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Report on Deliverable D5.5:

White paper on status and market potential OPV

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Description of deliverable achievement

1. Preface

As originally mentioned in the DoW, the aim of this final document is to generate a roadmap describing the requirements for potential applications of OPV in (selected) market segments like BIPV, automotive, outdoor remote and grid connected. The applicability will be determined by means of key parameters such as system costs, maximum power and voltage, energy yields, design, weight and/or long term stability of the modules on both glass and flexible substrates, and based on the outcome of the project and thereby with input from all WPs.

In the frame of WP5, a comprehensive report D5.3 “Final report on market analysis for targeted applications” was finalized in March 2014 and it presents an overview of the potential selling points and technical status of OPV, identification of targeted applications, market overview and market views of X10D partners, application requirements as well as a comparative assessment with other PV technologies to evaluate the competiveness of OPV.

This report presents an executive summary of the final market analysis report D5.3 and will include the most recent insights and achievements in the OPV field. The described technology status of OPV is not only a reflection of the achievements obtained within the X10D project, but is based on the overall technology progress achieved world-wide and to which projects like X10D contribute. It is in this respect important to note that X10D partner Heliatek is one of the most important industry leaders and front runners in OPV development and manufacturing.

The content of these reports will therefore mainly act as important/additional input for broader initiatives occurring in this field, for instance currently ongoing in the frame of the Organic Electronics Association (OE-A). The OE-A established recently the Working Group Organic Electronics Energy (OEE) to bring together the leaders in OPV. Its main mission is to promote OEE to the market, end-users and stakeholders such as key public and private opinion leaders.

The group is comprised of OPV manufacturers as well as equipment suppliers and leading research institutions. The OEE group was started with the support of OE-A members Armor, Belectric OPV, Eight19, DisaSolar, Mekoprint, CEA, CSEM, Heliatek, Holst Centre/Solliance and VTT.

This group is also working on a White Paper on Organic Electronics Energy, the OE- A Roadmap and testing guidelines for OPV. It is therefore very important to synchronize all these roadmapping activities in a coherent way and generate a consistent strategic view of OPV supported by the whole community. This report contributes to that goal.

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2. Introduction

Photovoltaics (PV) has shown a tremendous growth in the last 10 years which has resulted in a continuous decrease of the total costs, making PV almost cost competitive with traditional energy sources. The primary focus has been on efficiency enhancement, volume expansion and cost reduction and to go to TW scale production.

The PV technologies currently available on the market are wafer-based crystalline silicon with a share of 85-90 %, while thin film modules including Silicon, CdTe and CIGS are taking up a collective share that is substantially lower (10-15%).

The continuous price reductions of crystalline silicon has resulted in a slower development of thin film PV than expected and until 2017 it is anticipated that the portfolio of thin film PV technologies will slowly develop with a market share that will either stabilize or even decrease a bit over the next five years.

Organic Photovoltaics (OPV) is one of the latest emerging PV technologies that possess potentially unique assets that could lead to new application solutions especially in application areas that have traditionally been difficult for the current PV technologies. OPV will not replace traditional PV, but instead will create new markets and applications where its unique properties are fully valued.

In the next sections of this report, a sketch of the current technological status, the selling points and future market potential of OPV for specific targeted applications will be further outlined.

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3. Why Organic Photovoltaics?

3.1. Selling points

To motivate and justify the investments in OPV research and development, especially in times where conventional PV technologies show a rapid drop in costs, it is of great importance to profit from the combination of specific selling points that could make OPV unique and that would open up numerous new opportunities for large volume applications.

The opportunities that OPV could offer are the following:

- **Scalability:** the perspective of a highly automated, low energy consuming and low-cost roll-to-roll production through fast printing, vacuum deposition and coating techniques.
- **Good form-factor:** devices can be designed into many forms on light weight and flexible substrates and supports
- **Aesthetics:** the appearance of OPV modules can be designed by tuning the color, the shape and the thickness
- **Transparency:** OPV offers truly transparent product, in which the transparency can be tuned to meet the applications
- **Harvesting Factor:** The unique behavior of OPV at high temperature (in the sun) and at low light, allows for better energy harvesting than its efficiency at Standard Test Conditions (100 W/m2, 25 oC) would indicate.
- **Environmental profile:** it is expected that OPV will have an excellent sustainability profile in terms of energy pay-back time and carbon footprint. No heavy metals are used, in contrast to CdTe (cadmium) or Perovskite PV (lead)

These (combined) opportunities will result in “Unique Selling Points (USP)” for OPV leading to all kind of new applications in different market segments, where the OPV functionality can be integrated in a wide variety of structures and objects not covered by the technologies today.

