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# The development of a resource-efficient photovoltaic system

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**This paper presents the measures taken in the demonstration of the photovoltaic case study developed within the European project 'Towards zero waste in industrial networks' (Zerowin), integrating the D4R (Design for recycling, repair, refurbishment and reuse) criteria at both system and industrial network level. The demonstration is divided into three phases. The first phase concerns the development of a D4R photovoltaic concept, the second phase focused on the development of a specific component of photovoltaic systems and the third phase was the demonstration of the D4R design in two complete photovoltaic systems (grid-connected and stand-alone). This paper includes a description of the installed photovoltaic systems, including a brief summary at component level of the lithium ion battery system and the D4R power conditioning system developed for the pilot installations. Additionally, industrial symbioses within the network associated with the photovoltaic systems and the production model for the network are described.**

## 1. Introduction

Photovoltaic (PV) systems are made up of a variety of components (Figure 1), divided into PV modules and the balance of system (BoS), which includes controllers, batteries and inverters and accessories such as solar trackers, wires, fuses and so on. Energy that flows through a power system necessarily runs through a variety of devices and wires between the system's components. PV systems can be further classified as

- grid-connected PV systems (also called on-grid systems)
- off-grid PV systems (also called stand-alone).

Due to new market requirements and legal frameworks such as incentives for solar energy self-consumption and net-metering, this distinction between on-grid and off-grid systems concerning back-up systems is becoming invalid. Nowadays, a growing number of grid-connected PV systems that include energy storage are being developed, and therefore hybrid or mixed options can be considered. It is probably better to distinguish between systems where PV generation is injected to the grid and those in which PV generation is consumed on-site.

This is the approach followed in the Zerowin (Towards zero waste in industrial networks) project, since it focuses on an industrial environment where access to the grid is granted. The distinction of PV systems is then understood as follows.

- A grid-connected system is a PV system that is able to inject and export electricity into the utility grid.
- A stand-alone system is a PV system that cannot inject into the grid and all the PV generation is consumed on-site. The grid is then considered as a back-up system whereby electricity is taken from the grid when the batteries are discharged or in the event of poor PV generation.

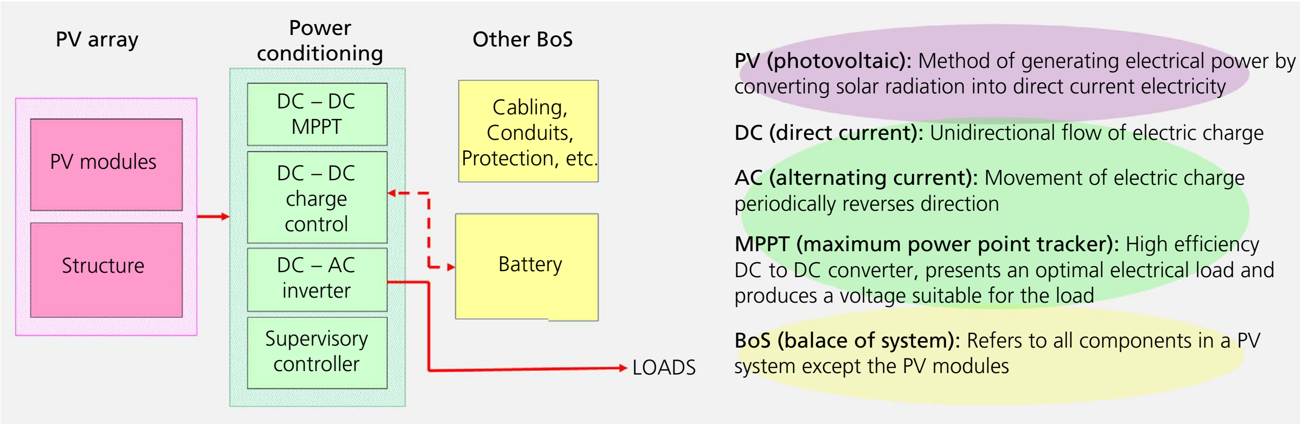


**Figure 1.** Basic characterisation of a PV system, where the battery will be only present in applications with energy storage (adapted from Arranz *et al.* (2011))

The PV sector is growing rapidly and will continue to do so. As reported by the European Photovoltaic Industry Association (EPIA) (Masson *et al.*, 2012), in 2010 the total cumulative PV capacity installed worldwide was 40·67 GW, in 2011 it grew to 71 GW and by the end of 2012 it reached 102 GW, with an annual generation of at least 110 TWh of electricity. Within this context, Europe has more than 50% cumulative installed worldwide capacity (68·6%).

Such rapid growth, however, is associated with a consequent increase in associated environmental impacts. Figure 2 gives an indication of the environmental performance over the life cycle of two baseline PV systems. The grid-connected system was modelled for a facility installed in Spain (installed capacity of 120 Wp (Watts-peak) and electricity lifetime generation of 118·026 kWh), while the stand-alone system was modelled for Cape Verde (installed capacity of 160 Wp and lifetime generation of 620·296 kWh). These two scenarios serve as the baseline for the PV case study (case study 2 within the Zerowin project). The stand-alone system shows higher impacts than the grid-connected PV system due to the use of the storage system.

For both of these scenarios, the relative contributions of the production, installation, use and decommissioning phases were determined by Obersteiner *et al.* (2011) who showed that the production phase bears the highest environmental impact. During normal operations, PV power systems do not emit substances that may threaten human health or the environment. In fact, through savings in conventional electricity production, they can lead to significant emissions reductions.

