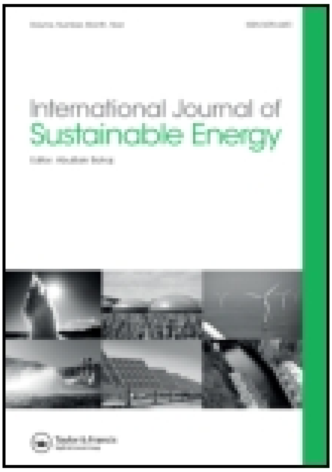

International Journal of Sustainable Energy
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gsol20

Beyond solar radiation management - the strategic role of low-cost photovoltaics in solar energy production

Felix Hermerschmidt[a], Panayiotis D. Pouloupatis[a], George Partasides[b], Andreas Lizides[b], Stella Hadjiyiannakou[b] & Stelios A. Choulis[a]

[a] Department of Mechanical Engineering and Materials Science and Engineering, Molecular Electronics and Photonics Research Unit, Cyprus University of Technology, 3603 Limassol, Cyprus

[b] Energy Service, Ministry of Energy, Commerce, Industry and Tourism, 1421 Nicosia, Cyprus

Published online: 22 Nov 2013.

International Journal of Sustainable Energy, 2015
Vol. 34, Nos. 3–4, 211–220, http://dx.doi.org/10.1080/14786451.2013.854244

Beyond solar radiation management – the strategic role of low-cost photovoltaics in solar energy production

Felix Hermerschmidt[a], Panayiotis D. Pouloupatis[a], George Partasides[b], Andreas Lizides[b], Stella Hadjiyiannakou[b] and Stelios A. Choulis[a]*

[a]*Department of Mechanical Engineering and Materials Science and Engineering, Molecular Electronics and Photonics Research Unit, Cyprus University of Technology, 3603 Limassol, Cyprus;* [b]*Energy Service, Ministry of Energy, Commerce, Industry and Tourism, 1421 Nicosia, Cyprus*

(*Received 30 August 2013; final version received 30 September 2013*)

This paper examines the role of renewable energy sources (RES), especially the sun, as a potential solution for solar radiation management concerns. It states how photovoltaic (PV), especially low-cost PV and other thin film technology, can be applied and what impact and share they can have on the European market – using the Cyprus market as an example of strategic implementation. The Energy Service of the Ministry of Energy, Commerce, Industry and Tourism currently reports a 7.5% share (as at end of 2012) of RES in overall final energy consumption and suggests ways in which that share can increase. In the near future, PVs will be the most significant electricity source if the cost per kWh produced is further reduced, as was proven recently during the award procedures for PV systems.

Keywords: renewable energy sources; low-cost PVs; solar energy production

1. Introduction

Renewable energy sources (RES) can help to reduce pollution and greenhouse gas emissions responsible for the planet's temperature increase, also known as global warming. Additionally, by replacing the use of fossil fuels, renewables can also provide independence from energy imports and therefore support a self-sustained energy economy. Especially photovoltaic (PV) technology can help in these efforts of replacing fossil fuels and the effects can have widespread economic impact (Dennler and Brabec 2008).

Generally, global warming refers to the rising of the average temperature of Earth's atmosphere and oceans. Earth's average surface temperature increased by about 0.8°C in the last 100 years, with roughly two-thirds of that increase occurring over just the last three decades (National Research Council 2011). Many scientists believe that increased concentrations of greenhouse gases, especially carbon dioxide (CO_2), produced by human activities such as deforestation and burning fossil fuel are responsible for global warming.

As solar radiation emitted by the sun enters, is reflected away from or is absorbed by the atmosphere, the greenhouse gases trapped within it can have an impact. The amount of energy contained in the sun's emitted radiation striking 1 m^2 of Earth's surface every second (averaged

*Corresponding author. Email: stelios.choulis@cut.ac.cy

over the entire surface) is in the order of 340 W/m^2, of which around 240 W/m^2 are able to enter Earth's atmosphere. Earth itself absorbs around 168 W/m^2, of which some is converted into thermal energy (heat). The infrared part is emitted to the atmosphere and partially into space. However, a significant amount of infrared radiation is trapped in the atmosphere because of the presence of greenhouse gases. The denser the greenhouse gas layer, the more infrared radiation is trapped (Dennler and Brabec 2008; IPCC 2007a).