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3.2. The technology and commercial status of OPV

Within the family of OPV, one may distinguish between devices that are based on organic semiconducting photoactive materials applied from vacuum or solution processing technologies. In the first case, the organic semiconductors consist of small molecules while in the second case, polymers as well as small molecules can be used for solution coating and printing. In X10D both concepts have been investigated and will differ mainly in processing speed.

In Table 1, power conversion efficiency data reported in the literature on polymer and small molecule devices are listed, ranging from values for small hero cells to pre- industrial larger area modules. The industrial level of OPV must be termed as mostly pre-industrial at this stage. There has been a growing industrial interest across the whole value chain to start R&D activities in this field from materials production to equipment manufacturing, but there are only a few potential OPV producers to date. Heliatek, X10D partner, is one of the frontrunner in OPV development and manufacturing and have clear ambitions to launch first commercial products in 2014/2015.

Table 1: Technological status OPV divided into three concepts

OPV Technology	Small molecule OPV (Vacuum)	Small molecule OPV (solution processed)	Polymer based OPV
Best research cell solar cell efficiency at STC	12.0 (1.1 cm^2) triple junction: Heliatek	11.1 (0.16 cm^2) single junction 10.7 (1.01 cm^2) single junction: Mitsubishi Chemical	10.3 (1 cm^2) single junction: Toshiba 10.6 (0.1 cm^2) tandem: UCLA
Best submodule efficiency at STC	9.8% (122 cm^2): Heliatek	N/A	8.2 (25 cm^2): Toshiba
(semi-)commercial PV module efficiency	6% (1000 cm^2): Heliatek	N/A	<2 (> 1000 cm^2): Konarka, DTU
Commercial status	Commercial in 2015: Heliatek	R&D	R&D / pre-industrial

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3.3. Targeted applications for OPV

In the OPV business and technology roadmaps general pathways are outlined how OPV is expected to penetrate the markets progressively via different market segments. In order to follow these roadmaps, it is important for the OPV community to continue R&D to push the technology further to its limits by making the necessary progress in module efficiency and lifetime in combination with demonstrated lower cost of the production. This is needed to make the next steps possible from small volume niche products to larger volume, more demanding applications.

On the other hand, it is very important to identify and develop the larger, specific applications markets by involving end-users in an early stage so that the technology development and integration can be steered by the requirements defined by the end- users. In that respect it is important to focus on some new drivers for development that become more and more important in the PV sector like aesthetics and sustainability.

As mentioned under the selling points, important application parameters like flexibility, conformability, transparency and the possibility to tune the transmission wavelength are believed to be key USP for OPV. This focus on the potential USP is considered as key for the future commercial success of OPV and would open up numerous opportunities for large volume OPV applications in market segments like for instance:

- **BIPV segment:** windows in office buildings, both new construction and retrofit, façade elements between glass or on metal, aluminum or concrete
- **Transportation segment:** Integration of OPV in mobile applications via vehicles like cars, freight trucks and trains for climate control in the vehicle and prevention of discharging of batteries
- **Off grid remote sector:** Flexible, light weight deployable structures to be applied in shelter, sun shades, greenhouses

3.3.1. SWOT analysis for targeted applications

Based on the information that was gathered within the X10D consortium and from external sources, it was decided to select a number of potential high volume applications as the basis for further analysis. Despite the fact that energy harvesting applications for indoor use could be a very important stepping stone for the market introduction, it was concluded that the highest benefit for high throughput, wide web coating production can only be realized if large area modules can be made.

In the following we will continue our analysis with three categories of market segments and applications, namely

1. **Transport:** automotive
2. **BIPV:** glass/metal facades
3. **Fast deployable apps:** light structures as shelters, sun shades, greenhouses

A general assessment of the applicability of OPV is done in the form of a simplified SWOT analysis for the above mentioned application areas. In Table 2, the key success factors needed to create impact in the market segments are listed as potential strengths leading to

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market opportunities in the selected segments and applications. In addition, weakness and threats are identified which could prevent the uptake of OPV as a competitive PV technology.