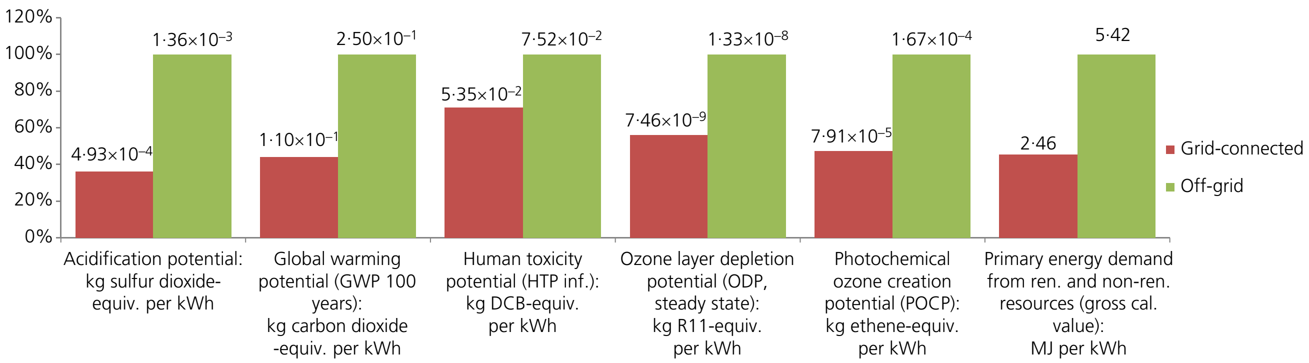


**Figure 2.** Relative values of grid-connected and stand-alone baseline PV system (100%) considering environmental indicators (adapted from Obersteiner *et al.* (2011))

Moreover, systems with higher efficiencies are accompanied by less production burdens per unit of produced electricity. Compared with the production phase, the end of life (EoL) phase has a minor influence. The recycling of materials within the EoL phase enables the substitution of primary materials, thus saving on both raw materials and energy. This leads to environmental benefits (instead of burdens) in most impact categories (Obersteiner *et al.*, 2011). Other studies have also reported minor impacts from the EoL phase, with the major contributor being the module production, followed by the production of the various BoS components and the mounting system (Frankl *et al.*, 2005; Jungbluth *et al.*, 2008; Müller *et al.*, 2006; Obersteiner *et al.*, 2011; Saft, 2008; Sander *et al.*, 2007).

### 1.1 PV modules

Within the production phase of the PV modules, the processes associated with extracting and purifying the silicon raw material and wafer and cell manufacturing are the main contributors. Consequently, the identification of mechanisms for the reuse and recycling of PV modules has been one of the key issues during the development of this case study. Following the European waste hierarchy, waste that cannot be avoided or reused should primarily be recycled. Regarding the collection and recycling of used PV modules, different initiatives are already in place within the EU, including those of PV Cycle (http://www.pvcycle.org/) and the thin-film PV modules manufacturer First Solar, with its own takeback and recycling (http://www.firstsolar.com).

The new Waste electrical and electronic equipment (WEEE) directive 2012/13/EU (published 4 July 2012) states that PV modules are to be considered WEEE from 2012 and they must be collected and recycled (EU, 2012). Each Member State should ensure implementation of the 'producer responsibility' principle and, on that basis, a minimum collection rate of WEEE should be achieved annually.

Nevertheless, the concept of recycling PV modules is still in its infancy. One of the most important prerequisites of recycling is disassembly of a module and the separation of single materials. The various designs and manufacturing procedures determine the means of module disassembly and layer separation. Currently, there is no suitable recycling process available for separating the lamination foil from broken cells (Fraunhofer IBP, 2012).

### 1.2 Balance of system (BoS)

With regard to energy storage systems (one of the BoS components), the most common types are open lead–acid batteries, but others such as valve-regulated lead–acid (VRLA) batteries either as absorbed glass mat (AGM) or gel battery ('gel cell') are also used (Middendorf *et al.*, 2010). Recent progress suggests that lithium ion batteries are the best placed alternatives to replace lead–acid types, given their much smaller size and weight (seven to ten times less, with an energy density of 150–200 $kWh/m^3$), higher efficiency (near 100%), higher durability and reliability (>3000 cycles with an 80% depth of discharge (as opposed to lead batteries with 2000 cycles) and maintenance-free operation) that offsets their comparatively higher costs (Eurobat, 2011).

Wearing action affects different electronic components in different ways. In general, the electronics associated with the BoS can work without problems for several years. However, after roughly 10 years, the availability of spare parts for their possible repair can be difficult because the rapid evolution of the related technology means that old models do not comply with the specifications set in newer designs. Moreover, in the current electronic market scenario, an electronic device is generally considered completely obsolete after 10 years of production/use. If these issues are considered, the life span of electronics components of the BoS is generally 8–10 years. After this time has elapsed, the final user will change the BoS electronics and the battery while, in general, the modules are kept or increased in number.

## 2. Goal and scope of the study

The overall goal of this case study was to apply the previously published Zerowin vision and approach to the PV sector (Curran and Williams, 2012; Williams *et al.*, 2011). The main goal of this case study was the creation and promotion of industrial networks within and around the value chain of a PV system, and which are focused on the integrated use of a combination of high-tech components of the electronic and electrical equipment industry, high-tech PV-specific components such as PV modules and electronics, and lower tech components in the bill of materials of a typical PV system. The targets for the reduction of the environmental impacts were a 30% decrease in greenhouse gas (GHG) emissions, 70% overall reuse and recycling of waste and a 75% reduction in the utilisation of fresh water.

This Zerowin case study set out to demonstrate how PV systems can be designed, manufactured, integrated (including transport stages from factory to distribution centres to target premises) and operated to produce electricity and decommissioned in a way that enables the creation of industrial networks that will interconnect the input and output flows of materials and components in the lifetime of a PV system so that the environmental impact of the installation is minimised. The following aspects related to PV systems are of key relevance for reaching the case study goals within the Zerowin project.

- High energy intensity in the production of some components, such as PV modules and batteries.
- Long operational life (25+ years) of the installations, with different typical life expectancies of the different components composing a PV system. Within this project, the

reference operational lifetime of a PV system is taken as 20 years (Dunlop *et al.*, 2005; Middendorf *et al.*, 2000; Obersteiner *et al.*, 2012).
- Use of valuable materials, such as precious metals and rare earth metals, in some of the components.
- Reuse options for some components and subcomponents used in different applications (structural elements in the construction sector, energy storage used by electric vehicles, etc.).

The scope of this case study included the following.

- Development of a complete PV system concept that includes the D4R (Design recycling, repair, refurbishment and reuse) criteria and measures to enable and boost the feasibility of an industrial network (such as modularity and standardisation), both for grid-connected and stand-alone systems.
- Development of two concepts and prototypes for power and electronic components to be used in these two types of PV systems (i.e. grid-connected and stand-alone).
- Construction of two demonstration installations for these two types of PV systems, installed in industrial premises, from sectors relevant to the synergies sought.
- Installation and testing of the constructed PV systems in industrial premises from relevant sectors.