2. Beyond solar radiation management

2.1. *Solar radiation management in the short term*

In light of this process, there is a widespread discussion in the media about utilising solar radiation management (SRM) in order to gain control over the greenhouse effect (Black 2012). Some scientists believe that this could occur if greenhouse gas emissions are reduced, while others believe that this can be achieved only by removing them from the atmosphere altogether. There is also a group of scientists that believe global warming can be eliminated by reducing the solar radiation entering the atmosphere and hence being absorbed by Earth.

As a result, there are several SRM or geo-engineering methods being discussed, many of them only useful for the relatively short term. This includes 'options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry' (National Research Council 1992). In other words, geo-engineering encompasses a range of techniques to remove greenhouse gases from the atmosphere, especially CO_2, or to reflect incoming sunlight.

Atmospheric projects involve techniques that seek to modify the atmosphere. Stratospheric sulphur aerosols such as hydrogen sulphide or sulphur dioxide are spread over the Earth's surface either by aircrafts or balloons aiming to modify its albedo or reflection coefficient (National Environment Research Council 2011). Cloud seeding has also been proposed, whereby the formation of high-altitude cirrus clouds is reduced in order to let surface heat escape (Storelvmo et al. 2013). A further technique is carbon sequestration using a process that removes and stores atmospheric CO_2 while yielding clean hydrogen that does not contribute to greenhouse gas generation (Rau et al. 2013). Terrestrial albedo modification projects use techniques that do not involve modification of the atmosphere but emphasise the Earth's reflectance enhancement. Painting the roofs and shells of buildings with bright colours that are more reflective, or covering the deserts with reflective plastic sheets, or even using floating litter within controllable areas in the oceans are some of the suggestions.

However, these kinds of projects were mainly proposed due to the immediate impact that they could have on the reduction of global warming and due to the low financial cost that some of them have. On the other hand, they could also create unforeseen disadvantages concerning the environment but also social and financial factors. The Intergovernmental Panel on Climate Change concluded in 2007 that geo-engineering options remained largely unproven and that reliable cost estimates had not yet been published (IPCC 2007b). Still now, it is unclear exactly what the costs and precise risks or benefits are.

2.2. *Renewables for a longer term solution*

The far longer term solution can only come from a direct use of RES and especially in combination there is vast potential available to provide energy for the world by replacing more traditional fuels (see Table 1).

Table 1. Potential of RES (UNDP 2000).

Energy source	Capacity (EJ/year)
Geothermal	5000
Solar	1575
Wind	640
Biomass	276
Hydro	50
Total	7541

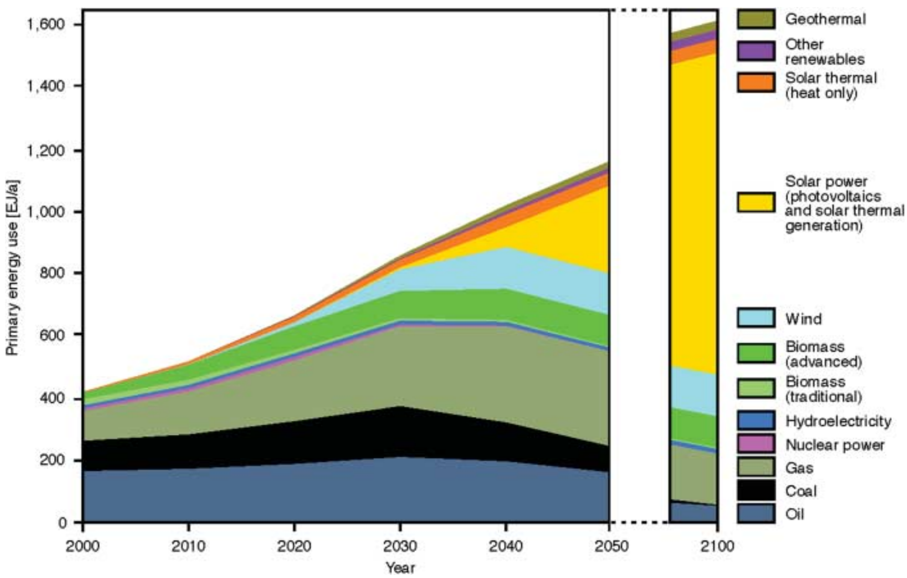

Figure 1. Transforming the global energy mix: the exemplary path until 2050/2100. Figure used with permission, © WBGU (WBGU 2003).

