ENVIRONMENTAL BENEFITS OF PV SYSTEMS IN OECD CITIES

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ABSTRACT: A report on selected environmental indicators of photovoltaic electricity in OECD cities was jointly published in May 2006 by the Photovoltaic Power Systems Programme of the International Energy Agency (IEA-PVPS), the European Photovoltaic Technology Platform and the European Photovoltaic Industry Association (EPIA). Based on a worldwide survey of existing studies concerning the energy input of PV systems, this report provides clear and well-defined figures. The energy pay-back time (EPBT) of a complete PV system is, depending on the solar irradiation of its location, in the range of 1.6 years to 3.3 years for a roof-mounted system, and from 2.7 to 4.7 for a PV-façade. Based on a commonly admitted 30 year-long commercial life cycle, the energy return factor (ERF) is between 8 and 18 for roof-mounted systems, and between 5.4 and 10 for façades. Varying widely from one country to another, using the energy production mix from each country, 1 single kW of PV panels can avoid up to 40 tons of Carbon dioxide (CO_2) during its whole commercial life cycle - 23.5 tons for a façade. With a view to both better reflect the varying reality and to facilitate the use of the results at national and local levels by making customised figures available, the performance of PV systems is assessed on a country-by-country basis and even a city-by-city approach in larger countries where the potential for urban-scale integrated PV is highest, covering in total 41 main cities in 26 OECD countries.
Keywords: Dissemination, Environmental effect, Façade, Rooftop

1 INTRODUCTION

Electricity production based on solar photovoltaic (PV) technology is pollution-free at the local as well as the global level, it does not emit greenhouse gases, it does not dip into finite fossil fuel resources and it can be easily integrated into the urban environment, close to major consumption needs.

These particularities make PV one of the major and most suitable options in the mid-to long term future for producing electricity worldwide in OECD and non-OECD countries.

However, prior to producing electricity, manufacturing and installing PV systems and later on dismantling and recycling them at the end of their commercial life, require spending a certain amount of energy, which must be “reimbursed” before electricity from PV can be considered as renewable and clean.

Although this is no longer an issue among the scientific community and PV-related industry, unfounded rumours still persist here and there that question the status as a renewable energy of PV, including an “infinite energy pay-back-time” and an overall negative impact on the global environment.

The purpose of this paper is to present a new report published in May 2006 [1] jointly by the International Energy Agency Photovoltaic Power Systems Program [2], the European Photovoltaic Technology Platform [3] and the European Photovoltaic Industry Association [4] to provide clear and well-documented answers to politicians, decision-makers and the general public about what PV can and cannot achieve in terms of renewable, clean energy production and environmental protection.

2 DEFINITIONS

2.1 Definition of Urban Scale Photovoltaic Systems

For the purpose of this study, only grid-connected PV-systems that are made of mainstream components available on the market (standard multi-crystalline silicon modules and standard grid-tied inverters) and architecturally integrated in buildings are considered.

Since the tilt angle of the modules when installed has a significant impact on the annual energy output of the PV systems, and therefore on their environmental benefits, the two most common types of PV systems are considered:

- Rooftop-mounted systems with a tilt angle of 30° (see Figure 1)
- PV façades with a tilt angle of 90° (see Figure 2)

It is furthermore assumed that all PV systems are installed in the most favourable conditions, i.e. facing South and without any shade at any hour of the day in all seasons. Thus, results found for rooftop-mounted PV systems can be considered as optimistic values and results for PV façades as pessimistic values so that the environmental benefits of a broad range of PV systems, for instance not ideally oriented, can also be evaluated

Figure 1 : 131 kWp Solar PV Community in The Netherlands (source: Bear Architecten)

Figure 2 : 92 kWp Solar PV Community in France (source: ADEME)

2.2 Definition of Indicators used

Consistent with the position of PV as an energy technology and with the fact that energy consumption is the major contributor to the environmental impacts of crystalline silicon PV, the study focuses on two energy indicators, the "Energy Pay Back Time" (EPBT) and the "Energy Return Factor" (ERF), and one environmental indicator considered as the most relevant indicator at global level (potential for CO_2 emissions), given the fact that it is assessed that the electricity produced by PV systems will substitute to the local energy mix composed mainly of conventional energy sources.

Energy indicators used are:

- the "Energy Pay Back Time" (EPBT), defined as the ratio of the total energy input during the system life cycle and the yearly energy generation during system operation, both expressed of course in the same unit, either in primary energy or in final electrical energy. The EPBT is expressed in years,
- the "Energy Return Factor" (ERF) defined as the ratio of the total energy generation during the system operation lifetime and the total energy input during the system life cycle. An ERF equal to ten means that a PV system produces ten times more energy than it consumes throughout its life cycle. The ERF is expressed as a single figure with no unit.

The environmental indicator used is:

- the "Potential for CO_2 Mitigation" defined as the quantity of greenhouse gas emissions that will be avoided by a given PV system. It is calculated by multiplying the energy output of a PV system during its lifetime by the average CO_2 content of the local electricity mix (taken at national level). It is expressed in tons of CO_2 per kWp installed.