### 2.1 PV modules

In order to reduce the relatively high environmental impact of the PV modules on the overall impact of a PV system, the case study aimed to develop schemes to reduce PV module disposal and increase the rate of reuse and recycling. Such schemes would

- increase revenue by creating economic value of production residues currently considered waste and create value for modules decommissioned at an early state
- decrease consumption of raw materials by increasing the use of off-specification (off-spec) and second-life PV modules.

### 2.2 BoS

As highlighted previously, the battery system is an important contributor to the environmental impacts of PV systems. In order to decrease these impacts, the enhancement of alternative technologies (i.e. lithium ion) in the market was one of the goals within this study. Moreover, the reuse of materials was highlighted in the production and installation phase as well as during the use phase of the PV systems. Specific actions for the study were

- the use of lithium ion batteries for energy storage
- the incorporation of used cabling in the PV systems
- the incorporation of used components for structural elements of the PV array
- redesign of the electronic components to ensure exchangeability of spare parts
- control and monitoring of features in the PV system.

The increased exchangeability of spare parts enables better repairability (creating less waste) and increases future reuse options. Redesign of the power conditioning equipment increases the performance ratio, which indicates the portion of the general current that can actually be used, as well as the PV system lifetime. By improving the performance ratio, the use of batteries and PV modules is reduced, reducing the waste, energy and water needed for their generation. These changes considerably reduce the life cycle impacts of the whole PV system as batteries and PV modules are the main contributors.

### 2.3 Boundaries

The boundary of the PV system case study is from the use of extracted raw material to electricity generation (Arranz *et al.*, 2011). The output of the baseline is energy (kWh), so electricity retailers and customers are considered to be outside the study boundary.

## 3. Methodology

This case study follows the zero waste philosophy, aiming to eliminate rather than 'manage' waste. It applies a few of the key strategies identified for applying zero waste in industry, namely

- eco-design – focused on new strategies to boost the efficiency of a PV system and prolong its useful lifetime
- industrial symbiosis – a particularly relevant concept for all Zerowin case studies, which seeks to reach zero waste by promoting networks across industries
- use of new technologies – investigation, design and testing of a new PV system applying the D4R method
- life cycle assessment – as a method to obtain the true environmental impact of the developed PV system.

In order to achieve the Zerowin targets and the goals of this case study, the work was divided in three phases (Figure 3).

- Phase 1 concerned the development of a D4R PV system and the concept of an industrial network around it (Arranz *et al.*, 2011).
- Phase 2 focused on the development of a specific component of PV systems – a power conditioning prototype – finished in April 2012 (Arranz *et al.*, 2012).
- Phase 3 is demonstration of the D4R design in two complete PV systems (grid-connected and stand-alone) (Arranz *et al.*, 2013b).

This paper describes the implementation of phases 2 and 3. Concerning phase 3, industrial symbiosis was used to achieve

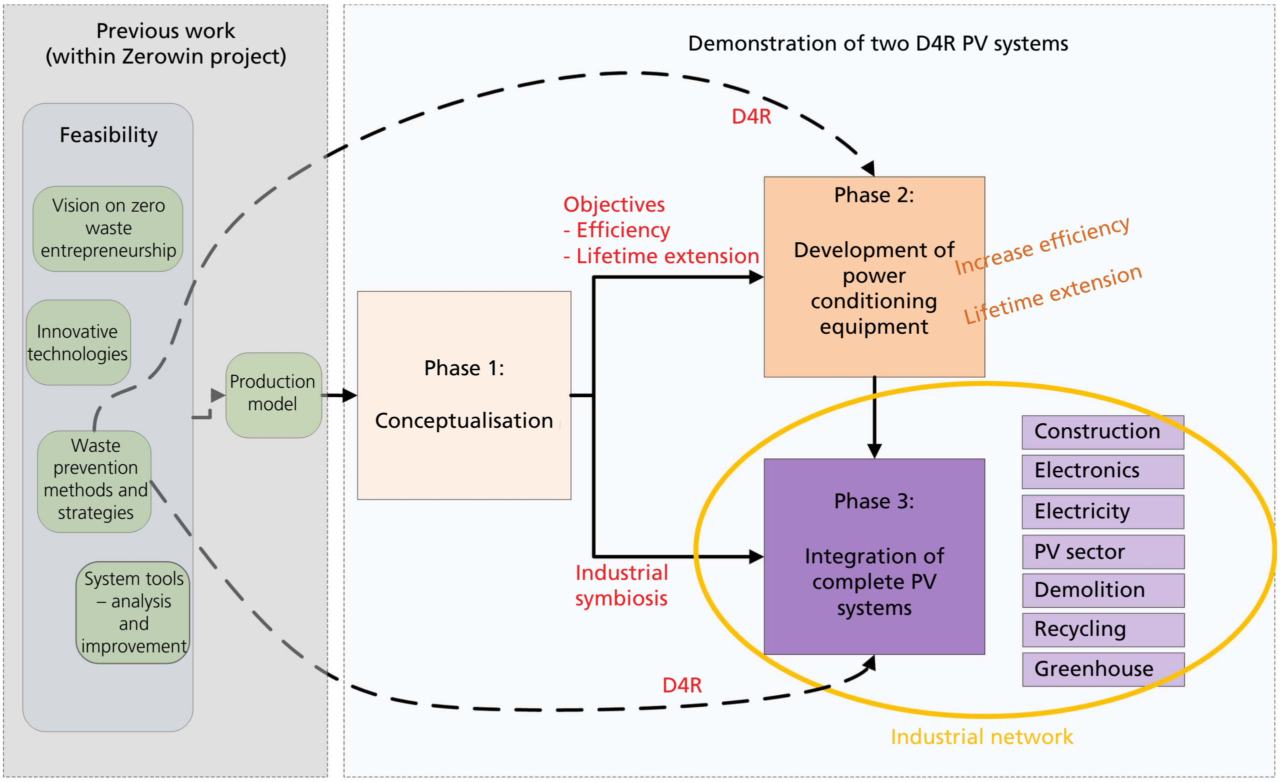


**Figure 3.** Work flow for the demonstration of two D4R PV systems within the Zerowin project (Arranz *et al.*, 2013a)

the project's objectives (Arranz *et al.*, 2013b). Figure 4 represents the final industrial network demonstrated in this case study. In the development of the PV systems, the following measures were implemented.