Table 2: A SWOT analysis of the applicability of OPV for three selected application segments

Market segment + applications	**1. Transport**	**2. BIPV**	**3. Fast deployable apps**
Strengths/ Opportunities of OPV	Thin and Light weight	Thin and Light weight	Light weight
	Aesthetics (color tune ability)	Aesthetics (color tune ability)	Thin and bendable
	Transparancy & conformable	Semi-transparency & conformable	Semi-transparency & conformable, custom designed dimensions
	Freedom of design (printed OPV): custom designed	Integration into multiple building materials: custom designed	Large market potential in sunbelt countries for off grid charging
	Harvesting factor	Harvesting factor + heat management (passive IR block or UV block)	Harvesting factor
	Green technology/ image: low Energy Pay back times	Green technology	Green technology
	Eco-Innovation: Credit to use against CO_2 target (EU) may create innovation pressure (market pull)	Nearly-zero-Energy-building directive (EU) may create innovation pressure (market pull)	
Weaknesses/ Threats	too low efficiency, lifetime and too high costs compared to established PV technologies	insufficient lifetime and too high costs compared to established PV technologies	too low efficiency, lifetime and too high costs compared to established PV technologies
	No existing market yet	Very large market but not aware of OPV opportunity	Very large market but not aware of OPV opportunity
	too limited surface area for any PV technology to power the motor - so only for additives, green image and CO^2 credit	meeting the building requirements (long lifetime, safety regulations	
	High quality demand of car industry	Very conservative industry with long innovation cycles	

It is interesting, that some of the weaknesses and threats may be tackled actively by the OPV community, teaching the benefits of the technology to the customers. One of the examples is teaching them that not cost per Watt peak must be regarded, but cost per kWh generated, where e.g. the significantly better harvesting factor od OPV as compared to conventional PV will play a significant role. This teaching aspect has been disregarded most often so far, and will be a requirement of future OPV activities.

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3.4. Market potential

3.4.1. Application requirements

The final market entry and commercial success of OPV will depend on whether and when the technology will meet the application requirements. Several application parameters (i.e. efficiency, lifetime and costs, weight, transparency, color tune-ability, mechanical, thermal, integratability) can be recognized and could be of different relevance for different applications. The units and metrics relevant for an application can even be different. For instance, the power conversion efficiency (in W/m^2) measured under standard conditions (full sun and at 25 °C) is often regarded as the key application parameter for a PV technology but often does not reflect the actual operation of a module at real conditions. The actual power output per year (in kWh/year) depends on location, temperature, irradiation, angle of incidence and this is where OPV can show a benefit compared to other PV technologies.

Table 3: Qualitative estimations on the relative importance of the key application parameters for the selected range of applications

	Application parameters	1. Transport Automotive	2. BIPV: glass, metal facades	3a. Fast deployable apps: Shelters, Sun shades	3b. Fast deployable apps: greenhouses
Performance	**Module Efficiency/ yield/ power demand**				
	% at STC	++	++	+	+
	% at ambient light	0	0	0	0
	kWh/kWp	+	++	+	+
	kWh/day, year	+	++	+	+
	Lifetime				
	Year	++	+++	+	++
	Costs				
	Euro/Wp	+	+	+	+
	Euro/m^2	++	+++	++	++
	Euro/kWh	+	+++	++	++
	Pay Back Time	++	+++	++	+++
Form Factor	**Energy density**				
	kgram/m2	++	++	+++	+++
	W/gram	++	++	++	++
	Flexibility				
	bending radius	++	+	+++	+
Appear-ance	**Transparancy**				
	(%)	**+++**	glass +++ metal 0		+++
	Color	+	++	+	+++
Environ-mental impacts	**Energy Pay Back Time**	+	+	+	+
	Carbon footprint (CO_2-eq./Wp)	**++**	**++**	**++**	**++**

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3.4.2. Comparative assessment with other PV technologies

In order to evaluate the competitiveness of OPV to enter specific market segments as described above, a comparative assessment against other (flexible) PV technologies is made based on a number of application parameters that were listed in Table 3. A fully reliable comparison cannot be made at this stage considering the different stages of development of the various PV technologies. In this respect, the recently discovered perovskite based solar cells have not been included in the assessment, since the level of maturity is still very low, despite the very high and promising power conversion efficiencies (up to 19 %) that have been achieved on the labscale.

In Table 4, a summary is given on the quantified performance status as it is now in terms of power conversion efficiency (at STC), lifetime (T80 warranty) and costs (in Euro/Wp).

In Table 5, a comparative assessment on a qualitative basis is made based on the selected application criteria for the targeted applications. For this comparison it is assumed that OPV has reached a maturity level that it could compete with other PV technologies on the market.