Geothermal energy is considered a sustainable and RES able to replace fossil fuels leading to reductions in pollution and greenhouse gas emissions. In 2008, geothermal power production exceeded more than three times that of PVs (Rybach 2010). However, although geothermal energy has the largest capacity within the RES, its current growth is steady and slow in stark contrast to wind and solar PVs, which hold the greatest potential for providing energy (see Figure 1). By 2100, the predicted use of solar power is substantially more than any other form of energy supply (WBGU 2003).

2.3. *The sun – the ultimate renewable*

To this end, the sun is the single most clean and sustainable energy source of our world. The energy contained in the sunlight striking the earth for 40 min is equivalent to one year's global energy consumption (Zweibel, Mason, and Fthenakis 2008). In the future, PVs might be the most significant electricity source if the cost per kWh produced is further reduced. The cost reduction can either be achieved by lower cost of the current commercial solar cell technologies or by the development of new solar cell materials and device concepts. A high performance low-cost PV technology will be the baseline for the development of solar grand plans, such as the one published by Zweibel, Mason, and Fthenakis (2008). It was resoundingly in favour of PV technologies and that their implementation was not a thing of the distant future, but that the technologies were ready to be made use of immediately. It envisages 69% of electricity in the USA being provided by solar power by 2050. There are different types of solar energy conversion methods – the two most distinct types being PVs and concentrated solar power (CSP). The PV systems directly convert the energy contained in sunlight into electrical energy, whereas CSP systems usually employ mirrors to focus sunlight onto a vessel containing a liquid with relatively high boiling point, which in turn generates electricity via a steam turbine. The following section will focus on the strategic implementation of PV technologies for solar energy production.

3. The strategic role of low-cost PVs in solar energy production

3.1. *PV technologies*

PVs employ the use of physical processes taking place inside the PV device upon sunlight hitting it to produce electricity. The least expensive commercially viable PV technology at the moment is based on cadmium telluride material (CdTe). These can currently convert roughly 10% of the energy contained in the incident sunlight into electrical energy. The modules would have to convert electricity with around 14% efficiency. This is in order to provide the US market with electricity at around US$0.06/kWh (Zweibel, Mason, and Fthenakis 2008).

However, CdTe contains the extremely toxic metal cadmium. Even though the current cost for installing CdTe solar fields is the cheapest (Zweibel, Mason, and Fthenakis 2008), this should not be the only factor in determining whether a field should be built. Cadmium needs to be recycled after use and this need to be considered when calculating viability.

The past decade has already proven the exponential growth of different kinds of PV systems installation capacity, with a combined annual growth rate of approximately 50% (EPIA 2012). In 2010, solar cell production was estimated in the range of 27 gigawatt-peak (GWp). The majority of the cells produced were made of multicrystalline silicon (mc-Si). The expected cell production for 2011 is over 50 GWp. The vast majority of PV cells is silicon-based and its market share is close to 90% in 2010 (IRENA 2013). Thin film technologies such as CdTe are still struggling to make significant impact in terms of market share.

However, the cost of existing Si-based technologies is still trying to be reduced to be able to compete with intense research efforts for future cost-effective PV technologies. This is because the vast majority of the cost of a silicon-based PV is the cost of the silicon itself (Green 2007).

Countries such as Cyprus are now increasingly developing their renewable energy potential. According to the European Parliament and the council on the promotion of the use of energy from renewable sources, PVs are expected to grow in significance to meet the target share of renewable energies of 20% by the year 2020 (EC 2009). Environmentally friendly low-cost PV technologies will undoubtedly retain strong positions in the future.

Meanwhile, research efforts on new lightweight, flexible and low-cost organic PV materials are starting to enter the market and can offer many new applications for solar cells, ranging from self-powered electronics to energetically self-sufficient buildings (Hoth et al. 2013).

