INTEGRATION OF HYBRID ORGANIC-BASED SOLAR CELLS FOR MICRO-GENERATION

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Contents

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ABSTRACT OF THESIS

submitted by Brian Azzopardi
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Despite the fact that the global photovoltaic (PV) market has grown rapidly during the last two decades, driven by global climate change concerns and public policy supports of renewable energy sources, a PV system is still considered an expensive alternative energy source when compared to other sources of electricity. Emerging organic-based PV solar cells may lead to significant price reductions of a PV system. Though, in the short and medium term, the lifetime, efficiencies and reliability are expected to be lower than current commercially available silicon wafer-based and mature inorganic thin film PV modules.

A consortium formed by inter-disciplinary scientists and engineers between the University of Manchester and Imperial College London was set-up to investigate organic-based hybrid solar cells. Potential solar cell materials with higher resultant conversion efficiency in research, targeting lower costs than other PV technologies were developed. The designs investigated feature hybrid organic-based quantum dot (QD) solar cells topology.

This research seeks to integrate this new PV technology concept into future PV micro-generators. The challenges faced by emerging PV technologies with regard to PV module lifetime, efficiency and cost / price were summarised. The uniqueness of this work is that, throughout this research, the issues for commercialisation of emerging PV technologies for micro-generation; in particular with regards to low efficiency, short lifetime and high efficiency degradation, and low-cost / price were extensively analysed in every aspect.

The technical, economic and also environmental viability perspectives of emerging PV technologies for micro-generation were found. A wide range of models and / or methodologies were developed, extended or applied for the first time to PV technologies for micro-generation, with particular focus where possible on the hybrid organic-based QD solar cells. Lifetime-adjusted calculations and life cycle costing were used to determine cost boundaries and PV electricity costs. Life cycle environmental impacts were determined by the use of life cycle analysis. A mixed integer single / multi-objective optimisation program was developed to determine optimal, compromise and trade-off relationships on PV system characteristics. These PV system characteristics, which are analysed on a systems level included module efficiency, grid interconnection rating, solar fraction, energy storage capacities, annualised life cycle costs, project worth value and environmental CO_2 impacts / benefit. Finally, PV technologies for micro-generation were ranked by the use of multi-criteria decision analysis. The results clarify, inform and suggest concepts for emerging PV technologies integration for micro-generation by providing boundaries, trade-offs and suggestions to all stakeholder including commercial, domestic and public bodies.

The direction for future research in emerging PV technologies for micro-generation is identified to be the development of customer decision tools for diversified PV technologies, policy adaptation for the inclusion of emerging PV technologies and large-scale manufacturing investigations on emerging PV modules that makes use of an organic-based PV technology.

Declaration

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Dedication

To the one I love

Acknowledgement

I am wholly indebted to my supervisor, Dr. Joseph Mutale, whose continuous guidance, consideration and patience contributed to my pleasant and challenging graduate studies. He was always available to discuss new topics and ideas and fully encouraged me to disseminate my research to the world.

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Abbreviations and Acronyms

ALCC	Annualised Life-Cycle Cost
a-Si	Amorphous Silicon
BIPV	Building Integrated PV Systems
BOM	Balance of Module
BOS	Balance of System
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Diselenide
CRF	Capital Recovery Factor
c-Si	Crystalline Silicon
DSSC	Dye-Sensitised
ECF	Electricity Carbon Footprint
EPB-T	energy payback time
FITs	Feed-in-Tariffs
GHG	Green House Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCEA	Life Cycle Energy Analysis
LCCA	Life Cycle Costing Analysis
LCIA	Life Cycle Impact Assessment
LCIC	Life Cycle Investment Costing
LEC	Levelised Electricity Cost
MEG	Multiple Exciton Generation
MIP	Mixed Integer Program
NER	Net Energy Ratio
NPV	Net Present Value
OPV	organic PV
PV	Photovoltaic
PR	Performance Ratio

Symbols

A	Area	m^2
C	Cost	£
δ	efficiency degradation limit	%
E	Energy	(kWh)
f	learning curve (experience curve)	%
g	annual growth rate	%
H	average solar irradiance received every square meter	(kWh/m2)
i	inflation rate	%
in	input	
I	investment	%
L	module lifetime	years
m	annual market	
M	cumulative sale	
max	maximum	
mPV	mature PV	
η	efficiency	(%)
n	Nominal Discount Rate	%
N	number of PV module replacements	
p	price	£
P	Power Rating	W
PR	Performance Ratio	
out	output	
r	real discount rate	%
S	energy storage	
SOC	state of charge	
σ	grid rate	£/kWh
t	studied period	(hourly, daily, yearly)
T	period of analysis	years
Z	objective function	

Glossary

Irradiance is a term specifically applied to solar energy irradiation.

Irradiation is the energy per unit area on a surface.

Feed-In-Tariffs (FITs) are policy instruments designed to support the adoption of renewable energy (RE) sources. It typically includes three key provisions: (i) guaranteed grid access, (ii) long-term contracts for electricity produced, and (iii) the cost of renewable energy generation.

Peak Sun Hours are the equivalent number of hours per day when solar irradiance averages 1,000W/m^2.

Performance Ratio (*PR*) defines the system losses such as shadowing, inverter inefficiencies and soiling effect. PR is the main index for characterising the system performance under certain conditions.

Photovoltaic (PV) refers to light to electricity conversion.

Photovoltaic Solar Cell is a semiconductor device that converts the energy from sunlight directly into electricity by the photovoltaic (PV) effect.

Quantum Dot (QD) discovered by Louis E. Brus and termed by Mark Reed is a semiconductor whose excitons inhibit in all three spatial dimensions. Thus, QDs have properties in between semiconductors and discrete molecules.

Renewable Energy (RE) is the energy generated from resources which are naturally replenished, such as sunlight and wind.

Smart Grid is a conceptual modernised energy network that delivers energy with two-way communication between the network operator and end-user to obtain energy management, reduce cost or increase benefits, and increase reliability and transparency.

Sustainable defined by Brundtland (1987) as the development that meets the requirements of the present without compromising the capacity of future generations to meet their own requirements.

List of Publications

The following papers were the result of the work undertaken in this research:

Journal Paper

B. Azzopardi and J. Mutale, “Life cycle analysis for future photovoltaic systems using hybrid solar cells”, Renewable and Sustainable Energy Reviews, vol. 14, pp. 1130-1134, Jan 2010.

Submitted Journal Paper

E. A. Martinez-Cesena, B. Azzopardi and J. Mutale, “Assessment of domestic photovoltaic systems based on real options theory”, Progress in Photovoltaics.

International Conference Papers

B. Azzopardi, J. Mutale and D. Kirschen, “Cost boundaries for future PV systems”, in the IEEE International Conference on Sustainable Energy Technologies (ICSET), pp. 589-594, Singapore, 2008.

B. Azzopardi and J. Mutale, “Analysis of renewable energy policy impacts on optimal integration of future grid-connected PV systems”, in the 34th IEEE Photovoltaic Specialists Conference (PVSC), pp. 865-870, Philadelphia, 2009.

B. Azzopardi and J. Mutale, “Smart integration of future grid-connected PV systems”, in the 34th IEEE Photovoltaic Specialists Conference (PVSC), pp.2364-2369, Philadelphia, 2009.

B. Azzopardi and J. Mutale, “Optimal integration of grid-connected PV systems using emerging PV technologies”, in the 24th European Photovoltaic Specialists Energy Conference (EU PVSEC), Hamburg, 2009.

C. Candelise, B. Azzopardi, J. Nelson, J. Mutale, M. Winskel and R. Gross, “Synergies that Effect Cost Developments in Photovoltaic Technologies”, in the 25th European Photovoltaic Specialists Energy Conference (EU PVSEC), Valencia, 2010.

Conference Presentations

B. Azzopardi, J. Mutale and D. Kirschen, “Integrating hybrid solar cells into micro-generation”, Graduate Research Conference, University of Manchester, 2008.

B. Azzopardi, “Multi-objective framework for optimal integration of grid-connected PV systems using emerging PV technologies”, in the EEE PGR Poster Conference, University of Manchester, 2009.

1

Introduction

This chapter gives an overview on the world energy resources highlighting the importance of solar energy and a diverse PV market to meet future energy demands. The challenges facing emerging PV technologies for micro-generation are discussed. Then the main aim and principal objectives of the thesis are identified followed by a summary of the main contributions and a brief outline of this thesis.

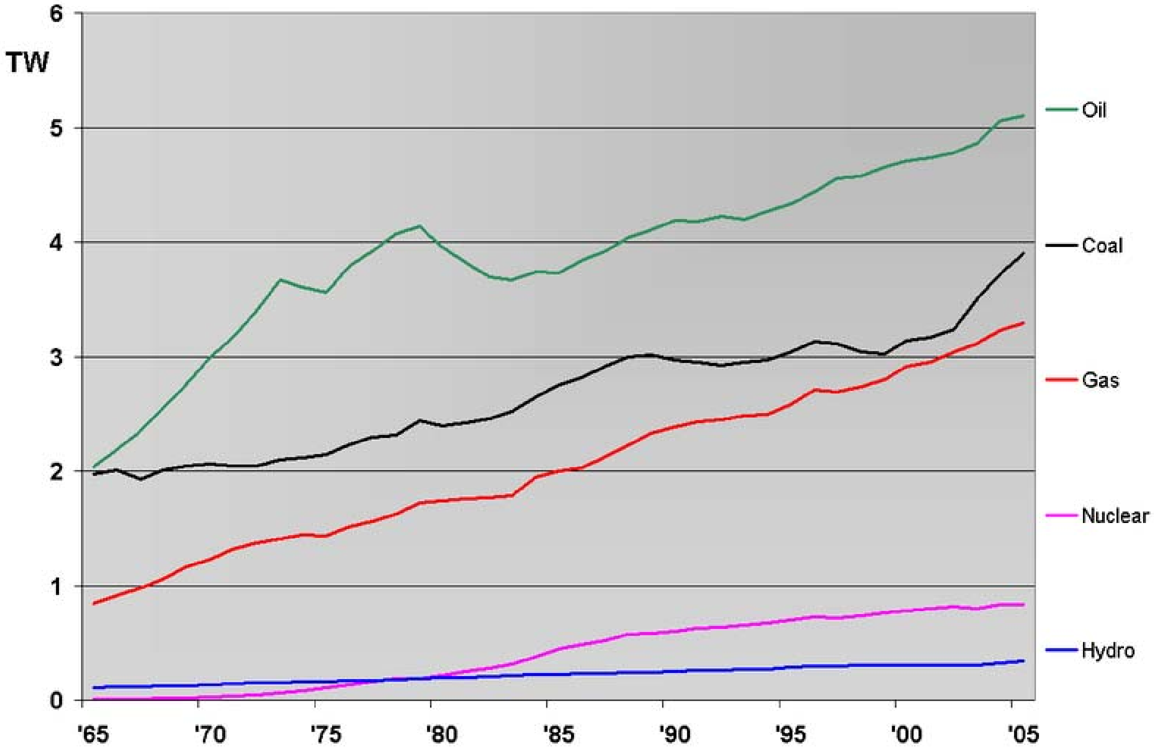
1.1 Overview

The call for alternatives to fossil fuel electricity sources is urgent to mitigate climate change and secure future electricity supply [1]. In 2008, total global primary energy consumption was 474EJ which is around 15TW average power consumption [2]. From a wide collection of plausible global developments the Intergovernmental Panel on Climate Change (IPCC) anticipates the average power consumption to go up to 20 - 50TW by 2050 [3]. Most of this current energy consumption, 87%, is driven from the combustion of fossil fuels, as seen in Figure 1.1. Nuclear amounts for another 6% and the rest is coming from renewable energy (RE) sources which is mainly driven by hydro power [2].

Solar energy is the most abundant energy resource, around 86,000TW per year is received, as seen in Figure 1.2. It is a globally distributed energy. Therefore, in addition to climate change mitigation, solar PV energy has the following attributes.

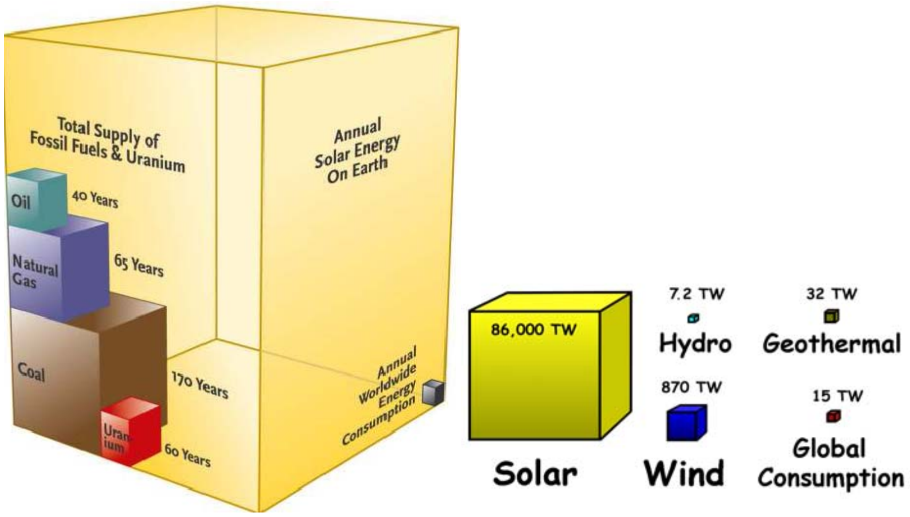
- It can improve energy security and independence by having a distributed energy source and increase the diversification of energy sources. This makes countries less vulnerable to the uneven distribution of energy supplies among countries and the price volatility risks in the oil and gas prices and any economic turmoil. The recent gas crisis back in 2006 showed Europe's vulnerability to this source of energy, and the spiking oil prices back in July 2008 showed modern society's strong dependence on oil.

- It has zero emissions, carbon free and zero waste, no radioactive waste. PV systems will exceed the energy needs during production by 8 to 30 times within their lifetime. In fact, solar PV electricity carbon footprint is also lower than traditional fossil fuel electricity energy source [4]. In addition, there is no direct pollution in the air such as noise pollution and harmful by-products during operation.
- It has low operations and maintenance costs. Most PV systems have no movable components and do not require any fuel to operate.
- It gives an added value to the area / building such as availability of electricity in a rural area and opens up many opportunities for better integration by the use of building integrated PV (BIPV) systems which can be aesthetically pleasant, in addition to the buildings' grid energy consumption savings.



In this review, primary energy comprises commercially traded fuels only. Excluded, therefore, are fuels such as wood, peat and animal waste which, though important in many countries, are unreliably documented in terms of consumption statistics. Also excluded are wind, geothermal and solar power generation.

Figure 1.1: Rate of world energy usage in terawatts (TW), 1965-2005 [2]



(a) *(b)*

The volume of the cubes represents (a) the amount of available fossil fuels and nuclear fuel in the world compared to the annual solar energy on earth, and (b) the amount of available renewable energy sources as the average global power availability in TW of geothermal, hydropower, wind and solar energy, although only a small portion is recoverable. The comparisons are performed with the global energy consumption per annum.

Figure 1.2: Available energy in the world [5, 6]

- It has the capability to create thousands of new green jobs in this new field. Jobs can be created due to market growth in the production, design, installation, distribution and supply chains. Other analytic and financial jobs are also attracted that deal with policies, funding processes and risk assessment.

It is clear, that solar PV energy has many attributes to merit worldwide deployed. Then, why there is no solar PV module on every roof? The reasons are primarily related to cost.

In 2010, the average solar module retail price index was \$3.72 per Watt peak (Wp) in the United States (US), and €3.31 per Wp in the European Union (EU) [7]. This may translate as an average PV electricity price index between 11 and 23p/kWh[1]. This electricity price index is based upon a climate with 5.5 hours of sunshine average over the year from large scale PV systems to small scale residential once. Hence due to lower solar resource the PV electricity price is higher than this index. Meanwhile the UK electricity cost for different sources is between 5 to 21p/kWh. The upper range refers to offshore wind and carbon capture technologies.

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[1] \$1.5589 = £1 as of sterling against US dollar forward rates by the Bank of England in 2010.

Hence in most cases the prices for PV electricity are still high to make a major impact without some financial support. The module prices usually follow the crystalline silicon (c-Si) wafer-based technology, which dominates the PV market with 70 to 80% share. Hence this high initial cost of PV modules, which accounts for 50-60% of the cost of a PV system, is holding the penetration and diffusion of this RE source into the electricity market. Therefore, PV for electricity generation is often limited by its high price, compared to electricity from traditional sources such as fossil fuels and nuclear.

Second generation thin film (TF) solar cells, classified as mature inorganic TF technologies, are amorphous silicon (a-Si), copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe). These technologies are currently cheaper to manufacture than c-Si. In fact, CdTe modules are manufactured at 0.98$/Wp by First Solar. However, on the market these inorganic TF PV technologies are still not cheap enough for widespread deployment.