(*a*) The use of off-spec PV modules with minor visual defects (e.g. scratches, incorrectly placed labels, PV cells of different colours) that would otherwise be discarded. By reprocessing off-spec PV modules, in-house reuse of waste is demonstrated. At least three different levels of off-spec PV modules were identified by manufacturers

- (*i*) PV modules with minor visual defects but the same functionalities as new modules
- (*ii*) PV modules with lower generation than new modules within a specific range
- (*iii*) PV modules with very low generation in comparison to new modules (all modules are tested once assembled).

(*b*) The array structures that support PV modules offered the possibility to use, in their construction, elements originated as waste in construction or demolition sites, creating the opportunity for industrial networking between PV system construction activities and the demolition sector. Moreover, the array structure is fixed with screws, thus avoiding concrete and enabling dismantling and reuse in further applications.

- (*i*) For the structure of the grid-connected PV installation, the elements were recovered mainly from structural elements of an industrial production line for printers, which was decommissioned at the time of this case study's conceptualisation.
- (*ii*) For the structure of the stand-alone installation, elements were recovered from the demolition sector (originating from a military camp and from a greenhouse in France).

(*c*) The power conditioning prototype was a central component for the D4R design and installation of the complete PV systems (Arranz *et al.*, 2012). Its modular design enables the reuse of the different components at the EoL of the PV system. The prototype is composed of

- (*i*) a charge controller, responsible for finding the maximum power point of the energy generated by the PV source and transmitting it to the battery

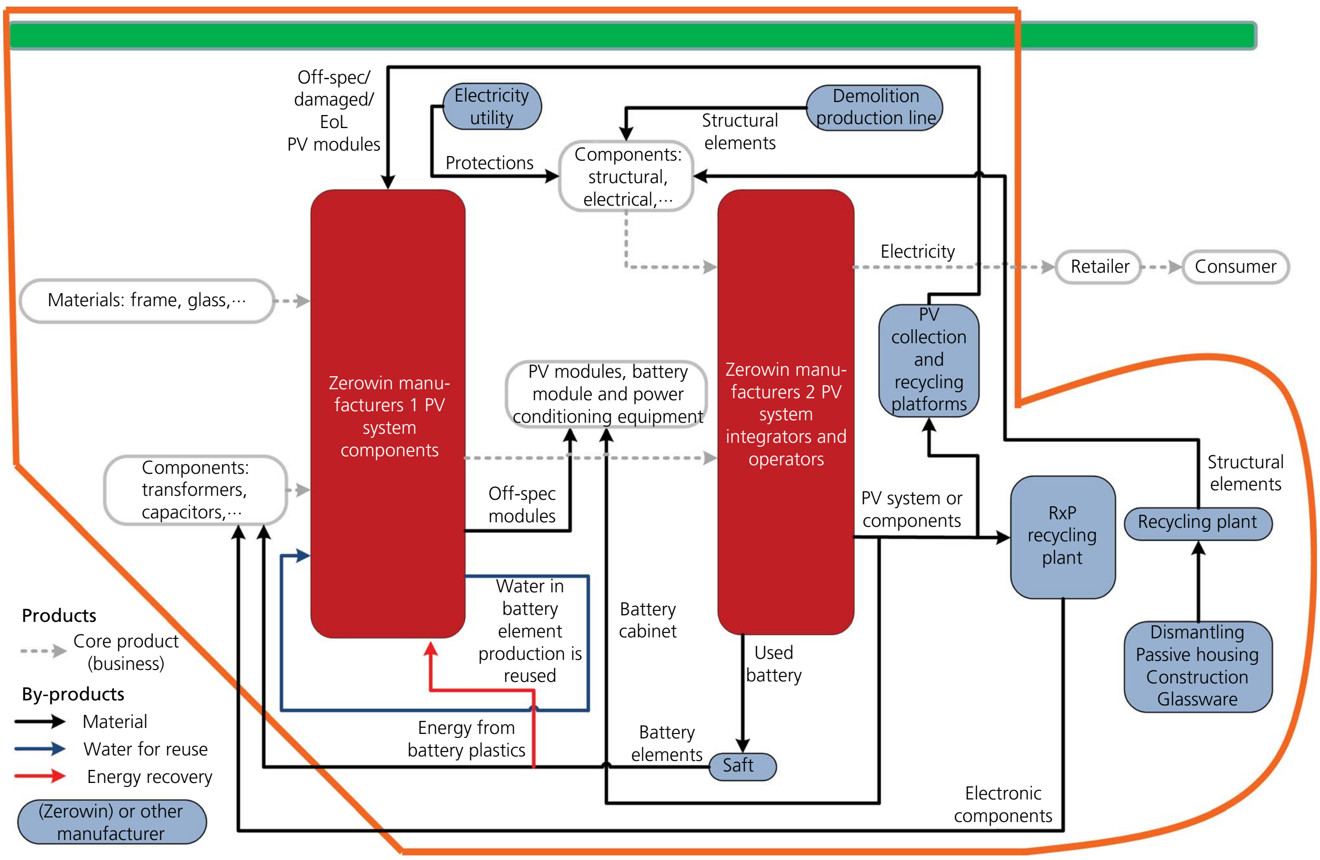


Figure 4. Industrial network demonstrated around PV case study within the Zerowin project (Arranz *et al.*, 2013b)

(*ii*) a supervisory controller (supervisor), which is responsible for control of the different components in a system with renewable generation and battery storage
(*iii*) an inverter, responsible for the conversion from direct to alternating current (DC to AC).

The charge controller and the supervisor were two components especially designed for the power conditioning prototype in this case study. The charge controller enables the reduction of capture losses and the supervisor reduces battery losses and extends its life cycle. The designs of both the charge controller and supervisor were carried out considering the guidelines and recommendations from previous activities in the project (Arranz *et al.*, 2011, 2012).