3.2. *Strategic implementation in Cyprus*

The main pillars of the energy policy of Cyprus rest on the security of energy supply, the contribution of the energy sector in increasing productivity and competitiveness of the national economy and environmental protection and sustainable development. Energy production must be sufficient, secure, economically viable and clean. To this end, the Energy Service of the Ministry of Energy,

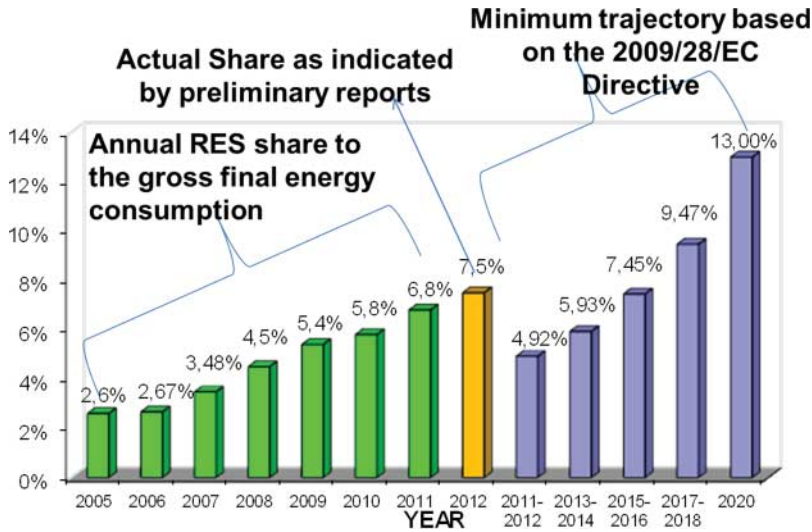

Figure 2. Annual RES share in gross final energy consumption in Cyprus (green bars); actual share as indicated by preliminary reports for 2012 (yellow bar) and minimum trajectory based on 2009/28/EC directive (purple bars).

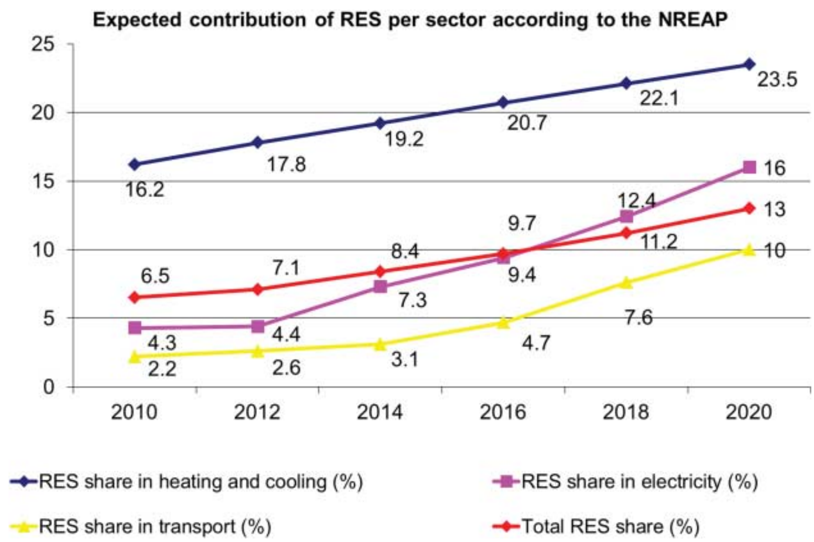

Figure 3. Expected contribution in Cyprus of RES per sector according to the NREAP.

Commerce, Industry and Tourism (MECIT) has set specific annual targets for the share of RES in the gross final energy consumption (see Figure 2).

Cyprus targets a use of 13% RES in its gross final energy consumption by the year 2020. In 2012, ∼7.5% of gross final energy was produced using RES, meaning the target for 2015–2016 has already been surpassed. The National Renewable Energy Action Plan (NREAP) foresees increasing amounts of renewable energies flowing into Cyprus' energy mix (Beurskens, Hekkenberg, and Vethman 2011). The targeted 13% by 2020 was estimated including several sectors of energy use, including heating and cooling, transport and electricity from RES. Figure 3 shows the make-up of these different sectors and their respective target percentage of RES contribution. The highest