Whilst high efficiency is desirable, substantial increases in efficiency often involve expensive processes or complex structures such as tandem cells. The long-term vision of any RE technology is to make energy use as sustainable as possible [8]. Hence, in the short and medium term, emerging organic-based PV including dye-sensitised (DSSC), organic-organic (OPV) and organic-metal oxide (hybrid-OPV) currently characterised by lower efficiency, lower cost and lower life expectancy than mature PV technologies, could present a viable alternative. These emerging organic-based PV technologies offer significant cost reductions due to the opportunities for radical changes in the solar cell material design and processes.

Emerging hybrid organic-based solar cells using inexpensive materials and production processes, were investigated within a consortium between the University of Manchester and Imperial College London. The aim of this consortium was to construct affordable hybrid organic-based solar cells for deployment in the UK and worldwide [9]. The consortium focused on the combination of low cost material synthesis and low temperature processing together with novel photon harvesting mechanisms in order to develop PV devices with the long-term potential to achieve power conversion efficiencies approaching 10%. This research has explored the combination of the light harvesting and charge transport properties of state of the art semiconductors and metal oxide nanostructures with the mechanical robustness and flexibility of polymer semiconductors to deliver a new polymer composite PV device technology, the Hybrid Organic-Based Quantum Dot (QD) Solar Cell.

The next section discusses the main challenges of emerging PV technologies for micro-generation.

1.2 Challenges facing emerging PV technologies

Most PV systems in operation today were installed with various financial support schemes. PV commercial viability requires understanding of a number of uncertain factors including electricity markets, cost of fossil fuels, environmental policy frameworks to penalise CO_2 emitters, PV system output correlated with local load, and the need for worldwide electrification [10].

Ultimately PV economic competitiveness is guaranteed by progressing towards the third generation, that is a high efficiency and low cost, PV technology. However, in the short and medium term, PV economic competitiveness may be realised even with low lifetime and low efficiency characteristics. These characteristics will pose challenges for low-cost micro-generation integration. These challenges which are important considerations in this research can be grouped into three categories, characterising every PV technology: namely lifetime / stability challenges, efficiency challenges and finally cost reduction challenges. A synopsis of these challenges is given below under these three categories.

1.2.1 Lifetime / stability challenges

Shall emerging PV technologies' lifetime / stability levels reach mature PV technologies?

Mature PV technologies, in particular c-Si, have been on the market since 1950 and therefore, have a proven track record that brings high customer valuation of the product due to their efficiencies and guarantees. In fact, performance guarantees are usually based on 80% of the original efficiency at 25 year lifetime, and efficiency degradation on the fifth and tenth year may also be guaranteed. To some extent this vast historical experience, in particular a-Si, is also attributed to mature inorganic TF technologies.

Emerging PV technologies are novel technological concepts and hence do not have a proven track record. Current emerging organic-based PV technologies suffer from disintegration over time and have only exhibited low lifetimes. Stability remains the main challenging problem, as materials are susceptible to degradation in the presence of oxygen and water [11-13]. Hence lifetime for OPV is most often defined as the time until the efficiency reaches 50% of its original or maximum value [14]. It can be critically argued that this may bring system performance down however these PV technologies may only reach few years life expectancy (3-5 years) for successful applications [15]. As a low cost PV solar cell technology, even with a short lifetime period, there is potential to increase deployment of this PV technology in domestic applications [16]. In this case, replacement of PV modules about their lifetime is necessary since a higher system lifetime is exhibited.

However, even with low lifetime and higher degradation rates, if produced inexpensive, emerging PV technologies will not only make it to niche markets such as portable electronic applications but also for micro-generation. This raises questions regarding general characteristic boundaries for emerging PV technologies, in the short and medium term, on PV module lifetime / stability and efficiency levels. Therefore, some methods and applications are required to discover these boundaries in terms of emerging PV technologies for micro-generation. The uniqueness of most contributions in this research is that, throughout this thesis, the issues for commercialisation of emerging PV technologies in the domestic environment for micro-generation, in particular with regard to PV module lifetime / stability and efficiency are extensively explored on a systems level.

1.2.2 Efficiency issues

Should solar cells efficiencies for micro-generation be the highest?

The efficiency of a PV solar cell is the ratio describing the fraction of incident photons that are converted into electricity. Hence the power produced from a solar cell depends strongly on the active area being hit by photons, light wavelengths and intensity. The PV active area is dependent on efficiency: the lower the efficiency, the bigger the active PV area and vice versa the higher the efficiency, the smaller the PV active area.

High efficiencies are exhibited by expensive multijunction concentrators and single-junction GaAs, technologies, which are reserved for specific applications. These are followed by c-Si, mature inorganic TF and emerging PV technologies as shown in Figure 1.3. Developments in solar cell performance with regard to efficiency have always been of high importance. Increase in efficiency means lower active area, and potentially, lower production costs for the same technological process.

So far, in traditional PV devices, any photon energy in excess of the band gap is lost as heat, and that accounts of around 47% of the incident photon energy. Hence, PV solar

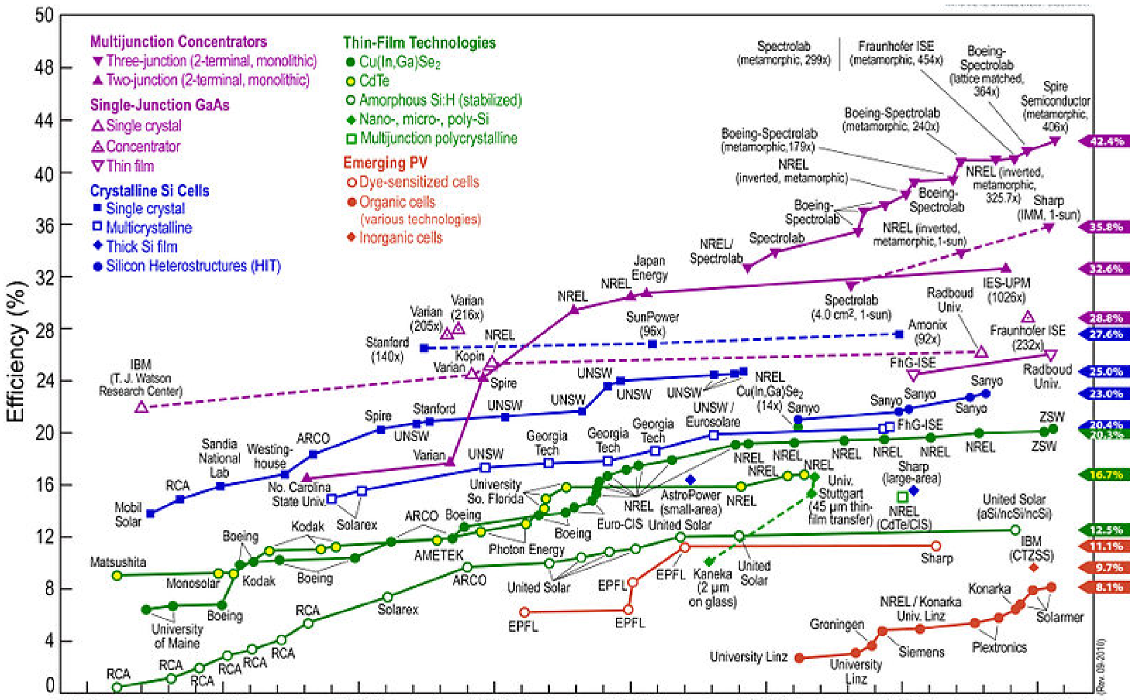


Figure 1.3: Best research-cell efficiencies [17]

cell efficiency has a fundamental cap for one photon per one exciton generation under solar irradiation, known as the Queisser-Shockley or Thermodynamic limit which is about 33% efficiency. However, nanoparticles offer a way in which this efficiency barrier can be broken and attain the third generation of PV technology, low cost and high efficiency. In nanoparticles, such as QDs, photoexcited carrier cooling rates can be slow compared to bulk semiconductors and a process known as impact ionisation becomes competitive. Here, photon energy in excess of the band gap is used to create additional electron-hole pairs instead. In theory, the quantum efficiency can become greater than 100%. This effect is known as Carrier Multiplication or Multiple Exciton Generation (MEG). Hence, various configurations of QD PV Solar cells that yield at laboratory scale high conversion efficiencies are suggested in the literature. This phenomenon has raised the possibility of organic-based QD solar cells with photoconversion efficiency of as much as 66% [9, 18-22].

For a PV module market price above \$2.00/Wp, increase in PV module conversion efficiency may not substantiate economic benefit [23]. On the other hand, as OPV efficiency increases from 5 to 15%, a cost reduction from 72% to 24% respectively may be achieved from the present cost of TFs [24].

New concepts and emerging PV technologies have always started from low efficiency, and their performance is optimised by further research and development. Currently lab-based OPV has reached 7.9% in 2009 [25]. However, emerging organic-based PV technologies are suggested to exhibit a minimum 5% efficiency for market deployment [26], while 5-10% efficiencies may be achievable with some stability concerns [27]. By the application of QDs for MEG, efficiency levels can also increase significantly for organic-based PV module.

However, it is evident that low-cost PV module will have a profound impact in the PV market. If area availability is not a concern, these low-cost PV modules, having low levelised electricity cost, may also integrate the micro-generation market. Under no financial support schemes, having domestic local load mostly not correlated with the solar resource may even favour smaller systems ratings or low efficient modules. However, as argued above lifetime and efficiency boundaries are also important for sustainability. Another niche market may be created through a trade-off between individual user interests and public expressed through the necessary supporting schemes for PV micro-generation to integrate emerging PV technologies.

1.2.3 Cost reduction challenges

What is the cost of hybrid QD solar cell and can we solve the problem of high initial capital cost in the short and medium term?

The capital costs for a PV system are typically divided into two:

i. the Balance of Module (BOM) costs / prices include modules' materials, production and overhead costs; and
ii. the Balance of System (BOS) costs include area and energy related costs for a complete system.

Nowadays, the BOM and BOS costs are fairly on the same level. In addition, the maintenance costs are minimal, hence most of the time neglected in grid-connected PV system studies, due to the current high reliability and in most cases absence of tracking systems.

The long term US Department of Energy TF solar cells goal is \$0.33/Wp [28]. PV system costs are falling. However, further reduction in costs may be achieved by economies of scales or cheaper PV technologies. On the other hand, TF technologies including emerging PV technologies are deemed to have a higher cost reduction potential than c-Si technologies thanks to several technology intrinsic advantages:

i. Better light absorption, allowing for much thinner materials;

ii. Potential to achieve low manufacturing costs by large-scale high-throughput module production;
iii. Potential for production on flexible substrates, allowing low-cost roll-to-roll manufacturing process. This increases the range of potential applications, in particular building integrated PV (BIPV) systems.

Target cost reductions of around 0.5€/Wp are deemed achievable by around 2020, provided that the expected increase in the production facility sizes and improvements in efficiencies are realised [29-31].

Emerging organic-based PV may hypothetically reduce even further production costs due to a number of reasons such as high throughput, simpler process and cheaper materials. However, emerging PV technologies must cost less than or equal to today's BOM costs, when considering same energy output as mature PV technologies. In this way emerging PV technologies will penetrate the PV market competitively with mature PV technologies. Though, the challenge to produce affordable and sustainable PV systems will remain.

Future eco-societies might tend to be encouraged by affordable capital on BOM costs to opt for domestic PV systems with emerging PV technologies. However, this encouragement remains as long as the energy production and present capital costs are maintained. Understanding the future PV developments is critical to formulate public policies. Public policy amendments could drastically affect the nature of investment, such as pay back time (PBT) and the RE market, affecting the supply and demand chains. This philosophical idea is another uniqueness of most contributions in this research that is emphasised throughout this thesis.

Studies on OPV manufacturing costs have already showed the potential of cost reductions [32, 33]. Hence understanding large-scale manufacturing costs of OPV and their hybrid version is important, as hybrid OPV might even offer a better efficiency performance. This interest is another contribution in this research work.

1.2.3.1 From laboratory to commercialisation

Many technical barriers and basic science questions need to be solved before these emerging PV technologies can make their way to the commercial stage. In order to face the challenges discussed above, several options exist from the lab to commercialisation development stages. One route is by reducing materials usage for an increase in efficiency or reducing material thickness. Another option is materials substitution and solutions that are currently explored for substitution of both PV active layers and transparent conductors (TCs) with alternative materials. Hence the innovation both at the material and device level can help in addressing possible future material concerns and in delivering TF technologies cost reduction potential. It could also play a decisive role in defining future relative cost level and market penetration for the main group of here considered TF technologies.

Therefore, in the short and medium term, regular PV module replacement within a PV system using emerging organic-based PV technology would be required every few years to re-gain its operational performance. Hence due to the attraction of low investment cost per module, even with a short lifetime period than current mature PV technologies, there may be increased deployment of PV technology especially in domestic applications [16]. However, before widespread commercial deployment can be achieved, three critical factors were suggested to be addressed:

i. The solar cell must attain a minimum 5% efficiency. 5 to 10% efficiency may be attainable with some stability concerns [27],
ii. The cells must be stable over their lifetime. Efficiency degradation is one main factor of stability. Lifetime over 10 years is desirable [34], and
iii. The solar modules must have an equivalent life cycle investment cost (LCIC) and possibly energy output to mature PV technologies.

As organic-based PV technology emerges from the laboratory and commercialisation begins, the result presents an opportunity for the PV market. Researchers are always seeking advancements that extend lifetime, improve reliability and provide higher efficiencies. Emerging PV technologies can lead to new value propositions, services, markets, and business models.

Therefore, emerging PV technologies are currently attracting interest within the academic and industry arena. These technologies are still at the research and development stage although some innovative industrial initiatives are beginning to explore the potential for their full scale commercialisation. As of 2009, eight companies were involved in the organic TF solar cell production process [35]. However, these challenges discussed above have not been yet addressed consistently with regards to emerging PV technologies for micro-generation. Traditional methodologies have been used to assess the feasibility of mature PV technologies for micro-generation and their financial support requirements. There is therefore a clear need for the extension, development and application of models and approaches to investigate the importance of these challenges posed by emerging PV technologies for micro-generation due to their possible market integration and future deployment.

1.3 Aim and objectives of this research

The developments in emerging PV technologies have excited interests in the integration of these technologies within micro-generation, the largest market for PV. Even with the issues to commercialise emerging organic-based PV technologies, such as, low efficiency, short lifetime and high efficiency degradation, this technology may potentially increase deployment of PV technology for micro-generation applications [16]. However to fully grasp this opportunity, appropriate frameworks and methodologies need to be used on the particular group of technology (organic-based PV) or structure (hybrid organic-based QD PV). Previous literature has not addressed boundaries, costs, environmental concerns and integration frameworks at system level for both end-user interest (micro-level) and public interest (macro-level), in particular for hybrid organic-based QD PV, due to lack of data availability, maturity of the technology and uncertainty in manufacturing processes. Therefore, this research provides the tools, analysis and frameworks necessary to assess any market integration within micro-generation for any emerging PV technology and suggests essential elements for market penetration. Therefore, the principal aim of this research is:

to investigate the integration of hybrid organic-based solar cells for micro-generation

More specifically this research aims to achieve the following five objectives:

i. **to investigate and identify emerging PV technologies cost boundaries with respect to mature PV technologies for market competitiveness (chapter 3)**

Emerging PV technologies upper price boundaries compared to the current commercialised mature PV technologies are crucial to enter the market competitively [36]. Economic competitiveness is compared with lifetime performances and costs. Lifetime performances, owed by probable high efficiency degradation for emerging PV technologies, are a relation to the energy production. In addition, the project costs may also be a factor of other future costs arising from regular replacements of PV modules. The developed lifetime-adjusted approach is based on life cycle costing (LCC) techniques. The methodology takes the following aspects into account efficiency degradation, PV module lifetime, PV module efficiency, system lifetime, and financial parameters. As a result cost / price boundaries are investigated and identified by the estimated price reduction factor (*PRF*).

i. **to develop a cost model for hybrid organic-based QD PV module and suggest large-scale manufacturing cost reduction opportunities (chapter 4)**

The few cost models on emerging PV technologies, based on DSSC or OPV, do not consider large-scale manufacturing, and therefore, are based on lab-scale productions. In addition, cost models for emerging organic-based QD solar cells do not exist. The interest in emerging organic-based QD solar cells is important as these technologies may offer the potential for higher efficiencies in the long term. Hence a cost model is developed and further assessment is based on large-scale manufacturing opportunities.

ii. **to develop a life cycle analysis for possible hybrid organic-based QD PV modules to demonstrate sustainability (chapter 5)**

Life Cycle Analysis (LCA) for hybrid organic-based QD cells does not exist, and emerging PV technologies LCA are based on DSSC or OPV. These LCA studies do not usually consider system integration. Sustainability was demonstrated on other PV systems using mature PV technologies. Hence, sustainable weightings on typical hybrid organic-based QD PV modules were developed based on an extended LCA methodology.

iii. **to identify methods for the optimisation of a PV system within a domestic environment for micro-generation and suggest essential technical, economic and environmental elements for market penetration (Chapter 6 and 7)**

This PV system integration framework draws attention to the optimal and compromise characteristics of PV modules in a PV system and also the optimal and compromise sizing of a PV system. While the former, PV module characteristics, were never suggested in literature, PV system sizing has yet not identified the potential of emerging PV technologies under a comprise solution between two objectives. Hence a systems level optimisation is developed for the optimal integration of PV technology. Parameters such as optimal efficiency / area, energy storage (if available) and grid interconnection are evaluated. The overall problem minimises the economic objective by the annualised life cycle cost (ALCC) or maximises the net present value (NPV) of the system. However, other objectives are also considered. These objectives are (i) minimising grid energy imports on a micro-level objective, or (ii) minimising CO_2 emissions on a macro-level objective. These added objectives, which in total consider the economic, technical and environmental factors, formed the basis for development of the conceptual framework for multi-objective optimisation for PV market penetration subject to energy management constraints in a domestic environment, grid interconnection and energy storage response constraints.

iv. to demonstrate a decision support tool for ranking current available PV technologies with potential developments in emerging PV technologies (Chapter 8)

The use of multi-criteria analysis (MCA) for ranking PV technologies in a domestic environment is required due to the wide range of future available PV technologies. The demonstration of MCA is performed with ELECTRE III method for a fixed available area site [37]. Both qualitative and quantitative criteria are identified based on technical, economic and environmental factors. However an MCA study has to be taken in the context of a number of assumptions and estimates that are the result of the compilation and integration of other sections in this research work and available literature.