(*a*) The cabinets for the battery systems used in both the grid-connected and stand-alone systems were previously used (the cabinets contained electronic equipment).
(*b*) Some of the cabling and cable protections were recycled items.
(*c*) In order to improve performance and increase lifetime, lead–acid batteries in the PV system were exchanged for a lithium ion battery prototype. Under the same conditions, the discharge cycle of a lithium ion battery is double that of a lead–acid batteries. The manufacturing process of the prototype battery was also environmentally efficient – both waste heat and water were used internally, thus decreasing net energy and water consumption. The lithium ion battery modules were equipped with a battery management module (BMM) for increased safety, lifetime and energy efficiency.

Moreover, a dismantling plan for decommissioning at the end of use phase for both installations was defined (Arranz *et al.*, 2013b). A sustainable EoL phase was thus assured for both cases.

## 4. Phase 2: Power conditioning equipment

A power conditioning prototype was developed within phase 2. The prototype is composed of the charge controller, the supervisory controller and the inverter. D4R criteria were


(a) (b)

Figure 5. Prototype of the power conditioning system developed within the Zerowin project. The figure shows the charge controller, and the charge controller and supervisory controller situated inside the cabinet (Arranz *et al.*, 2012)

demonstrated in the designs of the charge controller and the supervisory controller (Arranz *et al.*, 2012). Figure 5 shows the developed prototype.

Controlling and monitoring all the components of the power plant (generation, battery, charge controllers, inverters, DC and AC current flows and AC individual loads) and the generation and consumption of the PV plants enabled the identification of losses or faults in order to increase the performance ratio and the operational lifetime (expected to be increased to 30 years).

## 5. Phase 3: PV systems within an industrial network

Two complete PV systems were installed in phase 3. With regard to the industrial symbiosis demonstrated by installation


(a) (b)

Figure 6. Grid-connected PV generator with 12 off-spec polycrystalline PV modules mounted on the roof of Electra Caldense in Caldes de Montbui, Spain (Arranz *et al.*, 2013b)

| Components and specification | Remarks |
|---|---|
| PV panels | |
| 12 panels of 230 Wp (model: Atersa A-230P) | Off-spec |
| Power conditioning | |
| One MPPT charge controller 80 A | Prototype designed within Zerowin project |
| One supervisory controller | Prototype designed within Zerowin project |
| Dual-mode inverter (model: Studer XTM 4000-48) | New |
| Storage | |
| One ESSPV 48 V lithium ion battery pack 4 kWh | Prototype designed within Zerowin project |
| Cabinet | Reused |
| Other BoS | |
| Cabling | 24% reused |
| One connection box, three circuit breakers, two earth leakage relays | Reused |
| Signal converters, sensors | New |
| Mounting | |
| Array structure | Reused |
| Screws | Allow for easy decommissioning |

**Table 1.** PV system components used for the construction of the grid-connected system at Electra Caldense (Arranz *et al.*, 2013a)

of the PV systems, the location of the systems played a very important role. The final sites were selected according to the needs of industrial symbiosis.

## 5.1 Grid-connected PV system

The grid-connected PV system was installed at Electra Caldense, a utility group within 100 km of Barcelona, Spain. Figure 6(a) shows the installed grid-connected PV generator on the company's roof and Table 1 provides an overview of the main installed parts of the system.

### 5.1.1 Functioning of the grid-connected PV generator

The strategy for the grid-connected installation was as follows. The electricity generated feeds the loads as much as possible; when there is consumption on-site, electricity is then fed into the batteries and when the batteries are full the surplus electricity is injected into the grid.

Figure 7 shows simulations of the load and PV electricity generation profiles over one week in four different seasons. On Saturday afternoon and Sunday, when there is no activity at Electra Caldense, on-site consumption falls during the morning and increases at night, because the loads connected to the PV systems are outdoor lights. During the week, the loads connected to the PV system are indoor lights. Figure 7 shows

- the electricity generated by the PV system (PV generation)
- the fraction of the electricity generated from PV that is consumed on-site (self-consumption)
- the fraction of the electricity generated from PV that is injected to the grid (surplus energy)
- the electricity consumed from the grid (grid consumption)
- the battery state of charge (SOC).

The importance of an advanced control strategy for demand-side management is evident – without this, electricity generated over the weekend would be wasted. By selecting a dual-mode inverter that allows backfeeding of any excess energy to the grid, the energy produced by the PV generator during the weekend is not lost and, as a consequence, the overall performance ratio of the installation increases.

## 5.2 Stand-alone PV system

Sersall 95, S.L. (within 150 km of Barcelona) is a private waste separation and recycling plant. The company has diversified into various business services and, among others, it manages the collection of municipal solid waste (MSW), industrial waste, hazardous waste and separately collected waste, acting as an authorised service provider for Catalan Agency Waste. Figure 8 shows the façade of the company office with the installed stand-alone PV generator and Table 2 provides an overview of the main installed parts of the stand-alone PV system.

The inclusion of a waste separation and recycling plant in the industrial network enables an increase of the reuse rate, mainly for structural elements. Sersall is a member of the board of the non-government organisation SEBA, which has a permanent