3 METHODOLOGY

The main innovation of the present study lies in the assessment of the environmental benefits of PV systems for a broad range of specific locations where PV systems can be installed and produce electricity. The methodology used is divided into 7 steps:

- Selection of a sample of cities representative of the area covered by IEA on a country-by-country basis, completed by a city-by-city approach in the largest countries with contrasted climates, provided that the potential for urban-scale integration of PV is significant enough. This resulted in a set of 41 main cities spread over 26 OECD countries
- Calculation of the average annual energy production for each type of system (roof-top PV systems with a tilt angle of 30° and PV façades) in each city following the same protocol (same source of data and same software)
- Comprehensive survey of the latest available scientific publications concerning the energy input of PV component manufacturing, focused on silicon technologies
- Calculation of the EPBT for each system in each location
- Calculation of the ERF for each system in each location
- Evaluation of the average CO_2 content of the local electricity mix with the same source of data and the same protocol
- Calculation of the Potential for CO_2 mitigation for each system in each location

4 ASSUMPTIONS

4.1 Annual energy output

The annual energy output for each system at each location is estimated with the simplified conventional method:

$$E_{out}=H_i.P_o.PR \quad [5]$$

With:

E_{out}: annual energy output in kWh/year

H_i: global in-plane irradiation in kWh/m²/year

P_o: nominal power of the photovoltaic system in kWp

PR: Performance Ratio

The global in-plane irradiation is calculated with the global horizontal irradiation database Meteonorm 4.10 [6] and a conversion factor generated for each location with PVsyst 3.3 software [7] used to convert horizontal irradiation into in-plane irradiation (transposition factor). Although the Performance Ratio may vary from one location to the other, it is set at 75% for each system at each location, which is the average PR value observed by Task 2 - Performance, Reliability and Analysis of Photovoltaic Systems of the IEA PVPS program [8].

4.2 Energy input

Many scientific studies have been undertaken so far in view to assess the energy input necessary to manufacture a PV system. Most of them are now out-of-date and the conclusions are not relevant to modern photovoltaics. The Energy Input data used for this study comes from an up-to-date set of life-cycle inventories based on real, measured data from production lines of nine PV companies in Europe and the USA [9]. The Preliminary results of these up-dated data that have been published recently [10] for PV systems composed of multi-crystalline silicon modules are summarised in Table I.

Table I: Energy input of current technology grid connected PV system expressed in final electrical energy

	Electrical energy [kWh/kWp]
Laminate	2 205
Frame	91
Balance of system	229
Total system	***2 525***

4.3 PV systems lifetime

An average lifetime of PV-systems as power production facilities must be determined prior to being able to evaluate any specific indicators.

This study uses the maximum lifetime of PV modules, estimated to be 30 years consistent with most published studies on this topic. The actual PV modules power production capability guaranteed by major module suppliers worldwide is generally over 25 years [10].

The weakest part of a grid-connected PV system however is the inverter, for which the Mean Time Between Failures (MTBF) is claimed by inverter manufacturers to be between 80 000 and 100 000 hours, i.e approximately 10 years [12]. This means that although inverters are reliable devices, two repairs are necessary on average during the system's lifetime: this value has also been taken into account for calculating ERF, but has very little impact on the final results.

4.4 CO_2 content of electricity mix

Since the CO_2 content of the electricity mix is not directly available in international publications for each OECD country, it has been calculated for the purpose of the present study using two different sources of data:

- the "Electricity Information 2005" published by the IEA [13] provides the gross electricity production of each OECD country, given by type of fuel and for conventional or Combined Heat & Power (CHP) plants
- freely available on the Internet "Retscreen" software [14] provides the Greenhouse Gas (GHG) content per MWh for all electricity production primary sources, the specific GHG emission factors (see Table II).

Table II : Greenhouse Gas emission factor for electricity production by fuel type [14]

	[tCO_2/MWh]
Nuclear	0
Hydro power	0
Coal	0,999
Oil	0,942
Gas	0,439
Geothermal, Solar, Tide, Wave, Ocean, Wind, Waste and other	0

In case of CHP, the GHG factor specifically designated to the electricity production has been assumed to be equal on average to 40% of the total GHG emissions as given in table 3, in order to take into account the fact that not only electricity is produced, but also heat, and that therefore GHG emissions must be shared with regards to the ratio of heat and electricity produced.

4.5 Selected cities

Depending on the size of each country and the climatic variation observed between major cities in each country, from 1 to 3 cities of each OECD member country have been selected (see table III).

Table III : list of selected OECD cities

Australia	Sydney, Perth, Brisbane
Austria	Vienna
Belgium	Brussels
Canada	Ottawa, Vancouver
Czech Republic	Prague
Denmark	Copenhagen
Finland	Helsinki
France	Paris, Lyon, Marseille
Germany	Berlin, Cologne, Munich
Greece	Athens
Hungary	Budapest
Ireland	Dublin
Italy	Rome, Milan
Japan	Tokyo, Hiroshima, Sapporo
Republic of Korea	Seoul
Luxembourg	Luxembourg
The Netherlands	Amsterdam
New Zealand	Wellington
Norway	Oslo
Portugal	Lisbon
Spain	Barcelona, Madrid, Sevilla
Sweden	Stockholm
Switzerland	Bern
Turkey	Ankara
United Kingdom	London, Edinburgh
United States	Washington, Los Angeles, Houston

5 OVERALL RESULTS

5.1 Energy Pay-Back Time (EPBT)

For rooftop-mounted PV systems, the range of EPBT is between 1.6 and 3.3 years, with the best case in Perth, Australia and the worst case in Edinburgh, UK.

