# **R&D IN PHOTOVOLTAIC POWER SYSTEMS:** STATUS AND STRATEGIES IN IEA COUNTRIES

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ABSTRACT: The International Energy Agency (IEA) Photovoltaic Power Systems Co-operative Programme (PVPS), Task I, has performed an analysis of the existing photovoltaic R&D-programmes in participating IEA countries. The objective of this joint project is to present and analyse the status and the strategy of photovoltaic R&D in these countries (feedstock materials, cell technology and manufacturing processes, PV modules, support structures, BOS components, testing, monitoring, standardisation and international co-operations). The performed analysis allows comparisons between the different approaches to photovoltaic power systems, their various forms of application depending on the national energy policies, the strategic and operational issues of the different national programmes, the possible structures of R&D, the time frames for deployment as well as budgetary considerations.

Keywords: R&D and Demonstration Programmes - 1: Strategy - 2: Implementation - 3

#### 1 INTRODUCTION

The objective of this co-operative work is to present and analyse the status and the strategy of photovoltaic research and development (PV R&D) in 18 member countries of the International Energy Agency's Photovoltaic Power Systems Co-operative Programme (IEA-PVPS) covering the period between 1985 and 1996. The work is based on national status reports of the participating countries<sup>1</sup> which cover the strategic approach for PV R&D, the major R&D activities and their main results and identify the priorities and changes over the past 10 years. In this context, R&D covers all activities in public and private institutions and companies which contribute to produce more efficient, more reliable and cheaper components and products, their use and their understanding in a PV system. Finally, these national reports also identify novel approaches and future opportunities. The present contribution summarises the main findings giving a comparative overview of selected fields and identifies the trends in strategic and technological issues.

## 2 STRATEGY, POLICY AND PRIORITIES

In many countries, following the oil crisis on one hand and due to environmental concerns on the other hand, emphasis was given towards the development of new sources of renewable energies. Some countries have developed a vision about the role which renewable energies in general and photovoltaics specifically might play in a future energy economy and the time frame for such a deployment whereas other countries see these technologies rather as a possible option for the future.

Some countries follow a mostly scientific approach, which focuses mainly on material issues in cell technology and performance. Other countries concentrate on manufacturing technology on cells and modules. A clear emphasis is put on the need of an important cost reduction for PV systems. R&D can affect the system costs by reaching technological advancement in material performance and manufacturing technology, standardisation and industrial products. Although balance of system components (BOS) costs strongly affect the overall costs for PV systems - they represent 50 to 70 % of the total cost of a PV system -, particularly on the shorter time scale, R&D emphasis in this field is less pronounced. These questions are however dealt with more frequently in countries which also have an important amount of PV systems installed or which plan to do so in a near future. Therefore, a trend to increase R&D in general system aspects and mounting technologies can be observed. In contrast with these mostly technological approaches, some countries try to integrate the R&D strategy in a broader strategy regarding energy policy and market deployment.

The time frame expected for large scale market deployment varies considerably between the different countries and also reflects the priorities given in PV R&D. In a business as usual scenario, that is without some kind of incentives (energy output related, rate-based, investment related or tax credits), the deployment of PV will naturally take considerably more time than if these instruments are put into place. The value of PV and the related energy services is not frequently addressed explicitly. In several

<sup>&</sup>lt;sup>1</sup> Australia, Denmark, Finland, France, Germany, Italy, Japan, Korea, Netherlands, Portugal, Spain, Sweden, Switzerland, United Kingdom and United States of America; in part Austria, Israel and Norway

countries, however, the customer requirements, public opinion and the increasing amount of possible business opportunities, together with an appropriate support by government authorities, are believed to lead to costeffective applications in a more near-term. These countries consider decentralised, residential PV systems likely to become cost-effective between 2000 and 2005. In these scenarios, overall cost-effectiveness is expected between 2010 and 2020.

In some countries, the R&D activities somewhat reflect the countries policy for electric energy and the nature of the grid extension, namely a focus on the use of standalone and/or grid-connected systems. Other countries, however, follow an export-oriented approach which then may be more independent of the nature of the electricity production and distribution. In general and on the nearterm perspective, PV is developed for small decentralised electricity production (stand-alone or grid connected). In one country, Italy, the utility ENEL is the principal actor; this is reflected by a stronger emphasis towards larger PV plants (> 100 kWp).

In many countries, pilot and demonstration activities represent a direct follow up on R&D projects. This close link is however not always present. Although technology transfer is often not addressed in a specific manner, the involvement of the manufacturing industry is a common approach to bring the technology from research to the marketplace. In only few countries, education as a further measure in an overall strategy to develop PV is explicitly mentioned.

Table I gives an overview on the organisation and the structure of PV R&D in the participating countries.