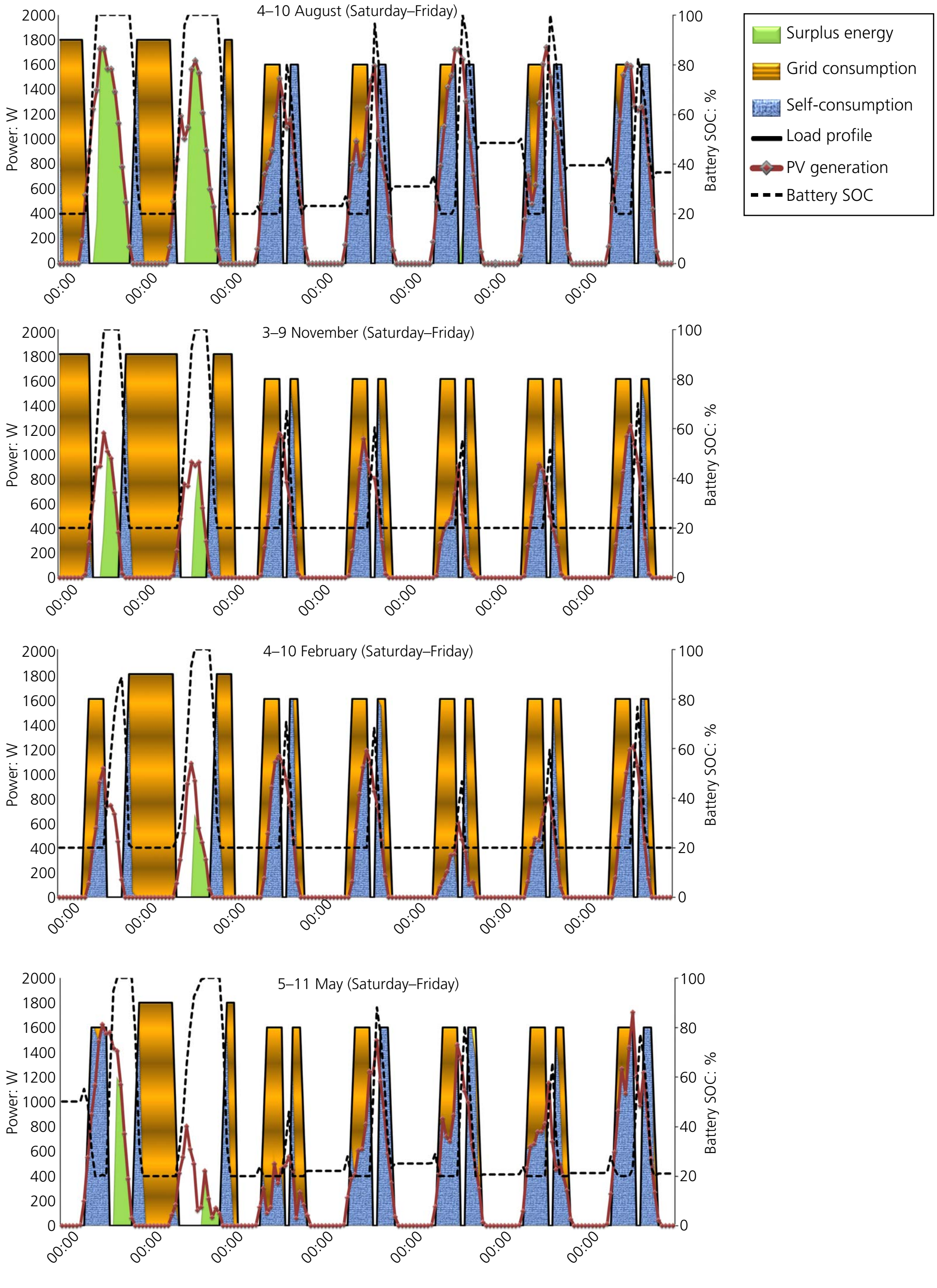


**Figure 7.** Load and generation profiles for the grid-connected PV system over one week in summer, autumn, winter and spring. The loads connected to the PV system are for external lighting at night at weekends and internal lighting during the day on weekdays (Arranz *et al*., 2013a, 2013b)

Figure 8. Stand-alone PV generator with 12 off-spec polycrystalline PV modules mounted on the façade of Sersall 95, S.L. in Castelló d'Empúries, Spain

exhibition house in Barcelona and promotes the use of renewable energy in general but particularly in industry.

Several sectors were involved in the creation of the industrial network around the PV systems, including the PV module manufacturer, the construction/demolition sector, electricity utility companies and recycling plants. All the flows presented in Figure 4 were implemented.

### 5.2.1 Functioning of the stand-alone PV generator

The strategy for the stand-alone installation was the following. Electricity generated from the PV generator feeds the loads and/or the battery according to the desired schedule. The strategy aims to maximise the fraction of on-site consumption that is supplied with solar energy during peak hours (peak tariff in summer from 11:00 to 15:00 and from 18:00 to 22:00 in winter) and, consequently, to reduce energy consumption from the grid and hence the electricity bill. If the batteries are full and the solar resource is higher than load consumption, surplus is lost. Figure 9 shows simulations of the load and PV electricity generation profiles over the period of one week in four different seasons.

As soon as the sun rises, the battery is charged by PV electricity generation. Once the battery is full, the PV electricity generated feeds the loads (never injected into the grid), which is represented by the surplus energy in Figure 9. After 15:00 in summer (August), there is still some solar resource and the battery is charged by the PV generator while the loads are supplied by the grid. The self-consumption rate and the surplus energy generated are more important in summer than in winter as the solar radiation is higher.

## 6. Achievement of the case study goals

A description of the achieved results of single measures and an estimation of the overall effects are provided in this section. Through better design of the PV system, the lifetime of the PV systems was increased from 20 to 25 years and its performance ratio was also improved, thus increasing the total energy production of the system compared with the baseline. The complete PV systems use an advanced concept including lithium ion batteries (aiming for higher efficiency, operational life and energy storage density) for both the stand-alone and

| Components and specification | Remarks |
|---|---|
| PV panels | |
| 12 panels of 230 Wp (model: Atersa A-230P) | Off-spec |
| Power conditioning | |
| One MPPT charge controller 80 A | Prototype designed within Zerowin project |
| One supervisory controller | Prototype designed within Zerowin project |
| Dual-mode inverter (model: Studer XTM 4000-48) | New |
| Storage | |
| One ESSPV 48 V lithium ion battery pack 4 kWh | Prototype designed within Zerowin project |
| Cabinet | Reused |
| Other BoS | |
| Cabling | Approx. 24% reused |
| Protection systems (circuit breakers, earth leakage relay, surge arresters, etc.) | Approx. 10% reused |
| Signal converters, sensors | New |
| Mounting | |
| Array structure | Reused |

Table 2. PV system components used for the construction of the stand-alone system at Sersall 95, S.L. (Arranz *et al.*, 2013a)