The EPBT for PV façades is logically slightly longer, since their production rate per installed kWp is significantly lower, all other parameters being equal, with a range from 2.7 to 4.7 years, with the best case in Perth, Australia and the worst case in Brussels, Belgium (see Table IV and Figure 3).

Table IV : Energy Payback Time of Urban Scale PV systems

	Minimum value [Years]	Maximum value [Years]
Roof-top mounted PV system	1,6	3,3
PV façade	2,7	4,7

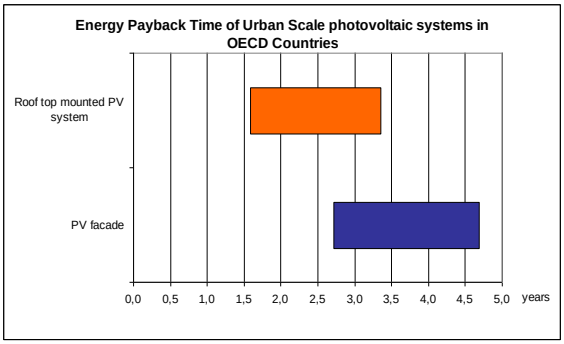

Figure 3 : EPBT of Urban Scale PV systems

5.2 Energy Return Factor (ERF)

Rooftop-mounted PV systems are expected to produce during their whole lifetime between 8 and 17.9 times the amount of energy that was needed for their manufacture, installation and dismantling, with the best case in Perth, Australia and the worst case in Edinburgh, UK

PV façades are expected to produce during their whole lifetime between 5.4 and 10.1 times the amount of energy that was needed for their manufacture, installation and dismantling, with the best case in Perth, Australia and the worst case in Brussels, Belgium (see Table V and Figure 4).

Table V: Energy Return Factor of Urban Scale PV systems

	Minimum value [-]	Maximum value [-]
Roof-top mounted PV system	8,0	17,9
PV façade	5,4	10,0

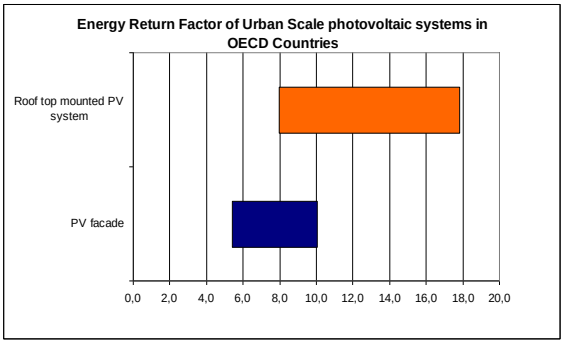

Figure 4 : ERF of Urban Scale PV systems

5.3 Potential for Greenhouse Gases Emissions Mitigation

Once they have paid back their energy input, rooftop-mounted PV-systems can avoid during their lifetime the emission of up to 40 tons of CO_2 for each kWp installed, with the highest value in Perth, Australia due to a combination of high solar irradiation and a high CO_2 content of the power mix, and the lowest in Oslo, Norway, with a combination of an almost carbon-free power mix and a low solar irradiation.

The corresponding figure for PV façades is limited to 23,5 tons of CO_2 per kWp installed, with the same best and worst cases (see Table VI and Figure 5).

Table VI – Potential for CO_2 Mitigation of Urban Scale PV systems

	Minimum value [tCO_2/kWp]	Maximum value [tCO_2/kWp]
Roof-top mounted PV system	0,1	40,0
PV façade	0,0	23,5

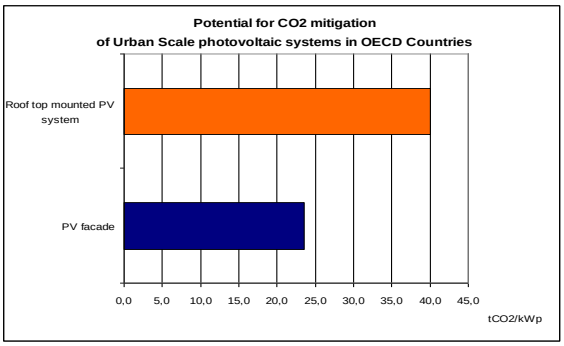

Figure 5 : potential for CO_2 mitigation of Urban Scale PV systems

6 RESULTS BY COUNTRY

The full report called "Compared assessment of selected environmental indicators of photovoltaic electricity in OECD cities" with all results country-by-country and also city-by-city can be downloaded from the IEA PVPS Task 10 website www.iea-pvps-task10.org or the EU PV Platform website www.eupvplatform.org.

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