Table 4: A comparison and overview of major PV technologies

Technology	**x-Si (mono) rigid**	**x-Si(poly) rigid**	**Tf Si Flexible & rigid**	**CIGS Flexible & rigid**	**CdTe rigid**	**DSC**	**OPV**
Best research cell solar cell efficiency at STC	25	20	10 (a-Si SJ) 12 (DJ) 13 (TJ)	20 (rigid) 20 (flex)	20	12	11 (SJ) 12 (TJ)
Best (sub)module efficiency at STC	22-23	18-19	10-12 (DJ)	15-17	16	8	8-9
commercial PV module efficiency	15-19	13-15	8 (SJ) - 10(DJ)(rigid) 4-6 (SJ) (flex)	11-13 (rigid) 8-10 (flex)	13-14	<3	5
Lifetime (T80)	20 years warranty	20 years warranty	Rigid 20 years warranty For Flex unknown	Rigid 20 years warranty For Flex unknown	Rigid 20 years warranty	?	10 to 20 years[1]
Module price (Euro/Wp)	0.5-0.8	0.5-0.8	0.4-0.5	0.5-1	0.5-1	>>1	>>1
Market share in 2012 (%)	83		6	4	3	0	0
Commercial status	Mature with large scale production	Mature with large scale production	Early deployment phase, medium scale production	Early deployment phase, medium scale production	Mature with medium scale production	R&D/pre-industrial	R&D / pre-industrial/ small scale production

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Table 5: A comparative assessment of PV technologies

Technology Application criteria	x-Si(poly) rigid	Tf Si Flexible & rigid	CIGS Flexible & rigid	CdTe rigid	DSC	OPV
Relative Yield (kWh/kWp, kWh/m2/year	0 (benchmark) Negative T coefficient, -0.4 % (rel.) /oC	+ Less negative T coefficient	+ Less negative T coefficient	+ Less negative T coefficient	+ Zero/pos. T coefficient, Good performance under various incident angles	++ Zero / pos. T coefficient. Good performance under various
Flexibility	Rigid	+, only possible with high T and metal substrates	+ , only possible with high T and metal substrates	Rigid	+, only possible with very high Tg or metal	++, possible with all kind of flexible
Form Factor, freedom of design	+, non-rectangular shapes are possible but more	0	0	0	++, non-rectangular shapes are possible by printing techniques	++, non-rectangular shapes are possible by
(semi-) Transparency	-, hard to achieve, only by pixilated structures	+, can provide partial transparency, but not	-	-	++	++
Color tuneability	+, possible by tuning of AR coating, no combination with	-, hardly any band gap variation possible	- hardly any band gap variation possible	-	++, wide variation in band gap possible	++, wide variation in band gap possible
EPBT	1-2 year for rigid outdoor module	1 year	1-2 year	0.8-1.0 year	Potential for < 0.5 year	Potential for < 0.5 year

Table 4 shows clearly that, at present, OPV is outcompeted on most performance metrics (efficiency, lifetime, costs, technology readiness level) and that important progress is necessary in the coming years to bring OPV to a maturity level that sufficient market pull can be created in the various market segments and a significant share of OPV in the market on the longer term.

The qualitative assessment shown in Tables 3 and 5, indicates that once this level is reached, OPV really could show competitive advantages over other (flexible) PV technologies for applications where additional parameters like transparency, form factor, flexibility, aesthetics are the drivers for future commercial success.

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3.5. Technology roadmap OPV

In the former sections, a number of targeted applications have been selected where OPV, once the technology has reached sufficient maturity, could be competitive and take sufficient market share. The relative importance of different key application parameters was addressed for three main application areas (Automotive, BIPV and off grid remote) by means of a qualitative assessment in Table 3. Existing OPV roadmaps (for instance OE-A, 5th edition) show general outlines how OPV is expected to enter the market via different product generations with increasing complexity. The most important technological challenges in terms of the key application parameters that needs to be tackled before OPV enters into these phases are discussed below:

1. **Efficiency:** At the current stage of the development, there is a wide gap between the power conversion efficiencies of hero lab cells (i.e. 10-12 %) and full scale modules produced (i.e. 6 % (Heliatek, mid 2014)) with scalable production technologies. The important challenge in the coming years is to minimize this gap by successfully demonstrating scalability of laboratory concepts, materials development and upscaling. According to the present insights of the OE-A roadmapping work group, the efficiency of a scaled OPV module (either via printing or evaporation) is expected to gradually increase and cross the barrier of 10 % efficiency somewhere between 2016 and 2020. If this development goes together with a positive temperature coefficient and relatively good performance at low light levels and different incident angles, this could favor OPV in terms of annual output as the more relevant performance parameter, over other PV technologies.