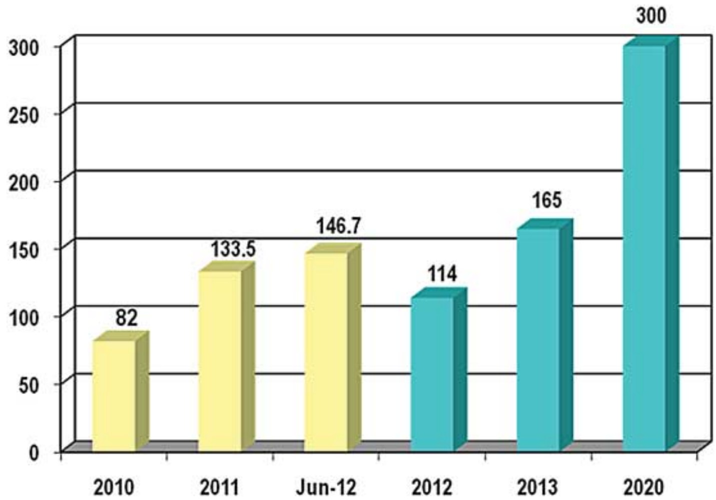

Figure 4. Currently installed wind capacity in Cyprus in MW (yellow bars) and projected (blue bars).

target is set for heating and cooling, where approximately a quarter of energy will be produced renewably.

In order to achieve these targets, there are a number of support schemes in place linked to the RES national action plan. For electricity generation from RES installations, the schemes provide feed-in tariffs for 20 years in order to support energy production from wind, PV, biomass and CSP. Additionally, for the first time in 2013 the net-metering scheme was introduced for PV systems. Similarly, support is provided for the installation of heating and cooling systems using RES such as solar and geothermal heat pumps. This is achieved using a special fund for RES and energy conservation by providing guaranteed purchase prices for electricity produced using these sources. The revenue for this fund comes to a large extent from existing consumers who pay an additional tax of 0.005 €/kWh.

Cyprus obtains its renewable energy through the use of three main types: wind, solar thermal and PVs. With regard to wind capacity, Cyprus is ahead of its target for 2012 (146.7 MW installed) of 114 MW capacity with an increasing trend (see Figure 4). However, clean energy production through the use of wind farms will always be a challenging RES technology, since there are a number of obstacles to be overcome. Cyprus has relatively average wind speeds, which do not allow for excessive gain from the installed wind farms, falling to zero gain if there is no wind present. The variations of the energy produced through the wind farms are a problem for the distribution system operators especially to isolated electricity networks. Furthermore, as Cyprus is a developed tourism country, there are issues of land planning to be considered as there is competition for land use for real estate development. Local communities also often oppose installation of wind farms due to land depreciation, for example. This is an issue facing a number of RES that require large areas of land use, including PVs.

A far more promising and in Cyprus extremely widespread approach is the use of incident solar energy for heating purposes in solar thermal energy production, utilising the space on the roofs of buildings. Approximately 92% of households and 53% of hotels are equipped with solar water heating systems, cumulating in a total area of 937,363 m^2 of solar collectors across Cyprus (see Figure 5(b)) (ESTIF 2011). This means that there is ∼1 m^2 of installed solar collector capacity per capita. The overall annual capacity of solar thermal energy production in 2011 was at ∼62 ktoe, which equates to ∼721 GWh (see Figure 5(a)). This is an enormous potential from which to gain energy and Cyprus is utilising its solar resources greatly in this way.