1.4 Main thesis contributions

This research has made significant and novel contributions in the area of integration of emerging PV technology for micro-generation focusing on technical, economic and environmental factors. These factors are investigated and compared mainly with the current PV technologies used in micro-generation based on the energy produced, investment, cost, and sustainability. The main contributions are summarised below:

- Literature review is presented in such a way as to make it accessible to all stakeholders: on PV technologies developments, trends and characteristics, including energy policy support schemes to encourage PV deployment, and updates of recent studies related to applied or extended methods or within the PV technology field. There is a throughout focus on low-cost hybrid organic-based QD PV. This is new on the system level discussions.
- Comparison of PV systems using mature PV technologies and emerging organic-based PV from the standpoint of economic, technical and

environmental considerations based on LCC and LCA methodologies. All the methodologies were extended to take into account frequent replacements of PV modules for emerging technologies. Different efficiency degradation and efficiency levels for the two PV technology groups, mature and emerging, and equal energy outputs were also included. These are notable features within the application of methodologies within the research.

- Development of the first cost model for a typical hybrid organic-based QD PV in comparison with OPV for large-scale production. This model adds to the few cost models on emerging PV solar cells available in the literature. This simplified cost model can be adopted for other emerging PV technologies.
- Development of emerging PV technologies cost boundaries and sustainability weightings for possible hybrid organic-based QD PV modules based on LCC techniques and LCA methodology. A lifetime-adjusted calculation model was proposed and developed. Also, LCI of ‘green synthesis’ of PbS QD, which was performed within the LCA study, expanded the lack of inventory data in emerging PV technologies.
- Application of single/multi-objective optimisation for the adaptation of emerging PV technologies within a domestic environment for two on-grid PV system configurations namely with and without energy storage. The optimisation problem was formulated as an hourly time series mixed integer programming (MIP). This conceptual framework showed trade-offs relationships between different objectives on the micro, as well as macro level namely energy costs, PV contribution to load and CO2 impacts / benefits; and suggested essential values of efficiency and cost of solar cell designs taking into account criteria such as module design, lifetime / stability, energy payback and overall environmental impact / benefit.
- Application of multi-criteria decision tool ELECTRE III to compare and rank current PV technologies with potential developments in emerging PV technologies for a micro-generation application. The need for MCA analysis within the micro-generation market is needed as the diversity of PV technologies is increasing. This demonstrated the first MCA study on PV systems.

It is thereby shown the relations and essential characteristics where these emerging PV technologies would become feasible considering the assumptions taken and case studies. By providing models based on tested techniques, this work supports future production and development of emerging PV technology.

1.5 Thesis structure

The topics covered in nine chapters of this thesis are sequentially organised, as per research objectives, to gather the knowledge required for an overall understanding of the issues related to emerging organic-based PV technologies and their integration in the energy system as micro-generators.

Chapter 1: *Introduction***.** This chapter gives an overview on the world energy resources highlighting the importance of solar energy and a diverse PV market to meet future energy demands. The challenges facing emerging PV technologies for micro-generation are discussed. Then the main aim and principal objectives of the thesis are identified followed by a summary of the main contributions and a brief outline of this thesis.

Chapter 2: *PV Technologies in a PV System.* This chapter starts by discussing the PV market status and a general overview on the financial support schemes for PV systems market integration as a catalyst for renewable energy deployment. An overview of typical PV system components is given followed by the system level fundamentals of a PV system energy analysis which is used throughout the research. A review is given on PV technologies, focused on the typical hybrid organic-based QD PV solar cell underdevelopment which makes use of the Multiple Exciton Generation (MEG) by Quantum Dots (QD).

Chapter 3: *Lifetime-Adjusted Calculations Based on Life Cycle Costing Techniques.* This chapter describes the basic philosophy of life cycle costing. A scenario description is illustrated to explain the aspects of lifetime-adjusted calculations. This is followed by a description on the developed methodology. Cost boundaries for emerging PV technologies are derived, and competitive module prices are shown.

Chapter 4: *Cost Assessment for Hybrid Organic-Based QD PV Module.* This chapter sets out the first developed cost model for typical hybrid organic-based QD solar cells which in parallel also analysis an organic PV (OPV) for large-scale production with well known components in this field. Some discussions on alternative material components and roll-to-roll high throughput manufacturing are performed throughout.

The PV levelised electricity cost (LEC) is then described, and comparison has taken place with other sources of electricity generation. Further discussion on the PV LEC grid parity is given based on irradiance, BOS costs, BOM costs and lifetime. Finally, the chapter concludes with a discussion on future development promise by emerging PV technologies.

Chapter 5: *Life Cycle Assessment for Hybrid Organic-Based PV Module.* The environmental aspects of typical hybrid organic-based QD PV modules are explored. In this chapter, LCA studies on PV energy generation are reviewed. The standardised Life Cycle Assessment (LCA) methodology is then introduced, and discussed LCA interpretation metrics used for sustainable evaluation. The assumptions and boundaries are given followed by the results, comparison with other PV technologies. Comparable criteria for sustainability of electricity-generating systems namely net energy ratio (NER), energy pay-back time (EPB-T) and electricity carbon footprint (ECF) are found to be lower than mature PV technologies. In addition, PV module lifetime and efficiency boundaries are found for the sustainability of emerging PV technologies.

Chapter 6: *PV System Optimisation Within a Domestic Environment.* This chapter sets the two system configurations namely with and without energy storage, and their mathematical models to formulate the mixed integer program (MIP). The general scenario is a PV system optimisation problem within a domestic environment which is investigated under no financial support schemes. Two case studies, with fixed and dynamic electricity tariffs, are presented to provide optimal characteristics of a PV module on a system level analysis followed by a discussion on PV module lifetime with respect to BOM costs and a sensitivity analysis of system parameters. Finally, the optimal sizing of PV system using emerging PV technologies is also investigated based on the technology and price development trends discussed in Chapter 4.

Chapter 7: *Multi-objective Optimisation of a PV System.* This chapter describes the proposed multi-objective (MO) approach as a basis of PV deployment support schemes. The MIP developed in chapter 6 is used to investigate another conflicting objective with the economic objective on a micro-level, which describes the end-user interests by minimising grid consumption, or macro-level, describes the public interests by minimising the carbon footprint. The application of three suggested MO methods is demonstrated on the two system configurations. Hence, the chapter firstly reviews MO studies for PV systems, which show the gap in studies related to on-grid systems. Then three suggested MO methods are explained, followed by the objectives definitions for the applied model. The trade-off results of 16 scenarios are illustrated, and discussions on their compromise solution set are provided. Finally, the chapter highlights the use of MO approach PV system integration framework that draws attention to the optimal and compromise characteristics of PV modules in a PV system and also the optimal and compromise sizing of a PV system.

Chapter 8: *Decision Support System for Ranking PV Technologies.* This chapter emphasises the need for a decision support system when designing a PV system. Hereinafter, a review on the use of ELECTRE III and similar ranking methods in RE applications is given. The ELECTRE III algorithm is then described. Next, the design and implementation of the decision support tool and its evaluation are discussed. Finally, a summary of the main points on PV technology ranks for micro-generation is given.

Chapter 9: *Conclusion.* This chapter highlights the main conclusions as well as contributions of the work undertaken in this research and suggests future research work.

2

PV Technologies in a PV System

This chapter starts by discussing the PV market status and a general overview on the financial support schemes for PV systems market integration as a catalyst for renewable energy deployment. An overview of typical PV system components is given followed by the system level fundamentals of a PV system energy analysis which is used throughout the research. A review is given on PV technologies, focused on the typical hybrid organic-based QD PV solar cell underdevelopment which makes use of the Multiple Exciton Generation (MEG) by Quantum Dots (QD).

2.1 Introduction

Over the last couple of decades, there have been rising concerns with reference to global warming and climate change caused by green house gas (GHG) emissions. In 1992, the Kyoto Protocol has been taken on board by the United Nations Framework Convention on Climate Change (UNFCCC). By January 2009, the Kyoto protocol was ratified by 184 countries [38]. This protocol suggested limits by which industrialised nations have to bring GHG emissions back to 1990 levels [39]. Renewable energy (RE) policies existed in few countries since the 1980's, however, these policies started to materialise in many more countries from the second half of the 90's, with a significant increase in the last few years [40, 41].

At the European Level, under the Kyoto Protocol, the European Union (EU) has committed to reducing GHG emissions by 8% from the 1990 levels between 2008 and 2010. Furthermore, the EU commission has published the so-called 20-20-20 package that sets an ambitious target by 2020 on all community which includes proposals:

i. to reduce GHG emissions to 20% of 1990 levels,
ii. to increase RE systems share to 20% of the overall EU energy consumption, and

iii. to reduce 20% in energy consumption by 2020 [42, 43].

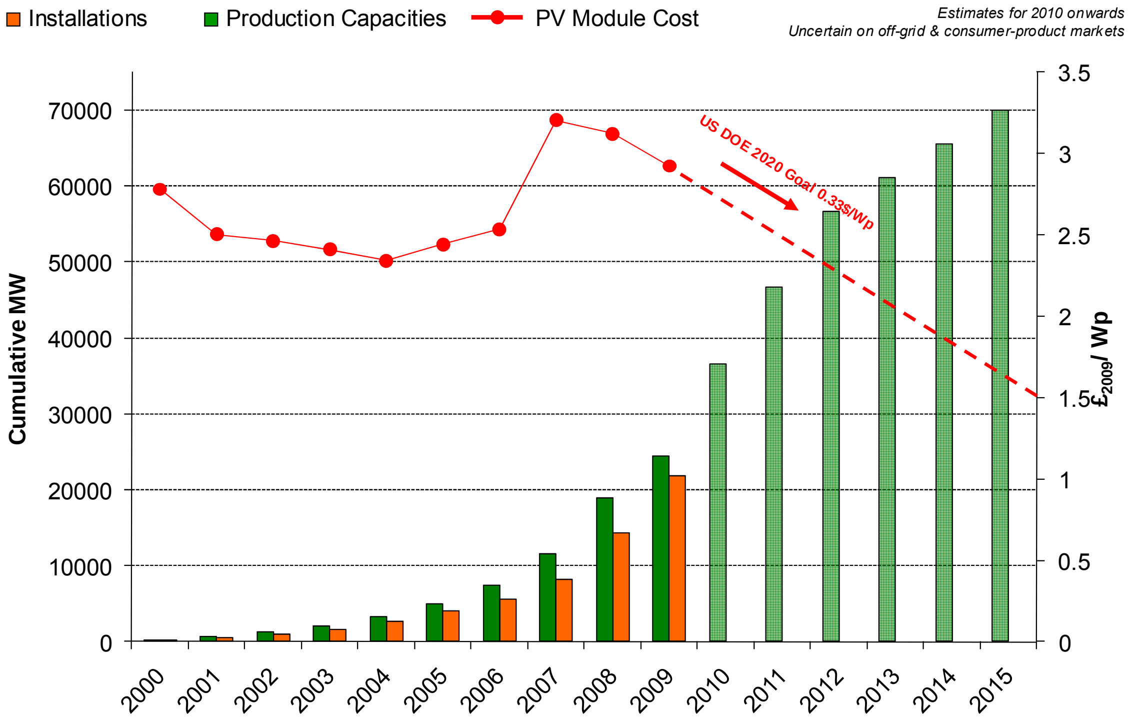
These targets are major policy drivers for RE deployment, including PV technologies. It is estimated that reaching 20% RE target requires 33% to 40% RE contribution [44].

2.2 The PV market status

By the end of 2009, an unexpected growth, due to the economic recession, was registered. The worldwide production volume of PV modules reached 11.5GWp, and a 22GW cumulative PV generation capacity [40]. Over the years, the PV market has grown radically, and the price for PV systems has decreased rapidly. This uninterrupted PV market growth made PV the world's fastest growing energy source. The market expansion in a number of countries is also overwhelming this continuous PV market growth.

This impressive PV market growth mostly represented by grid-connected PV market is mainly due to the variety of incentive schemes; thanks to regulatory and policy drivers [40]. These PV incentive schemes are designed to minimise the current PV burden of high capital costs and disparity with the grid electricity prices. This has also driven PV prices down thanks to the always expanding production and the grid-parity price target for all REs. Figure 2.1 shows the current PV market status and future trends, as well as estimates for the PV solar cell production, PV installations and price of PV modules.

Currently the EU is leading the installed PV capacity by nearly 70% (16GW) [40]. The EU goal of this decade is 20% RE sources of the current energy consumption. This means more than 35% RE electricity [45]. By 30 June 2010, the Member States had to notify the Commission about their National Renewable Energy Action Plans. So far, the PV share by 2020 within the EU RE electricity mix seems to be on average 7.3% from 19 member states [46]. As the EU electricity demand increases annually by 1 to 2 %, a further increase in RE is essential [47]. For PV systems to increase to 1% EU electricity share by 2020, there are challenges encompassing PV technology, RE support frameworks and grid interconnection constraints [48]. Therefore, future PV system design frameworks based on emerging PV technologies may have the potential to address these challenges and have the ability to mitigate both climate change and future electricity increasing demands amongst other RE sources.



Estimates for 2010 onwards
Uncertain on off-grid & consumer-product markets

Author's Compilation with adjusted prices to 2009 Sterling

Figure 2.1: PV module production capacities, installations and costs [40, 48-51]

So far, the PV market growth has not been homogenous among countries. Recent market growths were seen in Spain, Germany, France, United States, South Korea, Italy and Japan. A variety of incentive schemes were adopted over this decade. However, the recent PV market growths were mainly influenced by the feed-in-tariffs (FITs) introduced successfully by French and Italy. The FITs were initially adopted in Germany in 1999, and has been the model policy mechanism designed to encourage the adoption of RE sources. In fact, last April 2010, the United Kingdom (UK) launched its FITs for solar and other RE sources.

The search for affordable PV technologies to penetrate into the market competitively has increased as a result of the current PV demand, grid-parity RE energy prices and future smart grids. In the future, the importance of diversified PV technologies ensures a sustainable PV energy supply to the market.

2.3 Renewable energy financial support schemes

There is a number of regulatory frameworks and policy options for the promotion and deployment of RE technologies. RE support schemes can be broadly divided into operative, which consists of demand pull policies aimed to increase demand for a technology and hence its market size, and non-operative, which consists of supply push policies aimed at pushing technologies forward [52]. So far most RE support schemes have focused on subsidising RE energy prices to reach national targets both in the case of RE deployment, as well as GHG mitigation. This has increased demand for RE and increased the share of RE at the expense of escalating the 'true' cost of electricity. Figure 2.2 shows the range of possible financial instruments RE support schemes including possible future indirect supporting schemes.

The RE Obligation Scheme - Quota Obligation or better known as the Renewable Obligation Certificate or Tradable Green Certificates (ROC / TGC) has been an issue for PV micro-generation in the UK as the annual electricity production is typically low (1-2MWh). ROCs are issued per MWh of electricity generated either monthly or annually. Generation is rounded to the nearest megawatt; however, no ROCs were issued for less than 0.5MWh/yr and cannot be rolled over to the next period. In fact between 2006 and 2007, only 410 ROCs were issued to PV generators, an insignificant proportion with over 14 million issued certificates around the UK [53].

The Feed-in Tariffs (FITs) Scheme is adopted by most countries. The UK has just introduced FITs last April 2010. The German success with FITs has triggered other countries to adopt FITs as their incentive schemes. In fact, most EU countries are adopting FITs as their main RE financial support scheme. FITs give priority to access the grid while offering scheme guarantees, usually for a period of 20 years. If adopted correctly, this scheme offers tariffs for all system levels, small-to-large scale developments in relation to the level of technology, having long term investment guaranteed. It is simple to administer, and easy to explain. Butler and Neuhoff presumed that FITs regime lacks competition in small-scale generation. However, their results show that power plants become more competitive [54]. Besides, energy storage facilities may be prohibited within FITs schemes, which pose a future concern on the developments of energy storage systems.

