie inverter

4. Project implementation

The project evolved on time with the initial plan until March 2020. After that point in time the implications of COVID-19 affected the project timeline.

The LLC converters used as slave modules in the master-slave matrix were developed and tested by mid-2019, including the development of our own customized LLC transformers. Also, the master module and motherboards for the charger were ready and tested for that time. The slave and master boards for the grid-tie inverter were developed and almost tested by March 2020. Tasks related with the design and building of the common cabinet for both products were ready before COVID-19 crisis.

In March 2020, milestones M1 and M2 were completed. M3 was almost completed except for the implementation of the slave module for the inverter. The documentation tasks for M4 (documentation and certification) such as user manuals, labels, engraving files… were ready. Market study and product launch plan (Milestone M5) was prepared too.

However, the COVID-19 crisis created large delays in delivery time of components and printed circuit boards. Also delays in the external certification tasks, with the laboratories stopped or working partially for long periods. Last robot welded enclosures were received with long delays. A few months later, stock problems started in many of the components used during the design.

Another source of not expected problems was our lack of experience with the electromagnetic compliance of circuits. The project included a specific milestone (M4) about the certifications of the products under the European standards for electrical safety and electromagnetic compliance (EMC).

Once the external laboratory for certification started to work again by end of summer 2020, the charger was sent to it and the certification tests were planned in a crowded and delayed agenda. The main electrical safety tests were passed soon for the charger. However, during the EMC tests the charger failed and the needed improvements for the circuits took us more than usual due to the lack of many components and due to our lack of instruments for measuring the EMC levels.

We also faced some problems due to the special setup needed for testing of our products. Both the charger and the inverter have several inputs at high voltage and low power. The testing requires to simulate in the laboratory the electrical behavior of the plastic solar modules, using controlled high voltage power sources. In many cases, we had to advice the technicians at the certification laboratory since our setup was a new case for them.

The inverter had even more delays due to some stability problems of the last prototype, but final they were solved, and it was sent to the certification laboratory in June 2021. The electrical safety standard was also passed without problems. Here, we must remember that our grid-tie inverter has a power of 150W only, but due to the high voltage DC inputs, it must pass the same level of safety that multi-string inverters, that typically are rated for much higher power (> 5kW).

After several modifications and new EMI filters added, the certification for the battery charger is almost finished, having passed the conductive EMC tests, and missing only the radiative EMC tests. The inverter is still in the conductive EMC certification tests.

5. Project results

The original objective of the project was almost obtained. We have demonstrated the concept of power electronics scalability to fit the expected scalability in the plastic solar modules. We have implemented this concept in two real products for plastic solar modules, which just need some improvements in their EMC behavior to be ready for being launched to the market. The main reasons for this delay were COVID-19 crisis and the following scarcity of stock in electronic parts. These two reasons were difficult to predict and to mitigate. However, the delays experienced because EMC certification problems show that we underestimated the effort and time needed for developing a power converter working at high frequency and high voltage within the EMC standard limits.

5.1 Technological results

Chasing the project milestones, we have obtained remarkable technological results among we should highlight:

1) **Demonstration and implementation of the scalable matrix concept**. The project allowed us to apply this concept to the plastic solar modules problem. We materialized this concept, choosing the best topology and size for the slaves and master units, and implementing them. Furthermore, we implemented cabinets, layout, and assembly procedures to accommodate this electronic matrix in a real product functional and safe for the customer.
2) **Development of LLC converters applied to plastic solar photovoltaics**. We have customized and used these kind of power converters as slave units in the scalable matrix. They offer a high level of galvanic isolation with high efficiency and minimum number of components. Working at high frequency they can be designed with very small components, which make them great candidates to be integrated in the plastic solar module, offering the output of the module at low voltage. They are the perfect partner for high voltage plastic solar modules. The project allowed us to study, design and manufacture our own LLC transformers which are the core component of the LLC converter.
3) **Multi-unit communication protocol**. One of the tasks of the project was to provide a friendly user interface to access to the developed products. Since both products follow the

scalable matrix concept, they consist of different slave/master units, and we had to implement a simple communication protocol among different units, where some of them are using ultra-low power consumption microprocessors, to save energy and cost.

4) **Aluminum enclosures** were designed focus on mass production methods: prepared to be robot welded and laser engraved.