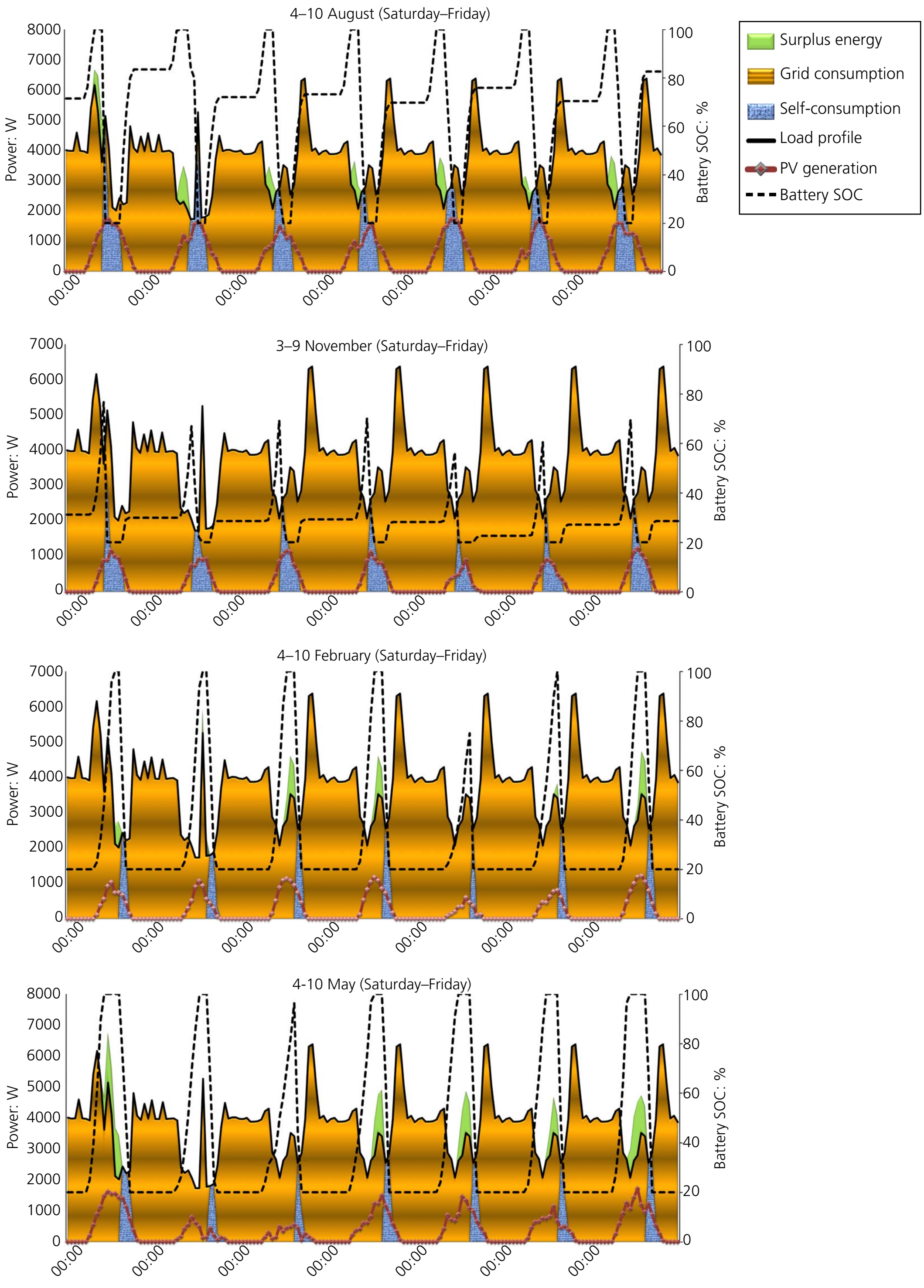


**Figure 9.** Load and generation profiles for the stand-alone PV system over one week in summer, autumn, winter and spring (Arranz *et al.*, 2013a, 2013b)

| Goal | Grid-connected system | Stand-alone system |
|---|---|---|
| Increase PV system lifetime (baseline 20 years) | 25 years | 25 years |
| Increase performance ratio (baseline 55%) | 61·3% | 61·2% |
| Reuse of parts | Off-spec modules, mounting structure, ≈25% of cabling and minor parts of BoS | Off-spec modules, mounting structure, ≈25% of cabling and minor parts of BoS |
| Increase total energy production (compared to baseline) | 39·3% | 39·1% |

**Table 3.** Case study goals and their achievement for the grid-connected and stand-alone PV demonstration systems (Arranz *et al.*, 2013a)

grid-connected systems as well as a complete monitoring and communication system. The use of the D4R concept for the recycling of lithium ion batteries allows a significant decrease in environmental impact (Siret, 2011).

Neither of the systems uses a concrete structure. Instead, metal arrays were used for both façade and roof constructed systems. The avoidance of concrete has a significant effect on decreasing the global warming potential (GWP) results, but has an adverse effect on the recycling potential of the systems (as the recycling of heavy concrete structures would lead to a high recycling rate of the entire system).

Components for PV system construction that would otherwise have entered the waste stream have been reused. In both demonstration projects, 100% off-spec modules were used. Apart from that, in the PV system structure, about 25% of the cabling and minor parts of the BoS were reused components. The modular design of the power conditioning system will allow the reuse of different components at the EoL of the complete PV system. Furthermore, the structure of the roof-mounted grid-connected system is fixed with screws, thus allowing for dismantling and reuse in further applications. For both the stand-alone and the grid-connected system, a dismantling plan for the EoL phase has been developed, containing recycling and reuse options for all the main components (Arranz *et al.*, 2012). Table 3 gives an overview of the results achieved in both systems.

A quantitative assessment of the PV systems demonstrated achievement of two out of the three Zerowin environmental goals – a 45% reduction in GHG emissions and a 91% rate of overall reuse and recycling of waste. The goal with regard to fresh water consumption (75% reduction) has not been achieved: the case studies showed an overall reduction potential of 41% compared with the baseline scenarios. The final assessment and results are included in a report by Obersteiner *et al.* (2013).

## 7. Identified barriers and outlook

The perceived barriers with regard to the industrial network and the reuse, repair, recycling and refurbishment of components are mainly because of a lack of guarantees for second-hand components, the high requirements of the technology and the fact that it is currently often easier and cheaper to buy a new product than to reuse or recycle one. In this regard, the following actions are proposed

- establish an EU-wide standard for second-hand and off-spec components to ensure quality and performance and enable the reuse of components and parts in order to encourage stakeholders to buy/use such components
- enhance the use of standardised components in order to increase the exchangeability of items in production, installation and repair, reuse and recycling
- support research for development of Best Available Techniques reference documents (BREFs) for PV reuse and recycling
- provide economic incentives to enable the adaption of machines and production chains in manufacturing and make recycling processes economically sustainable.

## 8. Conclusions

This case study focused on the concept of a Zerowin industrial network around a PV system prototype that was designed to operate more efficiently and allow higher resource efficiency due to industrial symbiosis.