	А	А	С	D	D	Е	F	F	G	I	I	I	K	Ν	Ν	Р	S	U
	U	U	н	E	N	S	Ī	R	В	S	T	P	0	L	0	R	W	S
	S	Т	Е	U	K	P	N	Α	R	R	A	N	R	D	R	Т	Е	Ã
Ministry of Science, Environ-		Х		Х									Х		Х	Х		
ment																		
Ministry of Economy, Energy		Х	Х		Х	Х	Х			Х	Х				Х		Χ	Х
Agency	Х							Х	Х			Х		Х				
Comprehensive gov. programme			Х	Х				Х	Х			Х		Х				Х
Central research facilities																		Х
Large research centers	Х			Х		Х					Х	Х		Х				Х
Small research centers	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х		Х	Χ	Х
Manufacturing of cells	Х			Х	Х	Х	Х	Х	Х		Х	Х	Х	Х				Х
Manufacturing of modules	Х		Х	Х	Х	Х	Х	Х	Х		Х	Х	Х	Х			Χ	Х
Manufacturing of system comp.	Х	Х	Х	Х		Х		Х	Х		Х	Х	Х	Х				Х
Research oriented					Х					Х						Х		
Product oriented	Х					Х	Х		Х						Х		Χ	Х
Implementation oriented		Х	Х	Х				Х			Х	Х	Х	Х				
Energy plan for photovoltaics			Х								Х	Х	Х	Х				

Table I: Organisation and structure of PV R&D in IEA countries

Table II gives the proportion of expenditures for PV R&D for the different sectors. A strong dominance in the cell & module sector can be observed and the trend shows increased activity in manufacturing processes.

 Table II: Break-up of public expenditure for PV R&D in different sectors

	Materi- als, PV cells & modules, Manu- facturing processes	B.O.S. compo- nents, PV systems	Testing, standar- dization	Interna- tional coopera- tion									
Public bud- get (%)	70 %	15 %	10 %	5 %									
Present	Less mo-	More	Slight	Slight									
budget	ney on	weight on	increase	increase									
trend	funda-	PV spe-	due to	in budget									
	mentals,	cific	demand	but									
	more on	system	in label-	mainly									
	manu-	compo-	ling and	stronger									

		facturing processes	nents and system design	standards	motiva- tion							
3	3 PHOTOVOLTAIC CELLS AND MODULES											

The R&D towards photovoltaic cells and modules has two basic aspects: the materials used for the conversion process and the accompanying manufacturing processes. With respect to these issues, R&D may be classified in short, medium and long term perspective with the characteristics of exploratory R&D (new materials), technical R&D (optimisation) and product R&D (manufacturing). Of all materials under development, only three have reached the stage of considerable industrial production, namely single-crystal silicon (sc-Si), multi-crystalline silicon (mc-Si) and amorphous silicon (a-Si).

The approach on the R&D of photovoltaic cells is similar for the participating IEA-countries with respect to the highest priority: cost reduction. However, the way to reach this goal differs. Lower costs does not only mean higher efficiencies but also higher production volumes, cheaper production technologies, low material use and product integration. In general, no country clearly decided for one PV cell technology to be the PV cell of the future, although in Japan definitely most effort is put on amorphous silicon technology. There is one point in which almost all countries agree: the PV cell of the future will be a thin film PV cell. Different technologies can co-exist even on an industrial level. This might be related with the fact that the different cell technologies have their own strengths and in the stage of early market introduction can supply different market sectors (depending on the costs, the provided service, the availability of required surfaces and driven by costs per Wp or per m2). Clear examples are the dominance of a-Si in consumer electronics, mc-Si for roof integration and sc-Si for higher power applications. The observed material variety could well be characteristic of the different applications also in the future.

A tendency in recent years is the interest in thin-film polycrystalline silicon PV cells (pc-Si) due to some technological breakthroughs with respect to efficiencies and the development of better processing and light trapping technologies. On the same line, organic PV cells receive (renewed) interest. Another trend is that in recent years more effort has been put in combination type (hybrid) PV cells (e.g. a-Si/pc-Si, a-Si/c-Si) in order to increase the efficiencies (two bandgaps) and to combine the advantages of both worlds (e.g. pc-Si adds stability in the case of a-Si). In general all cell technologies evolve in the same direction: thinner, more sophisticated semiconducting structures, more light trapping and optimum combination of bandgaps.

III/V-type PV cells are mainly used for space applications, although in some countries one also investigates the possibility to create thin GaAs layers by an epitaxial lift off method to be applied on top of other cell types. III/Vcompounds also constitute one material approach for the purpose of thermo-photovoltaic power generation.