   Technological challenges:

   - Continuous development of new and intrinsically stable “photoactive” materials with high charge carrier mobilities, optimal band gaps and aligned energy levels
   - Material upscaling strategies (batch reproducibility, maintenance of properties): a special effort should be focused on alternative coupling methods that do not involve tin (such as STILLE coupling) as it creates health risk at the pilot scale on how to handle lethal tin compound + all the problematic and costly solvent recycling effort. Alternatively, eco-friendly chemistry should be developed
   - Development of mechanically and chemically stable electrode materials
   - Development of scalable high efficiency device concepts (multi-junction architectures), photon management
   - Proof of scalability, minimization of cell to module loss by developing efficient interconnection technologies
   - Energy yield assessment

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2. **Lifetime:** Lifetime is considered as one of the critical points of OPV and will depend strongly on the application area and the chosen encapsulation technology (between glass or flexible). For the selected applications (fast deployable structures, automotive, BIPV) the minimum lifetime requirement can vary from > 5 years for certain outdoor remote applications to > 15 years for BIPV applications. Recent development in flexible encapsulation, both commercially available and through applied research centres, allow lifetimes to exceed 10 years. Rigid encapsulation (such as float glass for instance) allows for 10+ years lifetimes to be achieved on a faster time scale but this will compromise the attributes of flexibility in form factor.

   Technological challenges:
   - Development of intrinsically stable and scalable device layouts
   - Identification of intrinsic and extrinsic degradation mechanism to support improvements
   - Development of inherently low cost flexible encapsulation solutions (<10 €/m2) that comply with the application requirements
   - Development of suitable standard testing protocols

3. **Costs:** The low cost structure of OPV is recognized in a number of Cost of ownership assessments, for instance carried out by Holst centre in X10D. These assessments reveal that on the long term when sufficient level of maturity is achieved, the cost of OPV will be fully dominated by the Bill of Materials. The cost dimension however is business sensitive and application dependent. It can be expressed in €/unit, €/m2 (BIPV), €/Wp and €/kWh (energy power applications). To reach a cost advantage with respect to competing PV technologies on the longer run, important steps from laboratory demonstration towards pilot and high volume fabrication needs to be made. It is clear that at this stage of the development the production and materials costs are at a too high level, due to a lack of process base and economies of scale. Following "a stepping stone approach" as is reflected in the most recent edition of the OE-A roadmap, it is expected that the OPV technologies will move to the high volume production phase after 2016.

   Technological challenges:
   - Development of robust Roll to Roll production technologies (printing, coating, evaporation, drying)
   - Handling of flexible substrates (plastics, metals)
   - Tools for quality and process control
   - Maximization of yields, minimization of scrap costs
   - Processing with environmentally benign solvents in the case for printable OPV
   - End of life cycle and recycling: green chemical processes should be envisioned when possible and waste disposal as well as treatment of effluents should be minimized in the process (+ compliance to REACH)

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4. **Transparency and color tune ability:** As these are features where OPV can have a distinct advantage over other PV technologies, it can widen the application potential in BIPV, automotive and for instance greenhouses. In general, the challenge is to develop truly transparent modules, rather than semitransparent ones that have opaque cells separated by transparent space as is the case for most inorganic PV technologies. The application parameter which needs to be tuned is the optical transmission which is expected to gradually increase from 0 % for the highest efficient cells to > 50 % on the medium term (from 2017 onwards), while maintain a minimum level of efficiency (>5 %)

   Technological challenges:
   - Development of device layouts with transparent electrodes
   - Band gap engineering and energy level alignment: development and upscaling of dedicated materials for targeted applications

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4. Concluding Remarks and Outlook

Organic Photovoltaics should not be seen as a replacement for current PV technologies. Instead, OPV is a disruptive technology that opens access to completely new markets, where energy scavenging so far has not been exploited. This may have different reasons like e. g. aesthetic considerations, or more practical ones, as weight or form factor. OPV opens completely new design options, for example due to its ability to be adapted in colour, transparency or shape. As one of the first PV technologies, with OPV it is possible to produce large semi-transparent devices with full area coating.

Structuring f these devices can be carried out either by additive (as printing) or subtractive technologies or by subtractive (like laser ablation) ones. Each of these approaches has its own upsides and creates chances in different applications. All these properties make OPV an interesting option for applications in the automotive sector, as well as in the building integration PV market. These markets are enormous: World-wide, each year 20 million car roof windows are used. The use of facade glass is 20 million square meters annually, within the EU only. All these markets become accessible, once a certain threshold of device performance is reached.

The project X10D has had this topic in focus: The efficiency of OPV cells could be increased up to 12 % within X10D, which is the current world record for OPV The lifetime of OPV has been studied in detail as well, and the durability of OPV devices could be increases further, which is another prerequisite for a widespread application of OPV.

In summary, OPV is a truly green technology, giving access to so far non-developed markets. To reach this goal, however, continued research and development will be required before a commercial breakthrough can be expected.

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