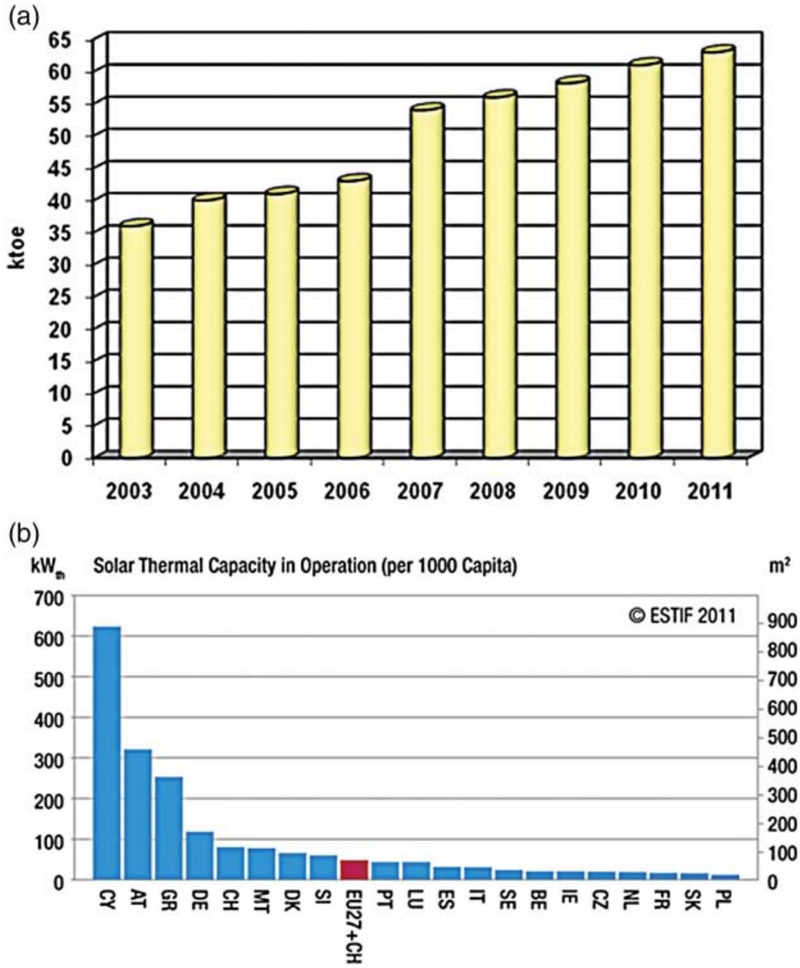

Figure 5. Annual solar thermal energy production in Cyprus (ktoe = kilotons of oil equivalent) (a) and solar thermal capacity in kWth and per 1000 capita of EU countries (b). Figure used with permission, © ESTIF (ESTIF 2011).

Aside from this use of solar energy for heating applications, the use of PVs for the direct conversion of light energy to electrical energy is also steadily increasing in Cyprus. Approximately 25 MW have been installed as at May 2013, of which 24.2 MW are grid connected (GC) and the remainder provide power for stand-alone (SA) systems (see Figure 6). The 1.1 MW PV systems were installed on the roofs of governmental buildings, public schools as well as army camps. The budget for this was co-financed by the cohesion fund of the European Union.

This overall rise in solar PV capacity is promising for Cyprus and the Energy Service of the MECIT predicts an even greater increase of PV capacity in the coming years. By raising investor interest in PV, it is hoped that the PV market will penetrate further into the grid. Simplified legislation, transition to net metering, deployment of smart metres and more control when generating the desired power should all help to improve the appeal of PV in the overall energy mix.

In addition to the above, the Cyprus government has recently announced the results of a bidding process for large-scale PV systems with a total capacity of 50 MW. Twenty-four projects were awarded with prices ranging from 7.41 to 9.90 cents/kWh, thus almost 40–45% less than the current electricity market price using conventional fuels (Cyprus Institute of Energy 2012).

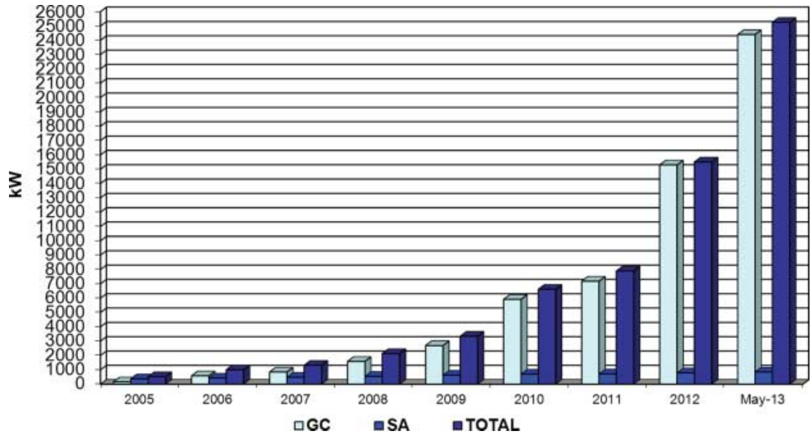

Figure 6. Installed PV capacity in Cyprus: GC (light blue bars), SA (blue bars) and total capacity (TOTAL, dark blue bars).