Development work started in the last couple of years to adapt photovoltaic modules to facades elements or sun shading elements for both new and refurbished buildings. This topic seems to gain importance in R&D programmes. The objective of the effort is to develop PV products and systems for buildings and photovoltaic roofing material that can replace, e.g., conventional roofing shingles.

Figure 1 shows the evolution of PV cell efficiencies for different materials.



Figure 1: Evolution of laboratory conversion efficiencies

Figure 2 shows the achievements in efficiencies for most PV cell materials in development.

Some countries are strongly in favour of an integral approach on PV cell and PV-component R&D. This means e.g. that the price of the cell and thus the module is treated as a part of the building integrated PV system: cheap roof integration techniques allow lower efficiency PV cells. It also means that in future the substrates of thin film PV cells should be applied in roof-integration constructions which are as cheap as the roof-tiles. In this respect we see a diversification of substrates in the R&D occurring (plastics, metals, ceramics and construction materials). At the moment, the application on roofs is still in favour of glass-substrates. Advantages of the integral approach are that the R&D gets more market driven and that the PV-systems are optimised in a balanced way.



Figure 2: Achievements in different cell technologies

Table III shows which cell technologies are being studied in the different countries.

	Α	Α	С	D	D	Е	F	F	G	Ι	Ι	J	Κ	Ν	Ν	Р	S	U
	U	U	Н	Е	Ν	S	Ι	R	В	S	Т	Р	0	L	0	R	W	S
	S	Т	Е	U	Κ	Р	Ν	Α	R	R	Α	Ν	R	D	R	Т	Ε	Α
Feed-stock				Ι				Р	Ι		Ι	Ι	Ι		Ι			Ι
Single-crystal silicon	Р			Ι	Ι				Ι	Р	Ι	Ι	Ι					Ι
Multi-crystalline silicon	Ι			Ι		Ι	Р	Ι	Ι		Ι	Ι	Р	Ι	Ι			Ι
Polycrystalline thin film silicon	Р		Р	Ι				Р	Ι		Ι	Ι		Р				Ι
Amorphous silicon	Р	Р	Ι	Ι	Р		Ι	Ι	Ι	Р	Р	Ι	Ι	Р		Р		Ι
CdTe	Р		Р	Ι		Ι	Р	Р	Ι	Р	Р	Ι	Р					Ι
CIS			Р	Ι			Р	Р			Р	Ι	Р				Ι	Ι
Organic	Ι	Р	Ι	Ι		Р		Р			Р			Р			Ι	Ι
III/V-compounds				Р							Р	Ι	Р	Р				Ι
Hybrid materials	Ι	Ι	Р	Ι			Р	Р	Р		Ι	Ι	Р	Р				Ι
Roof-modules	Ι	Ι	Ι	Ι	Ι	Ι	Р		Ι		Ι	Ι	Ι	Ι				Ι

Table III: Cell & module R&D in IEA countries (P = Public laboratory, I = Industrial & public laboratory)

Table IV and Figure 2 show the state of the art of the confirmed conversion efficiencies. A large difference is noted in the efficiencies reached on laboratory scale and which are produced as pre-commercial industrial prototypes.

 Table IV: Confirmed conversion efficiencies on laboratory scale cells and pre-commercial modules

Cell	lab-	lab-	module-	module-
material	efficiency	efficiency	efficiency	efficiency
	(1993)	(1996)	(1993)	(1996)
sc-Si	23.1	24.0	20.5	22.7
mc-Si	17.3	18.6	13.0	15.3
pc-Si	14.9	14.9		
CdTe	15.8	15.8	8.1	9.1
CIS	13.7	16.4		10.3
a-Si	12.5	13.5	9.8	10.2
organic		8.5		

The laboratory results can only be interpreted as perspectives, because some laboratory processes are too expensive to implement in a production line

#### 4 BOS COMPONENTS AND PHOTOVOLTAIC SYSTEMS

It has been seen previously that the novelty of PV cell materials and the challenge of reducing manufacturing costs of photovoltaic cells and modules attracted a great deal of attention of public research laboratories and the photovoltaic companies. Balance of system (BOS) hardware components did not receive, from the point of view of R&D, the same degree of interest since most of them where readily available off the shelf at an affordable cost. BOS components are used to maximise the energy produced: they include power processing hardware such as charge controllers and inverters, field wiring, switches, junction boxes and protection equipment. Their costs compared to the installed price of a photovoltaic system vary for different types of applications: it is never negligible, 70 % for a stand alone photovoltaic system including storage batteries, 30 % for a roof integrated PV system and 50 % for a power plant (>100 kWp).