Other non-operative support schemes that are considered, as good practices, to stimulate RE deployment include tax credits, obligatory PV systems on large new buildings, as well as public tenders for RE projects. These are all based on capital incentives, and therefore, mask also the 'true' electricity cost from RE electricity.

A single support instrument is hardly feasible to cover widespread use in a country, due to RE variations in costs, policies and potential. The EU Commission suggests that operative support schemes contribute to increasing RE sources. Furthermore, different

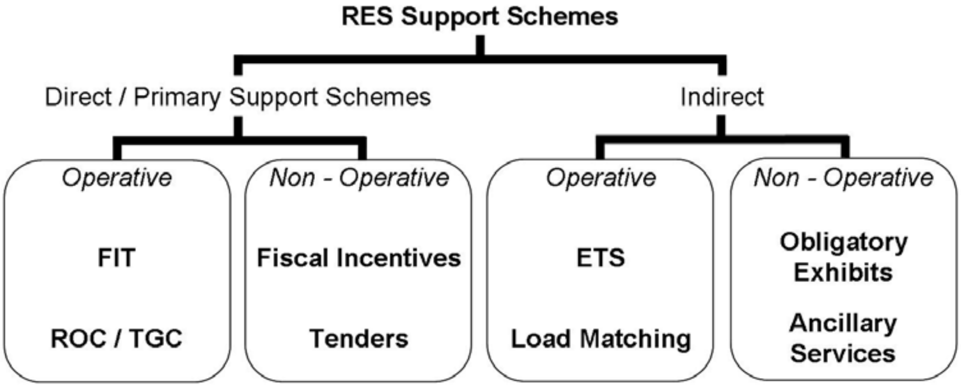


Figure 2.2: Range of possible renewable energy financial support instruments

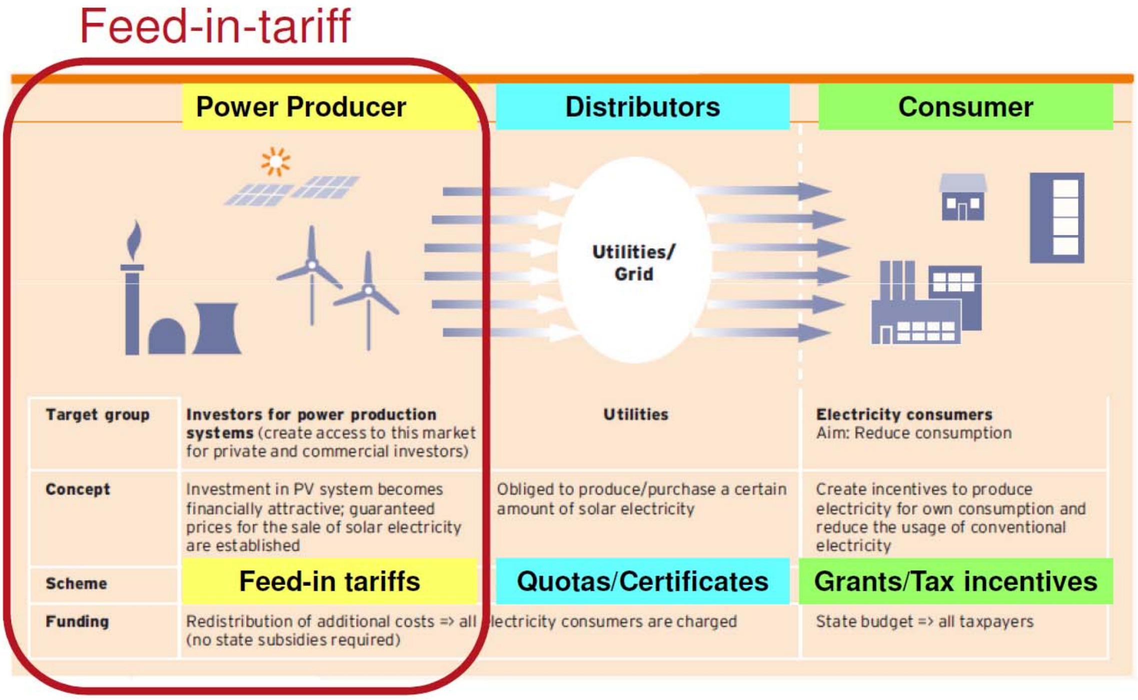
support schemes are accompanied by several RE grid interconnection schemes. Countries try to perform the most feasible RE policy for both the growth of RE share as well as the countries present and future economic scenarios.

Direct monetary support schemes would be phased out eventually as cost of RE electricity reach grid parity. The use of indirect incentives such as the emissions trading scheme (ETS) enacted in the EU in 2005 is one of the environmental policies to give flexibility in meeting emission targets. Furthermore, as shown in this research work, PV technologies will need further development to cut prices and become more affordable as micro-generators.

Past and prevailing energy policies and support schemes, based on FITs, have led to the high cost, high efficiency PV modules to be the most attractive option to generate income hence reducing the electricity cost for the domestic consumer. Figure 2.3 shows the three main support schemes that were adopted widespread in several countries. The progress from a customer oriented support scheme to distributor and power producer incentives is clearly illustrated.

Ultimately, the future essential conditions for the development of a sustainable PV market which acts independently from central government support schemes are:

- to increase the importance of cost reductions, and
- to have an effective incentive schemes until the PV technology becomes competitive with other generation technologies, without having a significant burden on the community.



	Power Producer	Distributors	Consumer
Target group	**Investors for power production systems** (create access to this market for private and commercial investors)	**Utilities**	**Electricity consumers** Aim: Reduce consumption
Concept	Investment in PV system becomes financially attractive; guaranteed prices for the sale of solar electricity are established	Obliged to produce/purchase a certain amount of solar electricity	Create incentives to produce electricity for own consumption and reduce the usage of conventional electricity
Scheme	Feed-in tariffs	Quotas/Certificates	Grants/Tax incentives
Funding	Redistribution of additional costs => all (no state subsidies required)	lectricity consumers are charged	State budget => all taxpayers

Figure 2.3: Consumer based to power producer based support schemes [55]

2.4 Overview of a PV system

There are mainly two types of systems:

i. on-grid (or grid connected) systems – these are the simplest systems that interface, with the electricity grid, to generate power for embedded generation. Some systems are considered as micro-generators while bigger systems are usually considered as centralised PV generators, and

ii. off-grid (isolated / stand-alone) systems – used to generate power where it is not viable to connect to the grid. These systems vary in applications such as commercial communication, signally purposes, product-based applications and remote villages.

Figure 2.4 illustrates the general PV system components:

- Arrays of PV modules each consisting of a number of PV solar cells connected together;
- Structural mechanical support for PV modules;
- Power conditioning (inverters and/or convertors), control equipment and measurement, protection equipment, monitoring equipment and wiring system;
- Energy storage system; and

- Any supplementary generation for a hybrid system, such as wind, diesel or micro-CHP.

A typical on-grid system does not require the last two components as this would increase the system cost while may not add value to the system. However, as we move towards a smarter grid in the future, more systems may incorporate battery energy storage to increase reliability and benefit from tariff incentives. One potential way to incorporate energy storage with PV systems would be to use plug-in electric and/or hybrid vehicles as energy storage, if these systems are used on a large scale. However energy storage growth is driven by low-cost energy storage with enhanced performance. In fact, as shown in future Figure 2.5, PV systems may be integrated with various loads, energy storage and electric power system. The Solar Energy Grid Integration System (SEGIS) will require changes to existing interconnection standards and these changes will be necessary as solar energy systems become a larger player in the electric power system. This thesis will focus on the present and future viability of on-grid systems using emerging organic-based PV technologies.

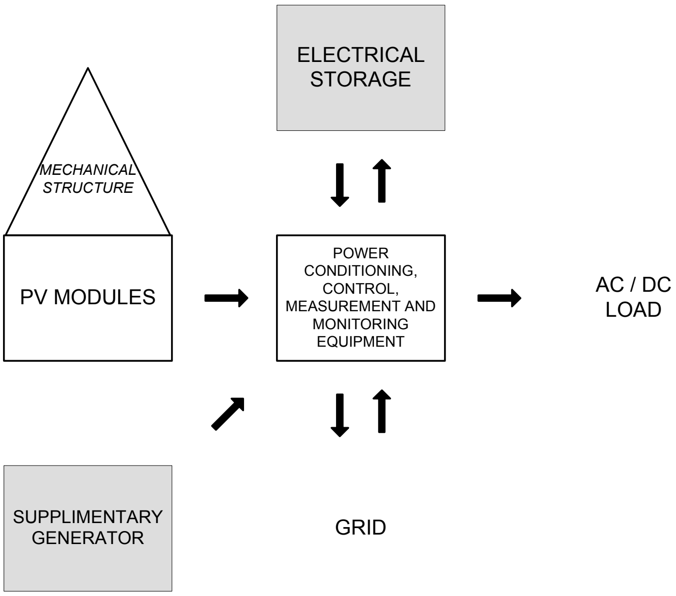


Figure 2.4: Photovoltaic system components [56]

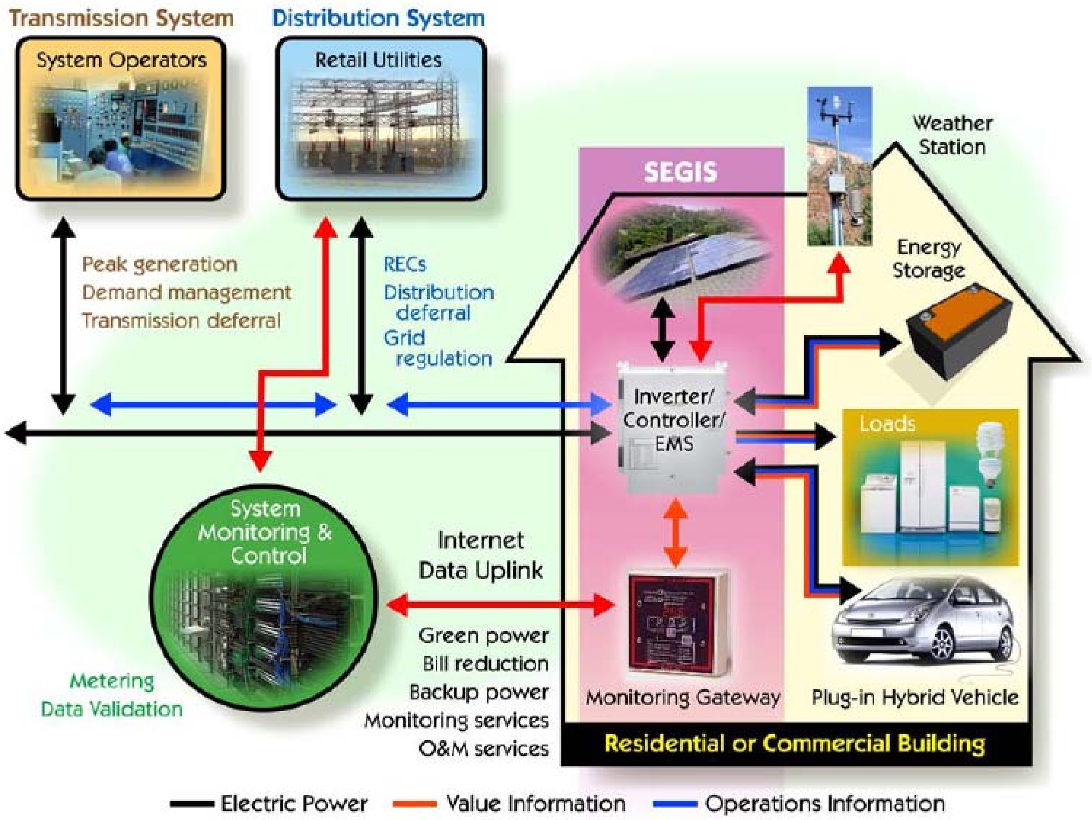


Figure 2.5: The SEGIS integrated with advanced distribution systems [57].

2.5 Fundamentals for PV systems energy analysis

The electricity generation directly from the PV system is proportional to the solar radiation (termed “irradiance”, symbol H) per square meter, the active surface area of the PV (A), the energy conversion efficiency of the PV (η_{PV}) and a Performance Ratio (PR – refer to APPENDIX B). The peak sun hours can be found by the measured irradiance. During the year, the peak sun hours diverge. This measure can be influenced by the Earth’s position in relation to the sun, latitude, atmospheric settings, and any shading caused by obstructions to sunlight at a given site, refer to APPENDIX A. Therefore, energy performance calculation for the hourly (h), daily (d) or yearly (y) energy delivery from a PV system (E_{PV}) is described by the following simple model in (2.1):

$$E_{PV} = H_{yr/d/h} \cdot PR \cdot A \cdot \eta_{PV} \tag{2.1}$$

Sizing a PV system depends on the type of system. On-grid systems are the easiest to size. A customer can decide to make up for part or all of their electrical consumption.

However the choice is mainly driven by the public policy incentives. APPENDIX D illustrates a simple sizing example for on-grid systems. On the other hand, off-grid systems require the provision of all the electrical demands, and an additional buffer period for climate cycles.

2.6 PV technologies

Green (2001) described the solar technology pathway in three generations with respect to efficiency and cost, refer to Figure 2.6 [58]. In addition, Figure 2.7, exhibits the types of PV solar cell technologies categorised by material. The current PV market is dominated by the first generation of PV, which is the most mature PV technology made from single or poly crystalline wafer- based silicon (c-Si) exhibiting operational efficiency of 10% to 18% reaching 25% in laboratories. The 20 to 30 years lifetime warranted by manufacturers on their performance, output up to 80% of the original efficiency, exhibits a reliable product. These c-Si solar cells exhibit high energy demand during production because of high temperature processes. The production is also limited by the silicon feedstock, though there is ongoing development for improved designs on this technology from manufacturers such as buried contacts, float zone silicon (better silicon-feedstock) and ribbon silicon (cheaper silicon feedstock).

Thin film (TF) technologies are mainly classified as the second generation. The first TF solar cell was commercialised 20 years ago back in 1980 using amorphous silicon (a-Si) technology. TF technologies have initially targeted consumer electronic products such as calculators and watches. Since 2005, TF technologies have experienced impressive growths and 30% share is estimated by 2010, refer to Figure 2.8. To date these growth rates were achieved by a-Si, copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe), classified as mature inorganic TF technologies [59].

Emerging PV technologies are attracting academic and industrial interests. These technologies can be grouped in two categories namely organic based PV and concentrated PV (CPV). Emerging organic-based PV technologies includes dye-sensitised (DSSC), organic-organic (OPV), and organic-metal oxide (hybrid-OPV). These technologies are an advanced form of TF technology. On the other hand CPV offers higher conversion efficiencies with an increased amount of mechanical structure considerations and hence maintenance.