Table 2. Market price of PV modules (factory gate price in Europe in US$/W) (IRENA 2013).

	2011				2012
PV module suppliers	Q1	Q2	Q3	Q4	Q1
High-efficiency c-Si	2.20	2.15	2.10	2.00	1.94
Japanese/Western c-Si	1.40	1.27	1.08	1.22	1.22
Chinese major c-Si	1.39	1.39	1.39	1.39	1.24
Emerging economies c-Si	1.36	1.31	1.03	1.02	1.02
High-efficiency thin film	1.16	1.05	0.98	0.93	0.93

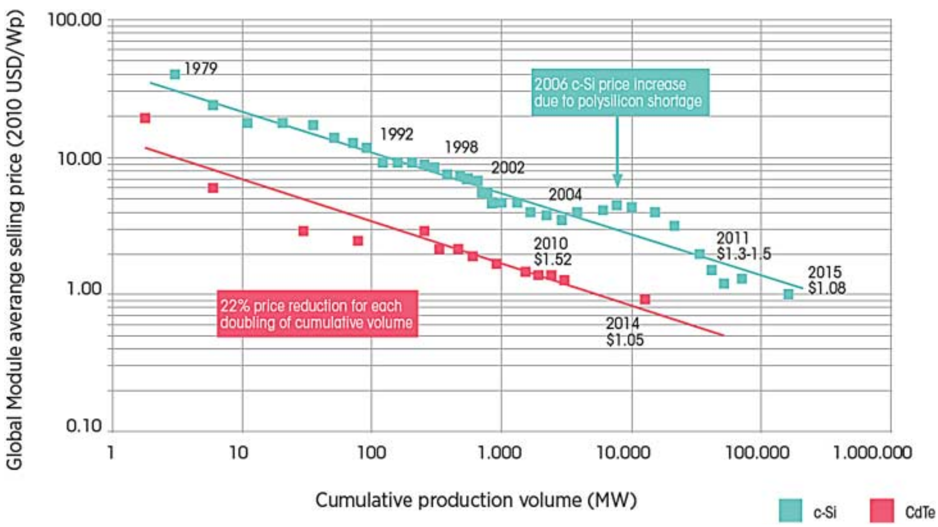

Figure 7. The global PV module price learning curve for c-Si wafer-based and CdTe modules, 1979–2015. Figure used with permission, © IRENA (IRENA 2013).

Additionally, the emerging trend of high-efficiency thin films will continue to drive prices down while maintaining efficiency levels at the desired requirements for energy production. The International Renewable Energy Agency (IRENA) predicts that prices of these thin film technologies will further drop, making them viable alternatives (see Table 2 and Figure 7) (IRENA 2013).

These thin film technologies form the heart of research efforts to develop sufficient, secure, economically viable and, above all, clean energy for years to come.

4. Conclusion

This paper has shown that while geo-engineering methods may provide short-term answers to the global warming phenomenon, only the use of RES can provide long-term solutions. Solar power especially has the potential to provide the world with sustainable energy and the paper has highlighted the strategic role of low-cost PVs for use in solar energy production, using the Cyprus market as an example for strategic implementation. The example of Cyprus has shown how this technology can be used to provide energy for use in heating (solar thermal) and also for GC electricity production (PV).

In order to achieve 100% clean energy production, the different sources (solar, geothermal and wind) have to be used together along with the appropriate infrastructure, so that the gaps in one technology can be filled by another. The Cyprus market has followed this concept and is utilising its available RES of especially wind and sun to provide clean energy, while intrinsically respecting the natural environmental that these systems are placed into. Fundamentally it is necessary to go beyond SRM by thinking on a much larger scale and combining efficiency, lifetime and cost of environmentally friendly renewable energy technologies well into a clean and renewable future.

Acknowledgements

This work was co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research Promotion Foundation (Strategic Infrastructure Project ΝΕΑ ΥΠΟΔΟΜΗ/ΣΤΡΑΤΗ/0308/06).

References

Beurskens, L. W. M., M. Hekkenberg, and P. Vethman. 2011. *Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States – Covering all 27 EU Member States with Updates for 20 Member States*. Petten, The Netherlands: ECN.