It is when photovoltaic system did not exhibit proper expected and safe performance and that various difficulties occurred in the field for example due to lack of reliability of some of the BOS components and certain types of loads that photovoltaic companies started to develop or improve them, particularly inverters and charge controllers. In the sector of domestic stand alone applications, the non-predictable consumption of domestic users and the lack of a proper basic maintenance contributed to premature wear-out of some of the BOS components (inverters, storage batteries). These difficulties imposed to rethink their design, their reliability and their cost.

Table V shows the BOS R&D activities of the different countries. The main areas are energy storage, charge regulation, inverters, support structures, system design and energy management. The nature of these activities makes them suitable for small and medium enterprises. Industrial activity in this field is frequently, but not always, coupled with the implementation strategy of PV systems in that country.

Table V: BOS components R&D in IEA countries (P = Public laboratory, I = Industrial & public laboratory)

	A	A	C	D	D	E	F	F	G	1	1	J	ĸ	IN	IN	Р	3	U
	U	U	Н	Е	Ν	S	Ι	R	В	S	Т	Р	0	L	0	R	W	S
	S	Т	Е	U	Κ	Р	Ν	А	R	R	А	Ν	R	D	R	Т	Е	Α
Power conditioning units	Ι	Ι	Ι		Ι	Ι	Ι	Ι	Ι		Ι	Ι	Ι	Ι				Ι
Inverters	Ι	Ι	Ι	Ι	Ι	Ι	Ι		Ι		Ι	Ι	Ι	Ι				Ι
Storage batteries	Ι	Ι		Ι			Ι	Ι	Ι		Ι	Ι	Ι	Р			Ι	Ι
Ageing studies batteries	Ι			Ι		Ι		Ι			Ι	Ι	Ι	Р			Ι	Р
Stand alone PV systems	Ι	Ι	Ι	Ι	Ι	Ι	Ι	Ι	Ι	Ι	Ι	Ι	Ι	Ι			Ι	Ι
Grid-connected PV plant	Ι	Ι	Ι	Ι	Ι	Ι					Ι	Ι						Ι
Grid-connected dispersed	Ι	Ι	Ι	Ι	Ι	Ι	Ι		Ι	Ι	Ι	Ι	Ι	Ι			Ι	Ι
Hybrid systems	Ι	Ι	Ι	Ι	Ι			Ι	Р		Ι	Ι	Ι	Р				Ι
Standards	Ι	Ι	Ι	Ι	Р			Ι	Р		Ι	Ι	Р	Р				Ι

### **5** IMPLEMENTATION

National photovoltaics programmes and private industrial initiatives such as utilities and other users have successfully forged a terrestrial photovoltaic industry. Through basic research and development coupled with system applications, the programmes helped develop basic science and complex products and at the same time have created qualified jobs.

Though not strictly speaking a R&D topic but possibly an outcome of it, it is interesting to note that the photovoltaic module industry evolved over the past 10 years from rather research and development oriented companies to more production oriented companies. Some vertically integrated cell/module companies are now qualified under the ISO 9000's standards: a proof of industrial maturity if needed to be demonstrated. ISO certification of photovoltaic system companies had not yet started at the end of the concerned period but some countries have been very active in publishing guides of recommended practices to which installers are encouraged to adhere to.

In addition to these system and material related issues, a number of subjects have been studied which may affect the deployment of PV systems strongly, such as on safety, quality assurance, environmental aspects and standards. It is generally accepted that these aspects will gain in importance as the implementation of photovoltaics proceeds. Along this line, non-technical-barriers and financing as well as the identification of business opportunities and potentials are being addressed more frequently.

The Technical Committee 82 of the International Electrotechnical Commission published 19 standards mainly on PV modules issues and in the recent past put effort in BOS components and PV systems. Some IEA countries were very active in the different working groups.

# 6 CONCLUSION

Following a steady increase, public budgets for PV R&D reached a summit in the early 90es. The global situation of public finance in most of the countries made this commitment more difficult and a decrease in public PV budgets was the consequence. Nevertheless at the same time appeared new sources of funding, e.g. for PV rural electrification programmes. In a number of countries, constructive and increased collaboration with the electric utility sector occurs.

For specific applications, mainly stand-alone domestic and non-domestic, PV is economically viable. PV is now entering a new phase of development. The time needed for transferring the laboratory results into commercial products is still too long. There are a number of needs that should be addressed particularly within a context of large scale deployment. They include not only advances in PV cell technology, for example manufacturing processes, manufacturing capacity scale up but also research and development of building components and systems, power handling, energy storage and BOS hardware. PV should be treated more consequently as an energy system.

Although the national photovoltaic programmes achieved many successful results and products PV R&D continues, and must continue in order to bring the costs down and performance of photovoltaic systems up. A stronger focus towards implementation will be beneficial to faster market deployment.

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