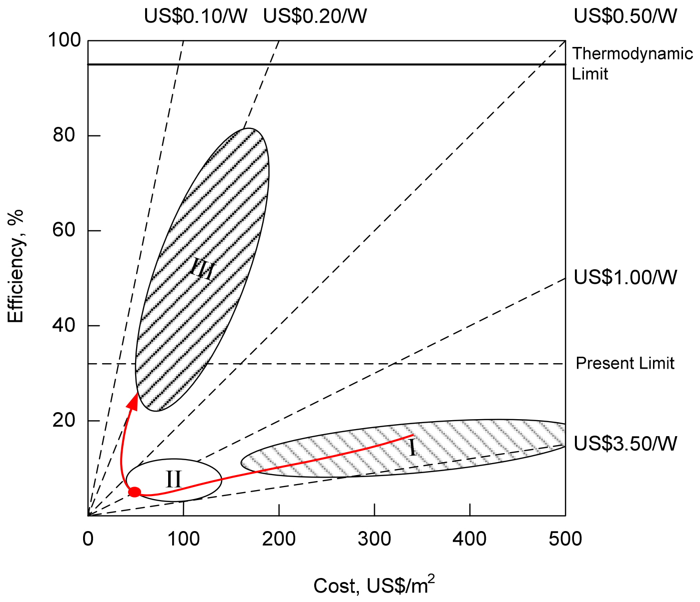


Figure 2.6: The three generations of PV technology [58]

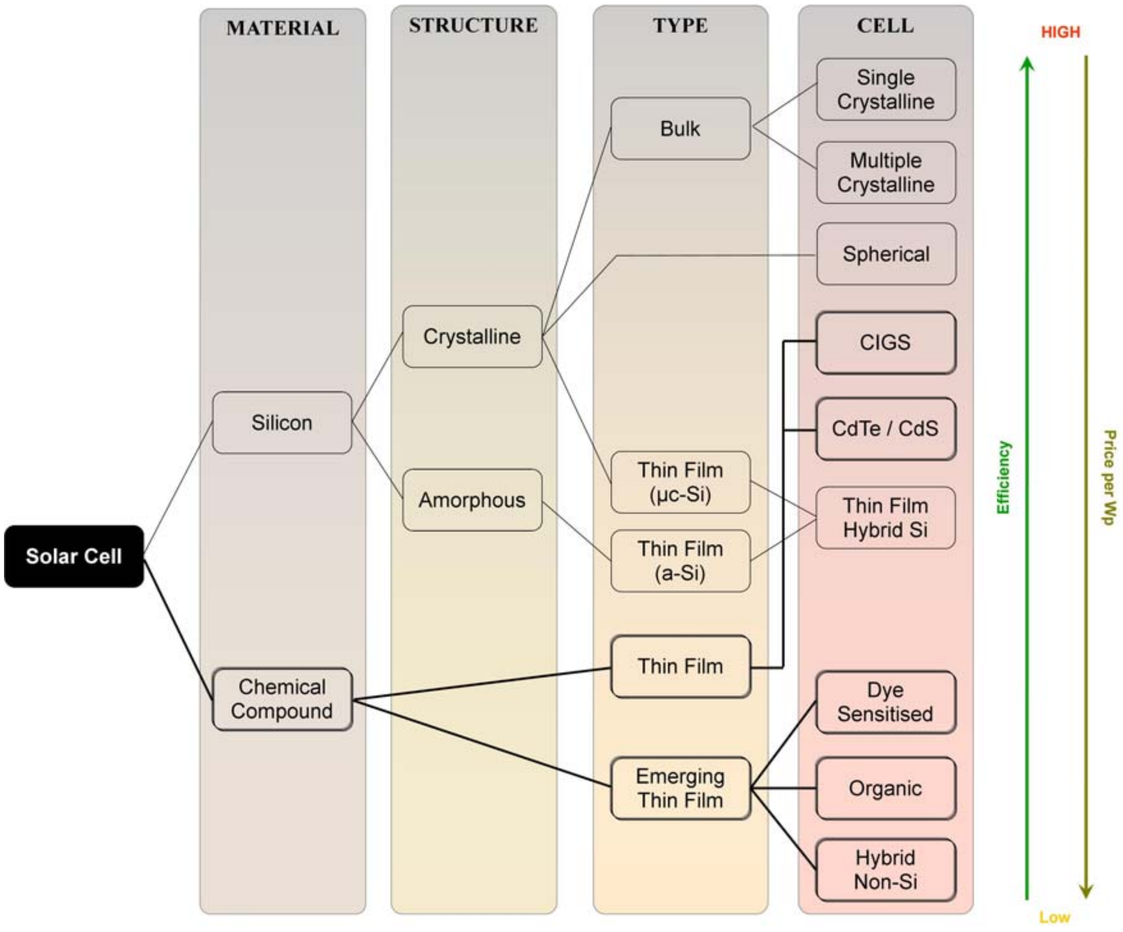


Figure 2.7: Type of solar cell by material, structure and type.

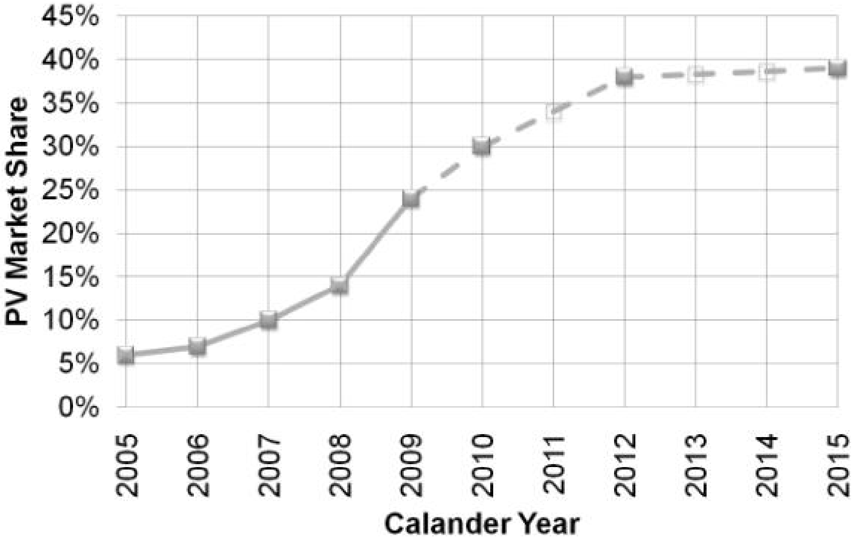


Figure 2.8: Worldwide TF PV market share versus calendar year [40]

2.6.1 Inorganic vs organic semiconductors [59]

The photovoltaic effect occurs within a semiconductor layer, also referred to the absorber material, when exposed to light. There exist a large number of suitable semiconductors. Currently commercialised TFs make use of inorganic semiconductors. On the other hand, emerging organic-based PV semiconductors raise increasing interest for commercialisation.

The main difference between the material systems is in the degree of localisation of the excited states, both excitons and charges. In an extended crystalline inorganic semiconductor charges and excitons are delocalised over very many repeated units of the lattice. In a molecular solid, as a result of the weak van der Waals bonding between molecules, excited states are localised on individual molecules or molecular segments. This has two important consequences for PV.

i. The neutral excited state generated by absorption of light, *i.e.* the exciton, is localised in a small volume of space, and as a result, the Coulombic binding energy between the electron and the hole is too large for the charges to separate at room temperature. The consequence of this is that charges can only separate within a binary blend film containing two electronically different materials. The use of two materials immediately reduces the maximum power conversion efficiency.
ii. Charged excited states that result from dissociation of the exciton are also localised on molecular segments, and have to move by a slow hopping process.

This slow charge transport places a limit on the thickness of the active layer that can be used.

In general, the semiconductor materials for TF technologies cannot normally be doped, and this makes the electrical connection between the semiconductor and electrode more critical and sometimes problematic. Typical TF device structures are shown in Figure 2.9 for single junction devices. The illustrated devices are represented by their materials' proportional thicknesses, and substrates are not included.

2.6.2 The organic-based PV solar cell

Classed as emerging organic-based PV solar cells, these technologies are currently under development, while being investigated for potential commercialisation. These solar cells can be much thinner and potential of low material costs than other TF technologies. A simple typical device structure includes an active layer with (i) organic-organic (OPV), such as a blend of conjugated polymer with fullerene derivative, or (ii) organic-inorganic (hybrid-OPV) sandwiched between two interfacial layers and two electrodes as shown in Figure 2.9 (e). Some hybrid-OPV classes in research include the embodied quantum dots (QD), which is the focus of this research work within the project consortium. Today, the efficiency of commercial organic-organic technology is around 2% [60] and a cell efficiency record of 8.13% [25]. These technologies have the potential to achieve very low costs, once current efficiency and stability issues will be solved.

The hybrid organic-based PV solar cells are a mixture of more than two or more types of semiconductor materials, getting the best from the two materials. These solar cells are non-silicon based solar cells. An organic semiconductor or polymer is well known for low price and flexibility, and an inorganic semiconductor is excellent in electronic properties [61]. The active layer contains an organic material which is typically the basis for active layer and nanoparticles (1nm to 100nm) made from an inorganic material such as Quantum Dots (QDs), synthesised within the active layer. Therefore, the hybrid organic-based PV solar cell technology promises a low material and manufacturing cost similar to OPV. Similar to other TF technologies, hybrid organic-based PV offers direct complete production of modules rather than individual cell production. In addition, like emerging OPV, hybrid organic-based solar cells may offer a range of applications as BIPV systems suitable for different shapes and designs and

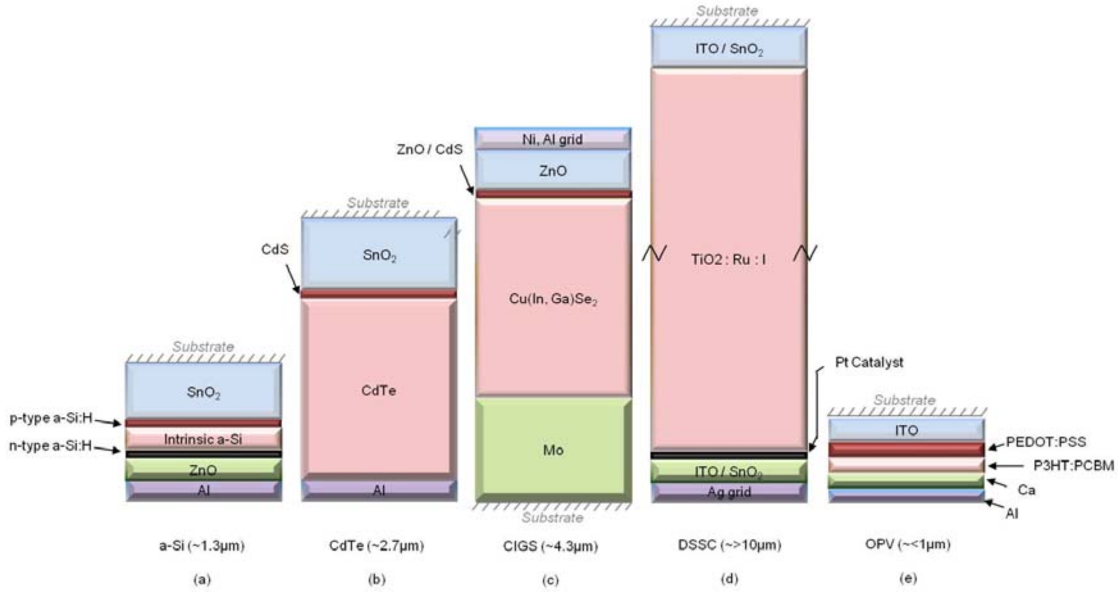
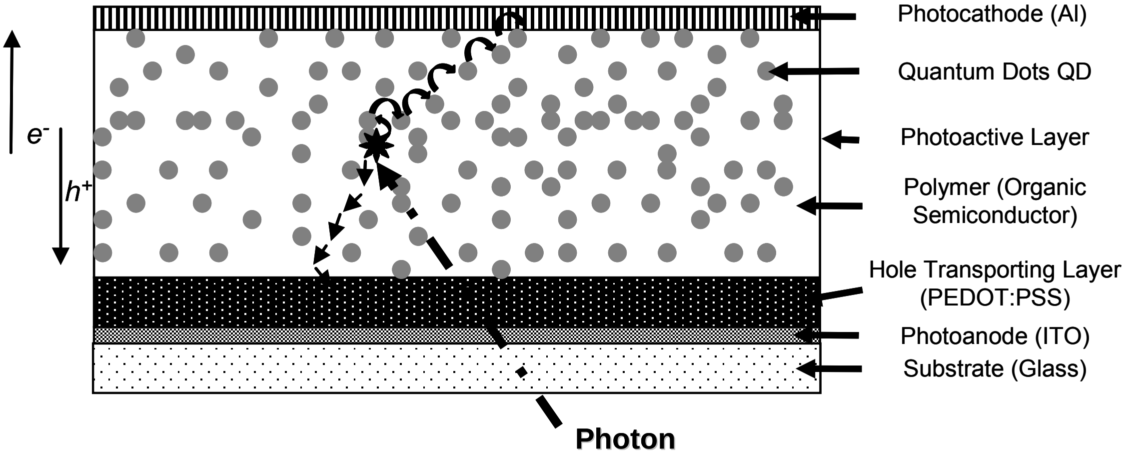
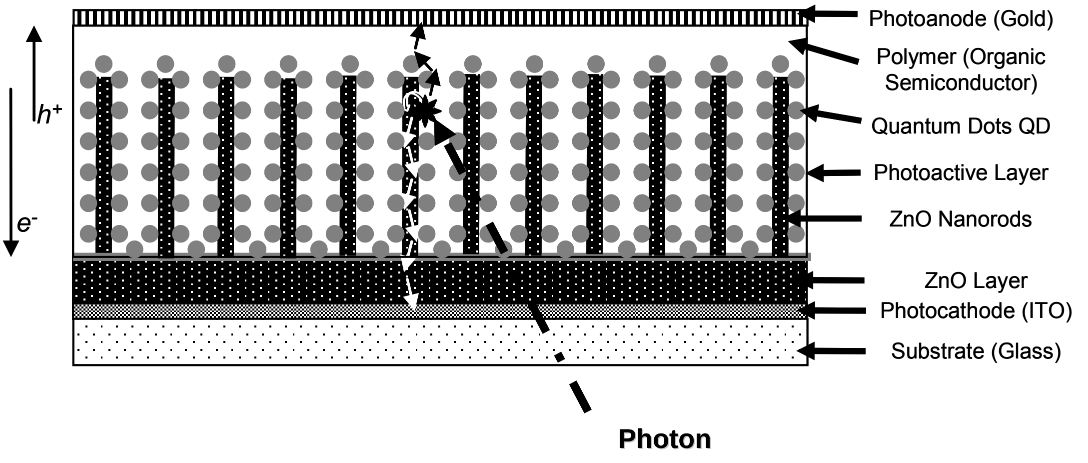


Figure 2.9: Typical device structure for TF technologies [59, 62-64]



Blend Type



Variant Type

Electrons (e$^-$) and hole (h$^+$) are collected at the photocathode and photoanode, respectively. The hole transporting layer enhances hole transport to the photoanode.

Figure 2.10: Typical hybrid organic-based QD PV devices

high production throughput, while may offer higher conversion efficiency as discussed in the Chapter 1.

Two typical hybrid-organic based PV device structures are illustrated in Figure 2.10. The polymer is the hole transport medium, also known as electron donor, while the nanoparticles shaped as rods and/or dots are electron transport medium, also known as the electron acceptor. When reference to material is made this research focuses on well known used materials in this field and project consortium contributions. Hence polymer known as poly(3-hexylthiophene) (P3HT) is used as the electron donor, while the Quantum Dots (QDs) are PbS QD is used as electron acceptor. P3HT is used worldwide by many research groups exhibiting high carriers' mobility to reduce current losses. At the same time, rod-shaped ZnO nanoparticles help electron transport to improve solar cell performance.

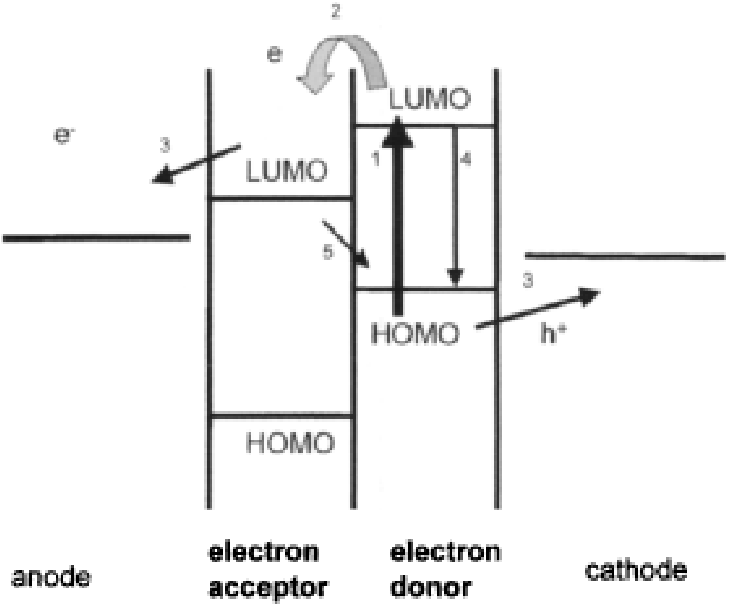
2.6.3 Organic-based PV solar cell operation

A PV module is made up of semiconducting material/s in the middle of the structure, electrical contacts at both ends and protective layers for the external environment. The properties of the semiconducting material will influence the overall thickness design, production cost and performance. Conventional solar cells operation described in Appendix C consists of pn junction/s, maintaining electric field at equilibrium.

The principle of operation of an organic-based solar cell is shown in Figure 2.11. The energy-band diagram of an organic-based solar cell is illustrating the donor-acceptor heterojunction photocurrent generation process. The terms in molecular semiconductor related to classical semiconductors models are:

- HOMO (Highest Occupied Molecular Orbital) – valence band (ground state) – Hole Transport Layer (HTL)
- LUMO (Lowest Unoccupied Molecular Orbital) – conduction band (excited state) – Electron Transport Layer (ETL)
- ▪ Acceptor – electron acceptor is the electron transport medium, nanoparticles - inorganic (similar to n-type)
- ▪ Donor – electron donor is the hole transport medium, polymer - organic (similar to p-type)

The electric field between the donor and acceptor drives exciton separation which



If both the excited state (LUMO) and ground state (HOMO) of the donor material lie at energies sufficiently higher than those of the acceptor material, then it is energetically favourable for an exciton reaching the interface to dissociate, leaving a positive polaron on the acceptor and a negative poleron on the donor. For efficient photocurrent generation, charge separation (2) should complete successfully with geminate recombination (4) after a photon absorption event (1), and transfer to contacts (3) should compete with interfacial recombination (5).