Black, R. 2012. "Geoengineering: Risks and Benefits." Accessed February 12, 2013. http://www.bbc.co.uk/news/science-environment-19371833

Cyprus Institute of Energy. 2012. "Σχέδιο Παροχής Χορηγιών για Ενθάρρυνση της Ηλεκτροπαραγωγής από μεγάλα Εμπορικά Αιολικά, Ηλιοθερμικά, Φωτοβολταϊκά Συστήματα και συστήματα Αξιοποίησης Βιομάζας [Grants scheme to encourage electricity generation from large commercial wind, solar thermal, photovoltaic systems and biomass utilization]." Accessed March 2, 2013. http://www.cie.org.cy/menuGr/anakoinwseis/Meiodotikos_aithseis_katarxin_epiloghs.pdf

Dennler, Gilles, and Christoph J. Brabec. 2008. "Socio-Economic Impact of Low-Cost PV Technologies." Chap. 20 in *Organic Photovoltaics – Materials, Device Physics and Manufacturing Technologies*, edited by Christoph J. Brabec, Vladimir Dyakonov, and Ullrich Scherf, 531–566. Weinheim: Wiley-VCH.

EC (European Commission). 2009. *Council Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. OJ L140/116*. Brussels: European Commission.

EPIA (European Photovoltaic Industry Association). 2012. *Global Market Outlook for Photovoltaics until 2016*. Brussels: EPIA.

ESTIF (European Solar Thermal Industry Federation). 2011. *Solar Thermal Markets in Europe – Trends and Market Statistics 2010*. Brussels: ESTIF.

Green, Martin A. 2007. "Thin-Film Solar Cells: Review of Materials, Technologies and Commercial Status." *Journal of Materials Science: Materials in Electronics* 18 (S1): S15–S19.

Hoth, Claudia N., Pavel Schilinsky, Stelios A. Choulis, Srinivasan Balasubramanian, and Christoph J. Brabec. 2013. "Solution-Processed Organic Photovoltaics." Chap. 2 in *Applications of Organic and Printed Electronics – A Technology-Enabled Revolution*, edited by Eugenio Cantatore, 27–56. New York: Springer.

IPCC (Intergovernmental Panel on Climate Change). 2007a. “Climate Change 2007: The Physical Science Basis.” Working Group I contribution to the fourth assessment report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.
IPCC (Intergovernmental Panel on Climate Change). 2007b. “Climate Change 2007: Mitigation of Climate Change.” Working group III contribution to the fourth assessment report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.
IRENA (International Renewable Energy Agency). 2013. *Renewable Power Generation Costs in 2012: An Overview*. Bonn: IRENA.
National Environment Research Council. 2011. “The SPICE Project: A Geoengineering Feasibility Study.” Accessed March 14, 2013. http://www.nerc.ac.uk/press/releases/2011/22-spice.asp
National Research Council. 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base*. Washington, DC: National Academies Press.
National Research Council. 2011. *America’s Climate Choices*. Washington, DC: National Academies Press.
Rau, G. H., S. A. Carroll, W. L. Bourcier, M. J. Singleton, M. M. Smith, and R. D. Aines. 2013. “Direct Electrolytic Dissolution of Silicate Minerals for Air CO_2 Mitigation and Carbon-Negative H_2 Production.” *Proceedings of the National Academy of Sciences of the United States of America* 110 (25): 10095–10100.
Rybach, L. 2010. “Status and Prospects of Geothermal Energy.” Paper presented at the World Geothermal Congress, Bali, Indonesia, April 25–29.
Storelvmo, T., J. E. Kristjansson, H. Muri, M. Pfeffer, D. Barahona, and A. Nenes. 2013. “Cirrus Cloud Seeding Has Potential to Cool Climate.” *Geophysical Research Letters* 40 (1): 178–182.
UNDP (United Nations Development Programme). 2000. *World Energy Assessment: Energy and the Challenge of Sustainability*. New York: UNDP.
WBGU (German Advisory Council on Global Change). 2003. *World in Transition: Towards Sustainable Energy Systems. Summary for Policy-Makers*. Berlin: WBGU.
Zweibel, Ken, James Mason, and Vasilis Fthenakis. 2008. “A Solar Grand Plan.” *Scientific American* 298 (1): 64–73.