Demonstration of the case study was carried out in two phases. The first phase concerned the D4R of the power conditioning equipment, which was completed at the end of April 2012. The second phase was demonstration of the D4R design of a grid-connected PV system (installed at the energy provision company Electra Caldense in Caldes de Montbui, Spain) and a stand-alone system (at the recycling company Sersall 95, S.L. in Castelló d'Empúries, Spain). With regard to the design, D4R measures have been especially demonstrated in the development of the power conditioning equipment and the manufacture of support structures. These measures will benefit future industrial networks.

Difficulties were encountered in the creation of industrial symbiosis around the reuse of high-tech electronic components, given the rapid evolution of the related technology and the difficulties in readapting these pieces in other models. However, redesign of the high-tech components led to improvements in the power conditioning system – the performance ratio was increased by up to 11% and the expected lifetime increased 25 years, 5 years more than the baseline scenario.

Quantitative assessment of the PV systems demonstrated the achievement of two out of the three Zerowin environmental goals – reduction of GHG emissions by 45% and an overall rate of waste reuse and recycling of 91% (Obersteiner *et al.*, 2013).

## REFERENCES

Arranz P, León I, Anzizu M *et al.* (2011) Implementation of design recommendations in high-tech products: D4R photovoltaic system. In *Deliverable 6A.1. Concept Papers for all Networks/Pilot Applications* (den Boer E and Wolf M (eds)). Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752, pp. 38–69.

Arranz P, Tarragó J and Anzizu M (2012) *Deliverable 6B.2. Prototype of Electronics Power Conditioner for PV plants*. Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752.

Arranz P, Vallvé X, Tarragó J *et al.* (2013a) Implementation of design recommendations in high-tech products: D4R photovoltaic system. In *Deliverable 6A.3. Final Case Study Report for all Networks/Pilot Applications* (den Boer E, Williams I and Curran T (eds)). Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752, pp. 53–109.

Arranz P, Vallvé X, Anzizu M, Pineau A and Tarragó J (2013b) *Deliverable 6B.3. Complete System Design and Installation of 2 Different PV Systems*. Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752.

Curran T and Williams ID (2012) A zero waste vision for industrial networks in Europe. *Journal of Hazardous Materials* **207–208**: 3–7.

Dunlop ED, Halton D and Ossenbrink HA (2005) 20 years of life and more: where is the end of life of a PV module? In *Photovoltaic Specialists Conference, 2005, Conference Record of the 31st first IEEE*, pp. 1593–1596.

EU (European Union) (2012) Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). See http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:EN:PDF (accessed 10/01/2013).

Eurobat (Association of European Automotive and Industrial Battery Manufacturers) (2011) *White Paper. Importance of Battery Energy Storage for Renewable Energy Supply. An Analysis of Battery Systems and their Application in Off-grid, Mini-grid and On-grid Configurations.* V1.1. See http://www.eurobat.org/position-papers#energy_storage (accessed 17/01/2013).

Frankl P, Menichetti E, Raugei M, Lombardelli S and Prennushi G (2005) *New Energy Externalities Developments for Sustainability, Deliverable 11.2 – RS Ia. Final Report on Technical Data, Costs and Life Cycle Inventories of PV Applications*. Project NEEDS, Sixth European Framework Programme. See http://www.needs-project.org (accessed 07/04/2014).

Fraunhofer IBP (Department Life Cycle Engineering (GaBi)) (2012) *Executive Summary of Life Cycle Assessment (LCA) Screening of the Maltha Recycling Process for Si-PV Modules*. See http://www.pvcycle.org/lca-screening-of-recycling-si-pv-modules/ (accessed 06/02/2013).

Jungbluth N, Tuchschmid M and de Wild-Scholten M (2008) *Life Cycle Assessment of Photovoltaics: Update of Ecoinvent Data v2.0*. ESU-Services Ltd. See http://www.esu-services.ch (accessed 07/04/2014).

Masson G, Latour M, Rekinger M, Theologitis IT and Papoutsi M (2012) *Global Market Outlook for Photovoltaics 2013–2017*. European Photovoltaic Industry Association, Brussels, Belgium. See http://www.epia.org/news/publications/ (accessed 12/12/2013).

Middendorf A, Griese H, Pötter H, Reichl H and Stobbe I (2000) Estimating the (remaining) lifetime for maintenance and reuse. In *Proceedings of Joint International Congress EGG2000+* (Reichel H and Griese H (eds)). VDE Verlog, Berlin, Germany, pp. 467–472.

Middendorf A, Chancerel P, Kersten C *et al.* (2010) *Deliverable 3.1. End-of-Life Impacts under Appropriate and Uncontrolled Treatment*. Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752.

Müller A, Wambach K and Alsema E (2006) Life cycle analysis of a solar module recycling process. *Materials Research Society Symposium Proceedings* **895**: 89–94.

Obersteiner G, Beigl P, Pertl A and Scherhaufer S (2011) *Deliverable 7.1. Report on Assessments of Pilot Cases: Baseline Assessment*. Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752.

Obersteiner G, Beigl P, Pertl A and Scherhaufer S (2012) *Deliverable 7.2. Report on Assessments of Pilot Cases: Mid-term Assessment*. Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752.

Obersteiner G, Beigl P, Pertl A and Scherhaufer S (2013) *D7.3. Report on Assessments of Pilot Cases: Final Assessment*. Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752.

Saft (2008) *Sustainable Energy Systems. New Technologies for Energy Carriers/Transport and Storage, Life Cycle Analysis Report*. Saft, Bagnolet, France, Project 019883-(SeS6) co-funded by the European Commission within the Sixth Framework Programme.

Sander K, Schilling S, Wambach K *et al*. (2007) *Studie zur Entwicklung eines Rücknahme- und Verwertungssystems für photovoltaische Produkte*, Ökopol GmbH, Hamburg, Germany (in Germany).

Siret C (2011) LCA study. *Proceedings of International Conference Batteries 2011*, *Cannes*, *France*.

Williams ID, Curran T and Ongondo F (2011) *Deliverable 1.3b. ZeroWIN Commonly Agreed Vision Paper*. Austrian Society for Systems Engineering and Automation, Vienna, Austria, Grant agreement number 226752.