Figure 2.11: Schematic energy-band diagram of a donor acceptor heterjunction [27]

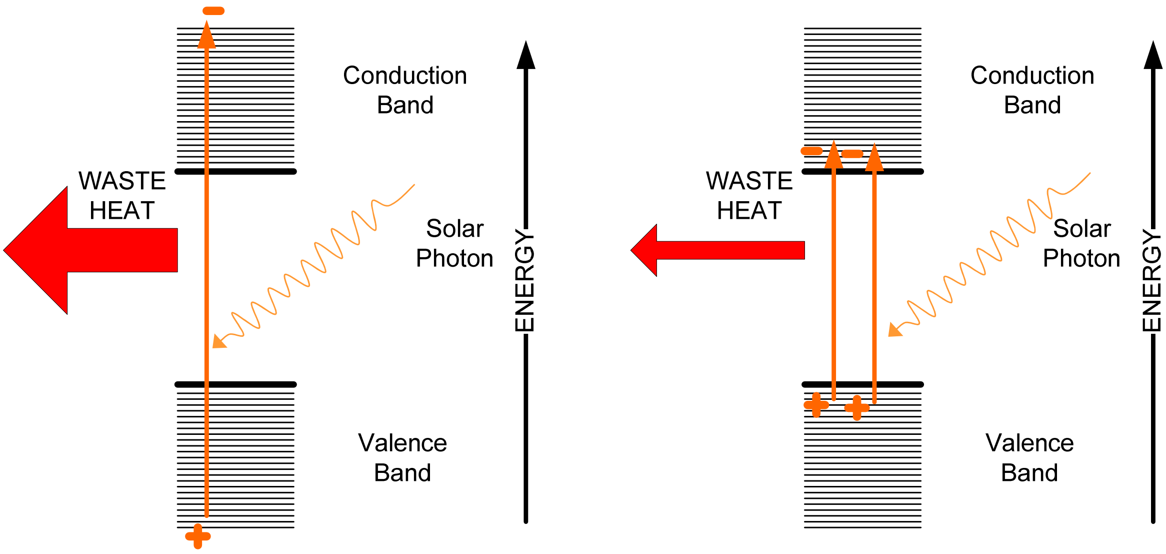
eventually may manage to reach the contacts generating an external electric current [26]. Simple device of a single organic material between two contacts excitons (electron-hole pair) generated from incident light are split due to the difference in work functions of the junction materials. However, these simple devices have only managed to achieve less than 1% quantum efficiency and less than 0.1% power conversion efficiency (PCE), due to unsuccessful splitting because of short exciton diffusion length typically less than 10nm [27]. Hence the hybrid organic-based solar cell, incorporating nanoparticles and QD within the active layer, brings interfacial distribution between materials, having different electronic structures. Therefore this PV device structure makes more likely to separate excitons and diffuse to the contacts [26].

2.6.4 Multiple Exciton Generation (MEG)

Conventional PV devices, making use of bulk semiconductor can only have one electron-hole pair per photon. This result in excess photon energy over band gap lost as heat, and hence, hot carriers rapidly cool. Under 1 sun silicon semiconductor have 47% incident power lost as heat which limits the theoretical efficiency to 33%, known as the ‘Schockley-Queisser’ Limit. On the other hand, in semiconductor nanoparticle, the impact of ionisation becomes competitive with cooling. In fact, the difference between the photon energy and energy band gap is used to create extra charges. Hence, one photon can excite two or more excitons, which contribute to higher photocurrent, consequently potential increase in PV device efficiency. This phenomenon is called Multiple Exciton Generation (MEG) also known Carrier Multiplication (CM) as depicted in Figure 2.12. By the use of current MEG performance with photon energy threshold 2 to 3 times energy band gap, efficiency between 30 to 45% can be achievable by semiconductor nanoparticles.

2.7 Conclusion

Current PV market is showing expansion in TF technologies. The search for more efficient and low-cost materials in the PV device structure is resulting in emerging PV technologies which are receiving a strong interest between stakeholders. The models and approaches developed in this research provide consistency to integrate emerging PV technologies for micro-generation and challenges can be transferred to opportunities.



Bulk Semiconductor Semiconductor Nanoparticle

Figure 2.12: Difference in bulk and nanoparticle semiconductor [65]

3

Lifetime-Adjusted Calculations Based on Life Cycle Costing

This chapter describes the basic philosophy of life cycle costing. A scenario description is illustrated to explain the aspects of lifetime-adjusted calculations. This is followed by a description on the developed methodology. Cost boundaries for emerging PV technologies are derived, and competitive module prices are shown.

3.1 Introduction

This chapter explores one of the first lifetime-adjusted calculations for photovoltaic (PV) modules based on life cycle costing (LCC). As in section 1.2.1, emerging PV technology may only require few years life expectancy of the order of 3 to 5 years for successful application. Therefore, it is important to understand how emerging PV technology and their PV systems may become an alternative to today's mature PV technologies on the market. Furthermore, the stability of the PV module, the most challenging task for emerging PV technologies, addressed by the efficiency degradation limits and different lifetimes, provides a guide for future PV designs with respect to energy output and investment cost of a PV system using the current mature technology (see section 3.5.1). This approach was a published contribution by the author [36].

3.2 Description of Life Cycle Costing (LCC)

Life Cycle Costing (LCC) is a technique to find out the total cost of ownership. It is a structured methodology which deals with all the elements of this total cost of ownership. Hence an expenditure profile of a system over its anticipated life-span can be formed. The results of an LCC study can be employed in the decision-making process over a number of products or systems. The accuracy of LCC analysis diminishes, as the project's finances are more into the future. Hence, long term assumptions are preferred on all alternatives.

Investment appraisal may be assessed with varies LCC metrics. The Net Present Value (NPV), or worth present value, is the most common technique [66, 67], representing the investment wealth level. The NPV is calculated on net annual cumulative present value cash flows, that is annual inflows less annual outflows. The benefit of an investment is indicated by a positive NPV. All net annual cash flows are discounted over the lifetime of the investment. This incorporates the time preference, which reflects the investor's preference of having money today versus future revenues.

Similarly, the Internal Rate of Return (IRR) indicates the rate of return generated by the investment and is the discount rate by which the NPV equals zero. The selection over alternative investments is based on the highest IRR. IRR entails more complex calculations than NPV and does not always provide a single answer [67]. In fact, IRR does not provide an indication of NPV sensitivity to cost of capital.

Another LCC metric for investment appraisal is the Profitability Index (PI), which represents the present value of future cash flows generated by the project per unit of invested capital. The viability is indicated by PI greater than one. Some other investment appraisal tools are Payback Time (PBT), defined as the period it takes for a project to recover cost outlays. Feasibility by payback period is predetermined by a period which is always significantly less than the project lifetime. Last but not least is the Annualised Life-Cycle Cost (ALCC) appraisal metric which averages upfront present value of the life cycle project cost over the investment lifetime [67].

For the purpose of life-time adjusted calculations, present value of the Life Cycle Investment Costing (LCIC) was chosen as the comparable metric for investment between two alternatives. The two alternatives are grouped as mature PV technology and emerging organic-based PV technology. Mature PV technology includes crystalline solar cells (c-Si) and inorganic thin film (TF) technologies, having 20 to 30 year lifetime. Emerging organic-based TF technologies includes DSSC, OPV, and hybrid-OPV that are still under further development, however, being on the verge of commercialisation with lower lifetime and durability. The comparison was also based on the equivalent energy output. The present value of all investments, in solar cell modules, is directly related to the objective of equalising the investor capital costs with other mature PV technologies to present worth investment.

3.2.1 Parameters

For the ease comparability of the results in this thesis, the following parameters are chosen to be the same throughout:

Period of Analysis (*T*) - The lifetime of mature PV technologies are between 20-30 years lifetime, which is likely guaranteed to produce up to 80% of the initial energy output by the end of its lifetime. Hence the baseline for period of all analysis is taken as 30 years, which is an plausible optimistic life expectancy of mature PV technologies in the short and medium term. Some calculations for 20 and 25 year period may be also presented within the text.

Lifetime (*L*) – Emerging organic-based PV might only reach a few years, around 3 to 5 years, for successful commercialisation, refer to section 1.2.1. Hence due to this uncertainty in the stability of these PV technologies short lifetimes between 1 to 15 years are considered including an average degradation.

Real Cost (C_r) - The cost at the base date, generally starting period, which excludes inflation rate but includes price movement mechanisms such as progress ratio and technology improvements. This is the initial capital cost and replacement cost.

Inflation Rate (*i*) - The rate of price increase.

Nominal Cost (C_n) - The expected price when a cost is outstanding: including inflation rate and price movement mechanisms.

Nominal Discount Rate (*n*) - The rate at which money increases in value if invested. A typical value is between 8 to 12%.

Real Discount Rate (*r*) – is the expression between inflation and nominal discount rate as in (3.1). 7% real discount rate was assumed throughout this research.

$$(1+r)=\frac{(1+n)}{(1+i)} \tag{3.1}$$

The LCIC calculation formula at base date, year is 0, is represented in (3.2); where I_y is an investment at year y.

$$LCIC=\sum_{y=0}^{T}\frac{I_y}{(1+r)^y} \tag{3.2}$$

3.3 Scenario description

As PV technologies progress from, wafer-based, first generation and, TF, second generation towards the third, advanced TF, generation, described in section 2.6, solar cell modules currently under development may present a different investment scenario from the present one. It is likely that, in the short term, commercial developments for emerging organic-based technologies are consumer products and in-door applications, rather than larger scale power generation [12, 68]. Emerging PV may also provide an interesting low cost alternative to conventional technologies, in particular for applications where flexibility is more important than efficiency. On the other hand, in the short and medium term, micro-generation applications in a domestic environment may still be of interest as these technologies will address the cost / benefit objective when incentives to PV technologies will dry out.

The financial comparative scenario illustrated in Figure 3.1 has the potential to become the norm for mass deployment of emerging organic-based PV technologies for micro-generation. The presented scenario reduces the weight of the initial high capital costs that make PV systems so unattractive amongst domestic users. Similarly, a lifetime-adjusted calculation considering different lifetimes and module efficiencies was performed for organic printed PV technology [8].

However, this chapter presents the comparison of the current scenario, presented by mature PV technologies, to the expected one with emerging organic-based PV technologies, for the short and medium term. This will result in cost and technical boundaries. Therefore, a simplified method is developed to determine the cost boundary of future PV technologies using LCC. The technical evaluation is based on the bases that similar life cycle PV energy outputs for current mature PV technologies make the system valuable within a domestic environment. Critical aspects of future affordable PV systems are also explained in the coming sections.

A PV technology is competitive if LCIC today is equal to current investment capital cost of mature PV technologies, as long as the mature technology has a positive worth present value throughout their lifetime under the current scenario. For a complete assessment of the potential of PV technologies, it is important to understand the economic viability of any PV module within a system application and for the type of potential end user [69]. For the purpose of the proposed lifetime-adjusted calculations, the economic viability is assessed with a comparison methodology based on energy outputs and NPV of capital investment, the LCIC. The following section 3.3.1 defines the assumptions to be taken to develop the methodology for the lifetime-adjusted calculations.

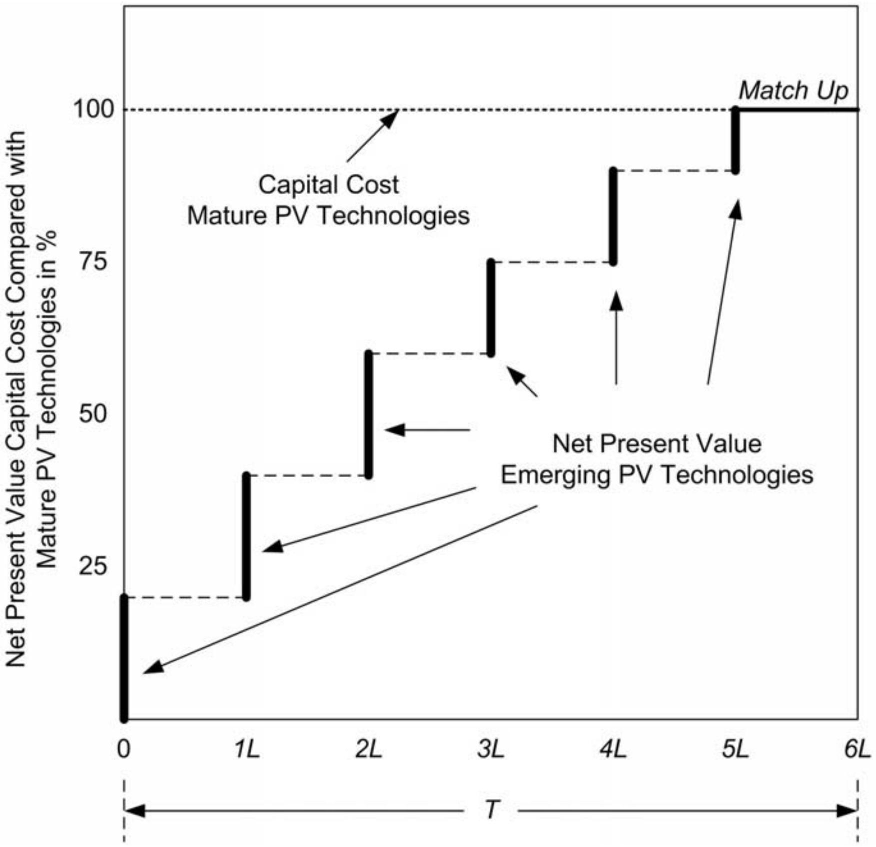


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Figure 3.1: Economic comparison of upfront vs regular PV investment [36]

3.3.1 Assumptions

Direct comparison between figures and results coming from different studies is not always straightforward because of differing approaches, assumptions and metrics. Hence, the assumptions taken in this section are consistent within this research for a coherent evaluation, unless otherwise stated, refer to Table 3.1.

The proposed methodology is based on the lifetime of a typical current system using PV technologies with a lifetime between 20 to 30 years, referred to as Period of Analysis in this research. Emerging organic-based PV technologies are available at a base date, which offer a significant low cost alternative. However, these technologies require regular replacements.

Therefore, the Balance of System (BOS) cost is equivalent at the base-date. It is assumed that the BOS components are not replaced and remain unaltered throughout the Period of Analysis. The BOS cost is also assumed to be equal for both mature and emerging PV technology based on the unit of energy generated. Hence only the Balance of Module (BOM) cost is considered in this study which includes a margin for replacement cost.

Table 3.1: General assumptions

Assumptions	Value	Typical	Units	Comments
Period of Analysis (T)	30	20 to 30	years	
Lifetime (L)	1 to 15	5	years	
Real Discount Rate (r)	7	5 to 10	%	i and n rates included
Efficiency Degredation (δ)	50 to 80	80	%	50% defined for OPV (section 1.2.1)
Performance Ratio (PR)	0.85	0.6 to 1.0		refer to Appendix A for more details

3.4 Methodology

This section describes the model for the lifetime-adjusted approach, which will result in BOM cost and PV system technical boundaries. In order to understand the model, a short description of a NPV profitable assessment is given in Figure 3.2. The annual net cash flow for a grid-connected PV system is divided into two sections, namely the outflows and inflows. The outflows represent costs including capital cost, replacement cost and operations and maintenance cost. The inflows represent any revenues from RE policies such as ROC and FIT, reward to export energy and savings from not importing electricity from the grid. However, for an equivalent energy comparable study between two PV technologies all variables that make up the net cash flow are coherent, based on the unit of energy generated, except capital cost and replacement costs as these are not dependent on the energy production. Maintenance costs are not considered for simplicity in this study.

Figure 3.3 provides a schematic representation of the simplified model developed based on LCC technique on invested capital. From the equivalent life cycle energy production calculation, a comparable PV system size in watts-peak (Wp) is determined for the same electricity energy output. This leads to a System Ratio (*SR*) parameter which requires design consideration if efficiency degradation is different in the comparable study. Meanwhile, the equivalent LCIC calculation leads to a boundary of the ‘real’ capital for BOM costs using emerging organic-based PV technologies in £/Wp. Finally, this BOM price boundary leads to the BOM price reduction factor (*PRF*) of an emerging organic-based PV technology. This is as a factor on the BOM price for mature PV technology. Therefore, the model consists of two consecutive calculations. One is based on the electrical energy production while the other is based on LCC investment.