5.2 Commercial results

The commercial results produced during the project can be summarized:

1) **infinityPV Stand-alone battery charger 75W**. Based on the scalable matrix concept, it is designed for 12V battery or battery packs, it offers up to 5 DC inputs for plastic solar modules, each of them can be configured for input rates from 60-180V and up to 12W of power. The charger optimizes independently the energy harvesting from each input, implementing a MPPT algorithm for each input, as well as safe charging, loads control and user interfacing. The charger has successfully passed the IEC Standard 60335-1 about electrical safety and partially the IEC Standard 61000-6-1 and 61000-3-1 about EMC. The user manual and launching documentation has been completed and it is ready to be released as new product in our website.
2) **infinityPV Grid-tie microinverter 150W**. Based on the scalable matrix concept, it is designed as grid-tie microinverter to inject the harvested energy from solar cells directly to the residential AC utility. It offers up to 10 DC inputs for plastic solar modules, which can be configured to accept different lengths and combinations of multiple solar inputs, while the total input can accept input voltages up to 900V and 180W of DC power. The slave section ensures the galvanic isolation between the high voltage inputs and the AC output, while the master section of the grid-tie inverter guarantees the control and mechanism required by the electrical standard for a safe current injection into the AC grid. The inverter has successfully passed the IEC Standard 62109-1 and 62109-2 about electrical safety and the tests for IEC Standard 61000-6-1 and 61000-3-1 about EMC are still in process. The user manual and launching documentation has been completed and it is ready to be released as new product in our website.
3) **DC transformer 180V15W**. Based on the development done for slave units on the scalable matrix concept, we have prepared a simple evaluation board, that contains a self-supplied DC transformer. It can be used as a step-down stage to transform the high-voltage DC characteristic of the plastic solar module into a low-voltage equivalent one at the output. This product is sold only as evaluation board, and it is oriented for hobbyists, integrators and specific customers who want to test the plastic solar modules.

5.3 Target group and added value

At the present PV market situation, OPV modules fit in the potential BIPV (Build Integrated Photovoltaics) market. The scalable electronics concept allows as to widen the offer in sizes/shapes, which will provide us a commercial advantage.

We have identified two initial groups of customers for launching the product line:

- Early adopters' individuals: customers that want low weight, no metal structure, customized size and easily integrable PV solutions for small applications.

    - Typical profile: owners of farms or houses with enough space for car park areas, workshop, sheds… DIY-lovers or handyman people.
- Professional PV integrators: as the BIPV market study shows there is a knowledge gap between integrators (architects, builders, furniture designers…) and the PV element manufactures. This is a niche of potential customers who cannot find in the traditional PV market what they are looking for.
    - Typical profile: companies or professionals who wants to introduce new concepts in their designs. They have already introduced some new concepts in its portfolio.

The final target group is everyone who uses electricity. Everyone who is building, maintaining, or repairing covered outdoor areas such as carports, terraces, canopies, and outdoor sheds where electricity is desired to be added. They will be able to feel that this is achieved and that they are doing something good for the environment and introducing sustainable energy into the system. The most obvious added value is that the roof solution can also be a solar cell that can harvest energy and either store it or supply it to the electricity grid.

5.4 Results dissemination

The project results will mainly be disseminated through marketing material and product / application data sheets. It will also be communicated through our website and through workshops in DIY stores, etc. When the products are launched.

6. Utilisation of project results

6.1 Utilization of the technological results

The technological results obtained in the project are a great value for our company in terms of acquired knowledge. Once demonstrated the scalable matrix concept, it can be export to other products.

Having seen the present situation about scarcity of components, the possibility of share voltages or currents by multiple smaller modules, open the possibility to replace the use of scarce and expensive parts by several common parts which work collaboratively.

The know-how acquired about small LLC converters design is clearly and advantage to offer more integrated and safer power electronics for plastic solar modules. At the same time this knowledge can be applied to many other power applications where a low power supply must be extracted from a high-voltage DC source.

The learning and development about EMC filters and design practices for avoid EMI problems will be definitely applied in our future designs.

6.2 Utilization of the commercial results

The commercial results will be use by infinityPV. The project results give us a unique chance to quickly enter the market with specific and certified power electronics for plastic solar modules. The lack of these electronics was a clear barrier for plastic solar modules.

After releasing the products to the market, it is planned to increase the production gradually. When the volume of the technology is increased and this is linked to future exports, the potential for a very large production company is very realistic.

6.3 Competitive situation in the market

The most dominant competitor is the electricity grid itself. For the traditional customer, if it is estimated that it is easier to buy electricity from the grid, no solar cell solution can compete.

The technology thus addresses the users who have a desire to install a solar cell solution. Here the biggest competitor is silicon solar cells which are cheap and very established. However, the plastic solar cell is very light and flexible and can easily be integrated into roofing sheet solutions based on polycarbonate. This is a clear advantage, and the silicon solar cell cannot be used here. The plastic solar cell solution is also very light and can be used on roof surfaces where the weight of conventional silicon solar cells does not allow integration.