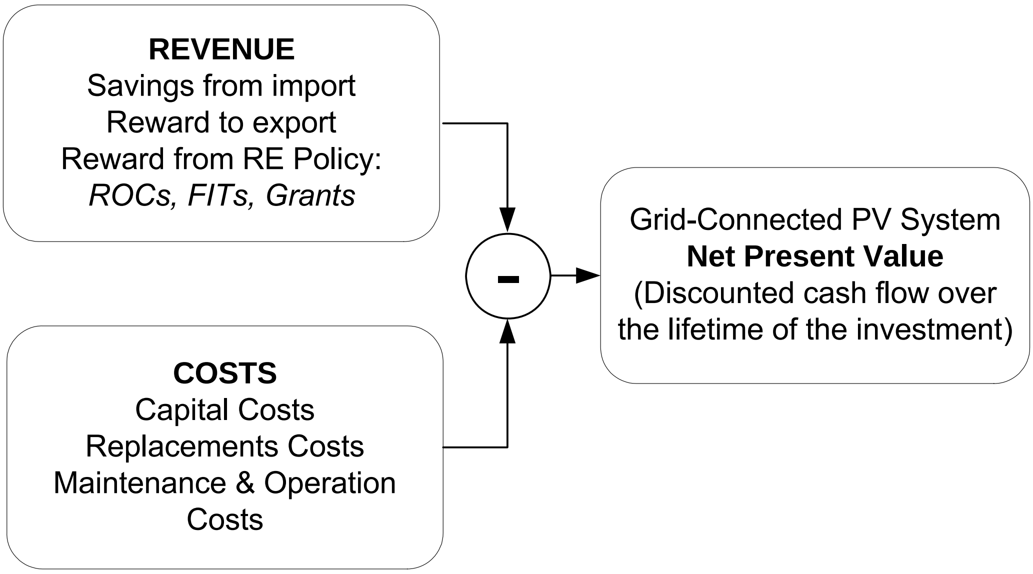

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Figure 3.2: Grid connected PV systems NPV model schematic representation [70]

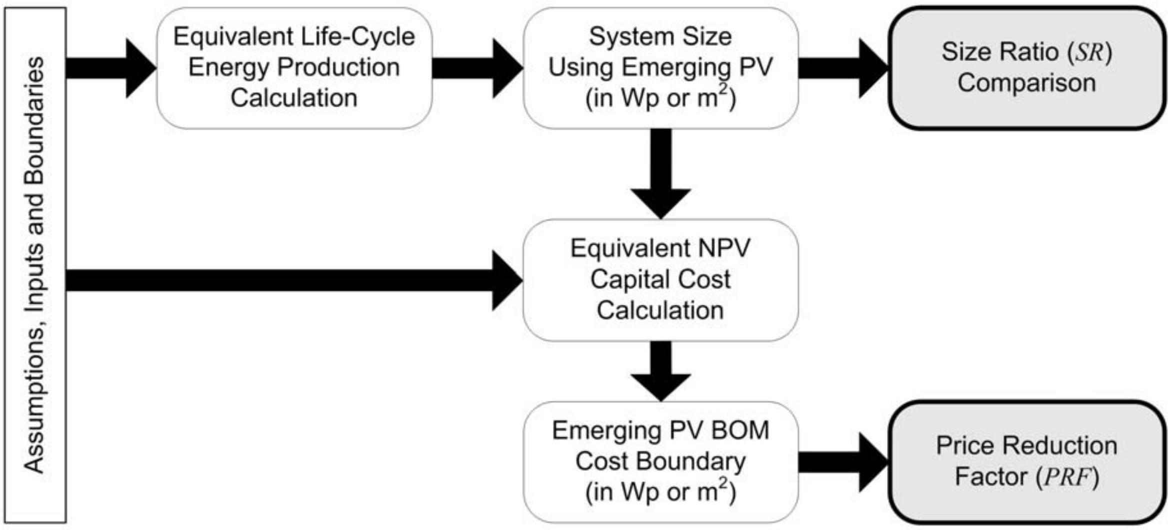

Figure 3.3: Schematic representation of the simple comparable model

3.4.1 Mathematical formulation

This section describes the mathematical formulation for the life-time adjusted calculations. The calculation is composed of thirty one year segments to represent 30 years as the period of analysis. The PV module rating in Wp is the maximum amount of direct current (DC) power rating ($P_{\max}^{DC}$) under 1.5AM (air mass) which is the Standard Test Conditions (STC) at 1000W/m^2, and 25^{o}C. Therefore, PV module rating is directly proportional to the module efficiency and PV active area covered represented in (3.3):

$$P_{\max}^{DC} = H_{STC} \cdot \eta_{PV} \cdot A \tag{3.3}$$

The efficiency degradation limit (δ), which is normally a missing term in PV system studies, is the power conversion efficiency level with respect to initial efficiency levels at the end of lifetime. The representation in (3.4) shows that the equivalent energy generation is dependent on the efficiency degradation limits, if emerging PV technologies (*ePV*) exhibits different stability and efficiency degradation limit warranties from mature PV technologies (*mPV*) as discussed in section 1.2.1.

$$\begin{gathered}
H \cdot \eta_{PV}^{mPV} \cdot \left(1 - \tfrac{(1-\delta^{mPV})}{2}\right) \cdot PR \cdot A^{mPV} \cdot T \equiv H \cdot \eta_{PV}^{ePV} \cdot \left(1 - \tfrac{(1-\delta^{ePV})}{2}\right) \cdot PR \cdot A^{ePV} \cdot T \\
\eta_{PV}^{mPV} \cdot \left(1 - \tfrac{(1-\delta^{mPV})}{2}\right) \cdot A^{mPV} \equiv \eta_{PV}^{ePV} \cdot \left(1 - \tfrac{(1-\delta^{ePV})}{2}\right) \cdot A^{ePV} \\
P_{rating}^{mPV} \left(1 - \tfrac{(1-\delta^{mPV})}{2}\right) \equiv P_{rating}^{ePV} \left(1 - \tfrac{(1-\delta^{ePV})}{2}\right) \qquad (3.4) \\
\frac{1+\delta^{mPV}}{1+\delta^{ePV}} \equiv \frac{P_{rating}^{ePV}}{P_{rating}^{mPV}} = SR
\end{gathered}$$

SR is the system ratio rating compared to mature PV technology under different efficiency degradation limit. A graph of SR against different stability scenarios is illustrated in Figure 3.4. The stability scenarios are represented by a range of efficiency degradation limits from 90 to 50%, on balance with an 80% efficiency degradation limit for mature PV technologies.

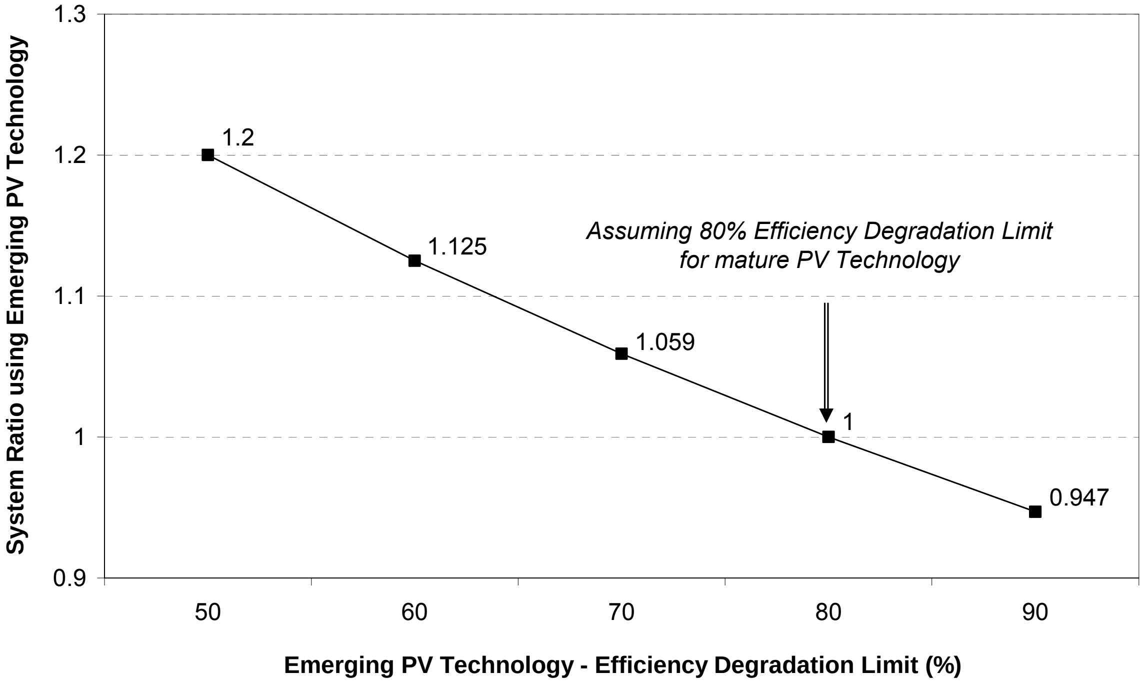

Figure 3.4: PV System Ratio (*SR*) for different efficiency degradation limits

This scenario mainly depends on the efficiency degradation limits. Therefore, PV systems using emerging PV technologies having different efficiency degradation limit than mature PV technologies may require up to 20% increase in system size rating for a comparable energy output. This may also lead to different initial capital costs for BOS components, which are not considered in this analysis. The model is dependent on PV module area which is a direct representation of a PV system rating in Wp. Hence, module efficiency is an independent parameter within the model. However, an increase in efficiency would ultimately reduce the active area and potentially production costs.

As discussed in section 3.3 and illustrating the scenario in Figure 3.1, the present value modules' capital costs of emerging organic-based PV technology modules are distributed over the period of analysis timeframe. Therefore, the equivalent economic calculation is represented by the LCIC of the two comparable systems to a base date in (3.5). Emerging PV modules require initial costs, purchase and installation, and replacement cost, in proportion to the price, that is net present worth. The cost adjustment factor (Cost^{adj}) , in (3.7), is implicated if the lifetimes of the solar cells had not expired at the last year of the analysis. The future PV solar cell price for emerging PV technologies can be determined by the price reduction factor (PRF) in (3.6).

$$\begin{gathered}
P_{rating}^{mPV} \cdot Cost_{BOM}^{mPV} \equiv \sum_{t=0}^{T-1} \frac{\alpha_{PV} \cdot P_{rating}^{ePV} \cdot Cost_{BOM}^{ePV}}{(1+r)^{t}} - P_{rating}^{ePV} \cdot Cost_{BOM}^{adj} \\
Cost_{BOM}^{mPV} \equiv \sum_{t=0}^{T-1} \frac{\alpha_{PV} \cdot SR \cdot Cost_{BOM}^{ePV}}{(1+r)^{t}} - SR \cdot Cost_{BOM}^{adj}
\end{gathered} \tag{3.5}$$

$$PRF = \frac{Cost_{BOM}^{mPV}}{Cost_{BOM}^{ePV}} \tag{3.6}$$

where:

t is studied period (yearly)

α_{PV} = 1 if replacement of PV module is needed, otherwise α_{PV} = 0

and,

$$Cost_{BOM}^{adj} = \left[(1+r)^{-NL} \cdot Cost_{BOM}^{ePV} \right] \times \left(1 - \tfrac{T-NL}{L}\right) \tag{3.7}$$

where N is the number of replacement during systems' lifetime calculated in (3.8)

$$N = \left\lceil \frac{T}{L} \right\rceil \text{-1} \tag{3.8}$$

3.5 Cost boundaries for emerging PV technologies

The calculated *PRF* that emerging PV technology's BOM cost must attain when compared to mature PV technology is shown in Figure 3.5. The graph shows three different period of analysis that is 20, 25 and 30 years scenarios which represent the compared lifetime with mature PV technologies. The analysis shown is comparing 80% efficiency degradation limit for mature technologies with 50% efficiency degradation limit for emerging PV technologies.

An exponential decay of the price reduction factor is depicted. Significant BOM costs / prices reductions are needed for frequent replacements. It is important to note that the cost boundaries are for the end-user BOM costs as described in section 1.2.3 and not for the module cost only as usually defined in the case of mature PV technologies systems. This means that the BOM costs / prices include modules' materials, production and overhead costs. In case of frequent replacements these overhead costs include mainly the labour costs to replace modules. These overhead cost may have an impact on the final module cost itself as a percentage of the BOM costs. Since this approach has not yet been applied in reality it is difficult to suggest this overhead cost margin. However a pessimistic figure would be 25% of BOM costs while an optimistic labour replacement costs would be as low as 2% of the module investment replacement cost, a typical value used in literature for maintenance and operation costs. This is later illustrated in an example in Table 3.3.

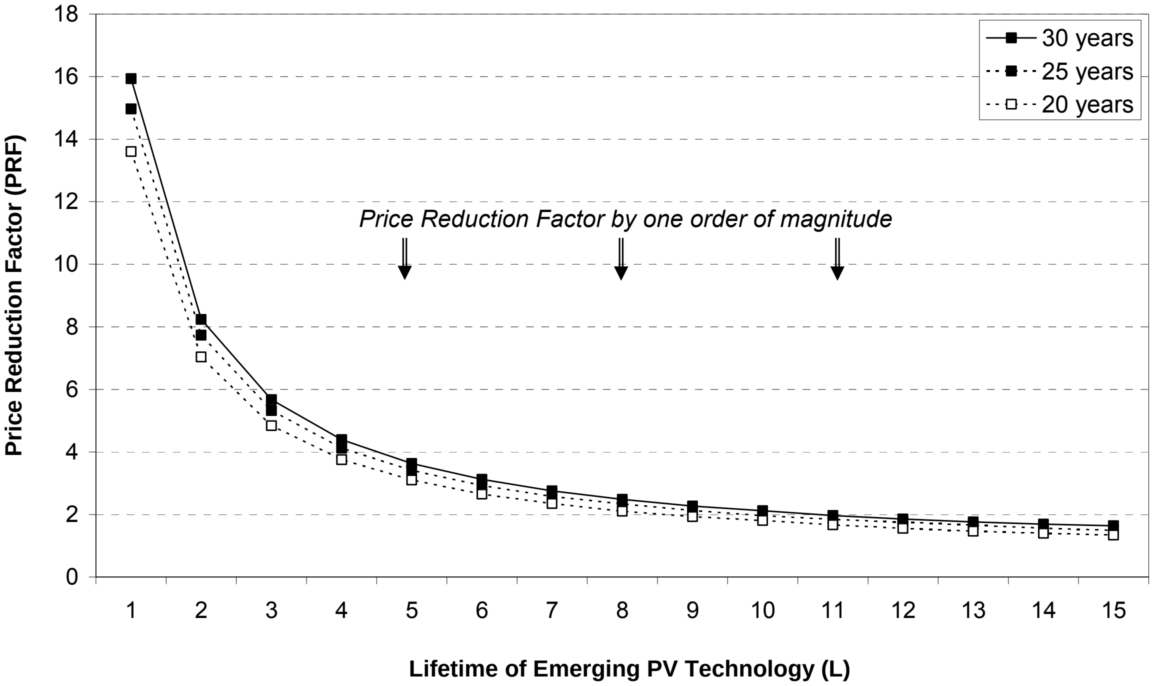

Figure 3.5: Price Reduction Factor (*PRF*) against lifetime

BOM costs *PRF* by an order of magnitude are reached with just two years lifetime. Hence, it is more likely that replacement periods higher than 4-5 years are probable to be more economically feasible as *PRF* for emerging PV technologies is lower than 5 times relative to base-date price of mature PV technology, as market penetration is suggested [71]. Though, lower lifetimes, 3 to 5 years, might still be useful for electronic devices working on PV energy. Therefore, to be competitive, the maximum price of more affordable PV systems with low life expectancies, low efficiencies and possibly high efficiency degradation must be approximately 4 to 5 times lower than that of a more mature PV technology with life expectancies of 20 to 30 years. Meanwhile, as PV market continues to grow, mature PV technologies' prices are even lowered.

3.5.1 Sensitivity analysis

The model aims to compare mature PV technology with emerging ones. In addition, the *PRF* is calculated for sensitivity analysis, which helps provide confidence in the model. The main uncertainties are the efficiency degradation limit, period of analysis and lifetime. Hence by sensitivity assessment these uncertainties are further analysed as listed in Table 3.2.