6.4 Entry or sales barriers

The underlying goal of this project is to overcome one the barriers for plastic solar cells to enter the market, i.e., solve the lack of specific and certified power electronics for its use in commercial applications.

Therefore, the commercial results of the project are breaking this technological barrier. However, as other emerging new energy technologies, plastic solar cells still have barriers to enter in a market dominated by the grid electricity itself and silicon solar cells as main solar alternative. Cost of the final electricity is seen as the clearest barrier, but this variable is clearly affected by the volume of production and the cost of the alternative power source.

The launching of certified power electronics for plastic solar modules will increase the volume production of plastic solar modules, leading to a cost reduction. It will also help to demonstrate the use of plastic solar modules for generating electricity in places where other alternatives are not possible.

6.5 Contribution to energy policy objectives

a) **Security of energy supplies**: The project ensures that the plastic solar cell can contribute to electricity production through accessibility for everyone. We estimate that we will be able to sell 20,000 square meters of thermal plates with plastic solar cells already in the year 2023 for carports, outdoor sheds, and covered terraces alone. This corresponds to approx. 1 MWpeak installed power. We will start our marketing in Denmark but soon expect to address the European market followed by the rest of the world in terms of the differences.

b) **Independence of fossil fuels**: The plastic solar cell presents, like any other solar cell technology, that the energy produced is sustainable and free of fossil fuels. Each MWpeak installed represents approx. 1 GWh (in Denmark) sustainable electricity.

c) **Climate and environment**: The production of the plastic solar cell takes place at very low temperatures and very quickly. Typically, at temperatures in the range 90-140 ^{o}C. The production speed is typically 20 meters per minute, thus the energy consumption during the production of 1 square meter of plastic solar cell is very, very low. This also means that the plastic solar cell, despite its low performance, has a very short energy payback time. The materials used in the production are, except for a few, completely non-toxic (most inks are based on alcohol and water). In-depth studies have been made of both recycling and impact on environment, e.g., if the technology fails and the materials are emitted to rainwater and soil. The conclusion from these studies was that the plastic solar cell does not pose any real risk compared to e.g., technologies involving cadmium, tellurium, etc. One of the main conclusions was also that it pays to recycle the materials in the solar cell (this also applies to all PV technologies). The plastic solar cell is thus a climate and environmentally friendly technology that can be easily integrated into a system and at the same time is easy to dispose of (by incineration) with material recycling as an option.

7. Project conclusion and perspective

This project has demonstrated that scalable power electronics is a possible solution to build specific and certified power electronics for plastic solar cells. The scalable matrix concept for the electronic design allows the power converter to adapt easily to the desired DC input voltage and power from the plastic solar module.

The plastic solar modules present, unlike other PV modules, a high voltage/current ratio which makes impossible the use traditional power converters with them.

We have implemented the scalable matrix concept through two commercial products which are the first specific and certified power converters for plastic solar cells:

- infinityPV Stand-alone battery charger 75W, a solution for harvesting the energy from plastic solar modules and store it in a 12V battery or battery pack.
- infinityPV Grid-tie microinverter 150W, which feeds directly into the grid utility the energy generated by the plastic solar modules.

These two products are based on the scalable concept, and they allow to work safely with plastic solar modules up to 900V but low power. In that sense they are unique in the world. The products are ready to be released, just missing a few EMC tests to be passed.

The development of these products to their final stage, including the certification tests and the preparation for low volume mass production, has given us a great know-how in many challenging areas, that will be used in our future developments. The efforts done in developing our own transformers or debugging the EMI problems found in these products are great values for future products and for solving future problems in large volume production.

The next step for these products is to face the large volume production. From the technological point of view, this includes to prepare optimised assembly and quality test lines. Scalability offers a great flexibility for the customer choice about number of inputs or power and voltage at each input, so it involves creating agile assembly procedures. From the commercial point of view, it needs to ensure the components and material flow which these days is specially challenging.

All in all, the project results break an important barrier to the market for plastic solar cell. We have produced and almost released the first specific and certified power converters for plastic solar cells.

It will affect positively to the perception about plastic solar cell in the market, demonstrating its easy and safe use.

8. Appendices

- Add link to relevant documents, publications, home pages etc.
  - infinityPV Stand-alone battery charger 60W installation and operation manual
  - infinityPV Grid-tie microinverter 150W installation and operation manual
  - Market study and product launch plan
  - Test report for Grid-tie microinverter IEC 62109-1 and 62109-2 Certification.