The sensitivity assessment studies the impact of replacement periods, between 1 and 15 years, efficiency degradation limits, between 90 to 50%, and period of analysis for 20, 25, and 30 years, on *PRF*. The *PRF* suggests the cost boundaries for emerging PV technologies at a base-date. Short lifetimes, denoting unstable and less robust

Table 3.2: Sensitivity analysis for Price Reduction Factor (*PRF*)

	20 years					25 years					30 years				
Lifetime	50%	60%	70%	80%	90%	50%	60%	70%	80%	90%	50%	60%	70%	80%	90%
1	13.60	12.75	12.00	11.34	10.74	14.96	14.03	13.20	12.47	11.81	15.93	14.94	14.06	13.28	12.58
2	7.03	6.59	6.20	5.86	5.55	7.74	7.25	6.83	6.45	6.11	8.24	7.72	7.27	6.86	6.50
3	4.85	4.55	4.28	4.04	3.83	5.33	5.00	4.71	4.44	4.21	5.67	5.32	5.01	4.73	4.48
4	3.75	3.52	3.31	3.13	2.96	4.13	3.88	3.65	3.45	3.26	4.40	4.13	3.88	3.67	3.47
5	3.10	2.91	2.74	2.58	2.45	3.41	3.20	3.01	2.84	2.69	3.63	3.40	3.20	3.03	2.87
6	2.68	2.51	2.37	2.23	2.12	2.94	2.76	2.59	2.45	2.32	3.12	2.93	2.76	2.60	2.47
7	2.37	2.22	2.09	1.97	1.87	2.61	2.44	2.30	2.17	2.06	2.77	2.60	2.44	2.31	2.19
8	2.15	2.02	1.90	1.79	1.70	2.35	2.20	2.07	1.96	1.85	2.50	2.35	2.21	2.09	1.98
9	1.97	1.84	1.74	1.64	1.55	2.16	2.02	1.90	1.80	1.70	2.30	2.15	2.03	1.91	1.81
10	1.81	1.70	1.60	1.51	1.43	2.01	1.88	1.77	1.67	1.59	2.12	1.99	1.87	1.77	1.67
11	1.71	1.61	1.51	1.43	1.35	1.88	1.76	1.66	1.57	1.48	2.00	1.87	1.76	1.66	1.58
12	1.63	1.53	1.44	1.36	1.29	1.77	1.66	1.56	1.47	1.39	1.89	1.77	1.67	1.58	1.49
13	1.55	1.46	1.37	1.30	1.23	1.68	1.58	1.48	1.40	1.33	1.80	1.68	1.58	1.50	1.42
14	1.49	1.40	1.31	1.24	1.17	1.62	1.52	1.43	1.35	1.28	1.71	1.60	1.51	1.43	1.35
15	1.43	1.34	1.26	1.19	1.13	1.56	1.46	1.38	1.30	1.23	1.63	1.53	1.44	1.36	1.29

Sensitivity analysis against: Lifetime, Efficiency Degradation Limit and Period of Analysis technologies, imply frequent replacements. Long lifetimes are desirable but may tend to be more costly [72], as suggested by significantly lower *PRF*. The price reduction factor reduces from as high as 16 times to approximately 1.5 times as lifetime increases, with no significant difference over 10 years lifetime. On the other hand, longer period of analysis lead to higher *PRF* for a given emerging PV technology lifetime.

3.6 Conclusion

This chapter has provided economic and technical boundaries for emerging organic-based PV technologies. These systems are likely to come at the expense of efficiency and durability. A methodology, based on LCC, was developed to determine cost boundaries for new PV technologies. Amongst other comparisons with existing PV systems, the *SR* and *PRF* were estimated on different scenarios. Preliminary indications show that a *PRF* of one order of magnitude can be achieved from lifetimes greater than 2 years. However, 3 to 5 years lifetime was suggested in literature as a feasible commercialisation point. It is important to note that the cost boundaries are for the end-user BOM costs as described in section 1.2.3 and not for the module cost production. Meanwhile, emerging PV technologies may, on balance, be found to have a different system rating compared to those systems using mature PV technologies for similar energy outputs due to different efficiency degradation limits.

PV module costs and stability parameters are very useful parameters to researchers and manufacturers. First, low-cost emerging organic-based PV technology should penetrate the PV market. The PV market is presently dominated by more expensive mature PV technologies. Table 3.3 shows the current and future price targets for PV technology and an example on how the *PRF* is used to determine the cost boundary at a certain base-date. For a 30 year system lifetime, 50% efficiency degradation limit, and 5 year lifetime, the cost / price boundary for 2020 is between 14 to 17p/Wp, while 2013 it is 20 to 21p/Wp, refer to Table 3.3. While today the price boundary for such a scenario is lower than 1£/Wp, increasing the durability by higher efficiency degradation limits and longer lifetimes may not significantly increase this price upper boundary.

Understanding future PV cost scenarios is critical to the formulation of public policies. It is worth noting that public policies affect the investment outcomes; such as pay-back time, and also the RE market with regard to variations in supply and demand chains. Hence emerging PV technologies upper price boundaries compared with the current commercialised mature PV technologies are crucial to enter the market competitively.

Table 3.3: BOM costs using *PRF* for emerging PV technology [73-75]

	€/Wp			**£/Wp$^{\wedge}$**			**emerging PV$^{\sim}$**		
	Today$^{\#}$	**2013***	**2020***	**Today$^{\#}$**	**2013***	**2020***	**Today$^{\#}$**	**2013***	**2020***
c-Si	3.00	1.35	0.75	2.33	1.05	0.58	0.64	0.29	0.16
a-Si	2.92	0.95	0.65	2.26	0.74	0.51	0.62	0.20	0.14
CIGS^{+}	3.33	1.00	0.80	2.58	0.78	0.62	0.71	0.21	0.17

$^{\wedge}$€ to £ using the OECD 2007 Purchasing Power Parity, for 2013 & 2020 estimates and OECD 2009 Purchasing Power Parity for Today International PV Spot Market

$^{\sim}$Scenario in for T - 30 years, δ - 50%, L - 5 Years, Hence $PRF = 3.63$

*With reference to EU PV Technology Platform 2007 *(a-Si module on glass substrate)*

$^{\#}$International PV Spot Market (February 2010) www.pvXchange.com

Type, Origin	**€/Wp**	**Average Turnkey PV system BOM cost multiplier**
c-Si, Europe	1.98	1.5-1.9 (~1.7)
c-Si, China	1.52	
c-Si, Japan	1.82	
TF CdS / CdTe^{+}	1.36	1.8 - 2.5 (~2.15)
TF a-Si / μ-Si	1.55	

	Emerging BOM costs in £/Wp considering overhead costs for replacement								
High Labour Costs 25% of BOM costs	BOM	Module	Labour	2013*	Module	Labour	2020*	Module	Labour
	0.64	0.48	0.160	0.29	0.22	0.072	0.16	0.12	0.040
	0.62	0.47	0.156	0.20	0.15	0.051	0.14	0.10	0.035
	0.71	0.53	0.178	0.21	0.16	0.054	0.17	0.13	0.043

	Emerging BOM costs in £/Wp considering overhead costs for replacement								
Low Labour Costs 2% of BOM costs	BOM	Module	Labour	2013*	Module	Labour	2020*	Module	Labour
	0.64	0.63	0.013	0.29	0.28	0.006	0.16	0.16	0.003
	0.62	0.61	0.012	0.20	0.20	0.004	0.14	0.14	0.003
	0.71	0.70	0.014	0.21	0.21	0.004	0.17	0.17	0.003

4

Cost Assessment for Hybrid Organic-Based QD PV Module

This chapter sets out the first developed cost model for typical hybrid organic-based QD solar cells which in parallel also analysis an organic PV (OPV) for large-scale production with well known components in this field. Some discussions on alternative material components and roll-to-roll high throughput manufacturing are performed throughout. The PV levelised electricity cost (LEC) is then described, and comparison has taken place with other sources of electricity generation. Further discussion on the PV LEC grid parity is given based on irradiance, BOS costs, BOM costs and lifetime. Finally, the chapter concludes with a discussion on future development promise by emerging PV technologies.

4.1 Introduction

When plastic solar cells, or better known as organic PV (OPV), become competitive, plastics manufacturers can look forward to large new sales markets. Hybrid organic-based QD PV comprises of two different materials, a polymer and a metal oxide. These two materials are blended together. Charges are created at their interface when the blend is illuminated by the sun. The goal for emerging organic-based PV technology producers is to offer flexible and economic film-based PV for novel applications, such as Building Integrated Photovoltaic (BIPV) for micro-generation. So far, the cost of manufacturing OPV was studied from a lab-scale scenario without any discussions on improve efficiency by using QDs [32, 33]. Hence this is the first developed cost model of a typical hybrid organic-based solar cell, which although there is not yet any large-scale manufacturer, the cost assessment is estimated on mass production of the cells and their component materials. Further timely discussions are given on grid parity PV LEC by emerging organic-based PV technologies and their future development promises.

4.2 The cost model of organic-based PV module

A recent simplified cost model for OPV was presented [33]. However, the costs for the hybrid organic-based QD solar cell are still unknown. Firstly the material costs are discussed, calculated and analysed followed by production and process costs as in Figure 4.1. The material costs are assumed as the material requirements corresponding to the solar cell structure while the production and process costs are assumed on capital investment, labour and overhead costs. Some estimates were unable to achieve, and hence, general estimates were used instead. A continuous reference to a typical OPV is made throughout to provide a basis for comparison. Based on the discovered cost estimates per square metre, the module cost is calculated in £/Wp under standard test conditions (STC) at 1000W/m^2 to an assumed efficiency. This is a comparable metric between PV technologies. However, in order to identify the market viability, an average LEC in £/kWh is calculated. The LEC is dependent on the lifetime, degradation, orientation and location of the system, and finances.

Organic-based solar cells have a similar device structure shown in Figure 4.2. In the next section, the materials costs are investigated, and alternatives to potential material uses are discussed. The substrate can be either glass or plastic. Plastic substrates

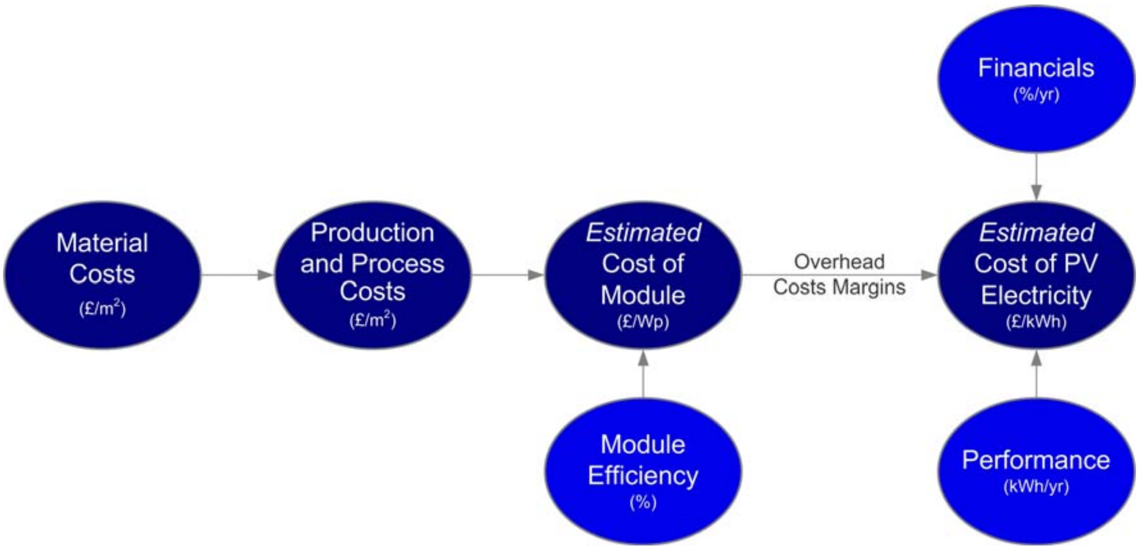

Figure 4.1: Cost model for a PV module

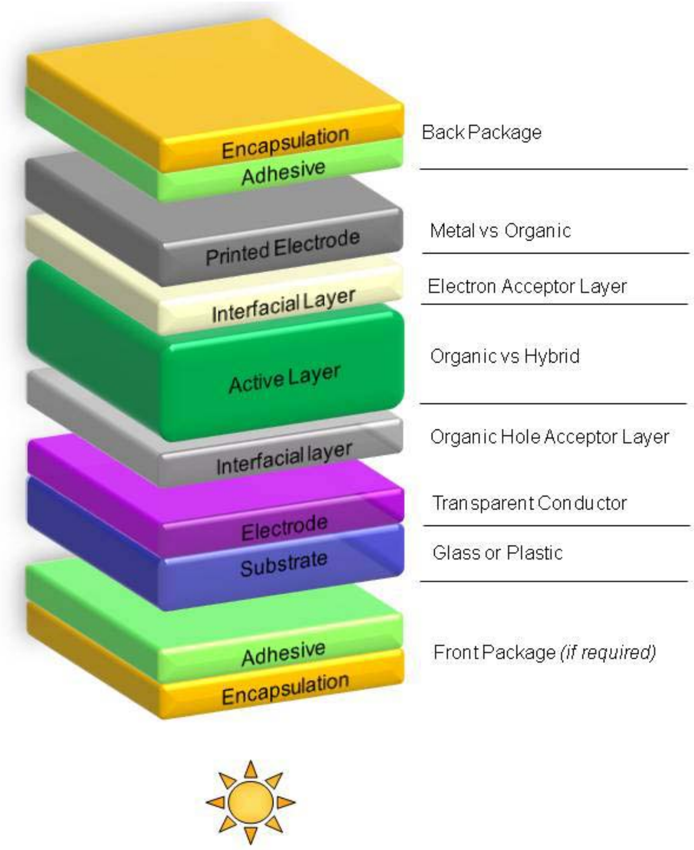

Figure 4.2: The device structure for an organic-based solar cell

provide low cost and flexible PV modules. The most common transparent conductive oxide (TCO) layer is currently indium tin oxide (ITO), however, fluorinated tin oxide (FTO) and organic conductors were investigated in the literature and offer a relative lower costs and more easily availability. While OPV have an organic polymer active layer, a hybrid version is made from a polymer and inorganic nanostuctures such as nanorods and / or quantum dots (QD) which are promised to offer better efficiency performance. The current metal contact, which is silver, may be replaced by an organic layer such as VPP:PEDOT or aluminium.

4.2.1 Material costs

There is a number of potential alternatives that can make up an organic-based solar cell. The results summarises the highest and lowest boundaries discovered from the most likely material alternatives. On the other hand, the cost estimates for individual material alternatives involved in the device structures are investigated. These are industry estimates based on large quantities of approximately 1Mm^2 p.a. (per annum), which is what would be required for a 50MW module maker at 5% efficiency on a glass thickness of about 3mm.

Transparent conductors (TCs) play an important role in the TF PV technologies. During this current rapidly growing use of materials such as tin oxide in ITO or as doped tin oxides such as FTO, the TCs materials are of comparable importance to the solar cell active materials. Hence such materials, as always, will follow traditional supply-demand economics, and the drive to produce competitive and advantageous alternatives may be required. There are currently four potential alternative TCO layers and two potential substrates. The potential substrate may be either glass or flexible substrate, such as PET, coated with a TCO layer. Depending mainly on the substrate, the four potential alternatives TCs, are ITO, aluminum-doped zinc oxide (AZO), FTO and organic TC. Examples of organic TCs are VPP:PEDOT (vapour phase polymerisation (VPP) of PEDOT (Poly(3,4-ethlenedioxythiophene))), highly conductive PEDOT:PSS (PSS is Poly(4-styrenesulfonate), a polymer used as dopant for PEDOT) or Polyaniline (PANI). Other alternatives, which were discussed in the literature include the use of carbon nanotubes [76], graphene [77] and a variety of other nano-engineered materials such as the use of nanoparticles and nanowires dispersed in a binder; and a variety of nanostructures: nanodots, nanowires and nanoplates based on indium or zinc oxides [78].

At the moment, the price for TCs is mainly dependent on the process and its market, rather than its reserve. ITO is one of the most costly TCO. Hence may not be preferred by today's most common thin-films on the market. However, it is dominantly used for LCD displays and within the OPV research field [78]. In addition, ITO is not stable at high temperature [79]. The process may still require around 300^{o}C during deposition though room temperature depositions are found in literature [80].

FTO is the cheapest, used by First Solar on the CdTe thin film PV modules, as it is usually deposited as part of the glass manufacturing process with required deposition temperatures of around 500^{o}C, which makes this TCO restricted to be used on glass substrates only [81]. AZO slightly more expensive than FTO, is the preferred TCO for CIGS thin-film PV modules [82]. Usually, AZO requires a temperature deposition between 300 to 350^{o}C. However, AZO can be controlled for roughness which may improve solar cell efficiency. AZO is sputtered deposited followed by etching, in hydrochloric acid, to create a rough surface texture. However, AZO room temperature deposition process can also be found in literature [83].

All three alternatives can produce similar electrical characteristics and durability. However, with any organic-based solar cell there could be some concerns about the work function between the layers. So an interlayer may need to be deposited between a basic TC and the active layer [84-87]. Besides these oxides' cost factor, these TCO are fairly brittle, and thus are not likely suitable for flexible application [88]. In addition, flexible substrates cannot withstand high temperatures above 150°C [89]. Hence conductive polymers such as PEDOT and other 'nano' alternatives are in parallel development [90].

Using a flexible substrate coated with TC can reduce costs from a glass substrate. Flexible substrates may become the key for wider PV applications. Based on current commercial available flexible substrates, the cost for a roll to roll flexible plastic substrate is assumed £3/m^2. On the other hand, based on cost estimates for ITO coated flexible plastic substrate [62], the process costs for a TCO deposited on a flexible substrate is taken at £0.30/m^2. The minimum cost estimates of ITO on glass substrate is taken as the maximum boundary for ITO on flexible substrate ones.

From Aldrich catalogue, ITO costs £1.95/g. Assuming 1g/m^2 of ITO is required (that is £1.95/m^2), and using the estimates for flexible substrate and process costs; an optimistic estimated cost for ITO-coated flexible plastic substrate is in (4.1):

$$ITO_{\text{cost}} = \pounds 3.00/\text{m}^2 + \pounds 1.95/\text{m}^2 + \pounds 0.30/\text{m}^2 = 5.25\pounds/\text{m}^2 \tag{4.1}$$

Meanwhile, the cost estimate for AZO-coated flexible substrate is based on the aluminium doping on zinc oxide TF produced by pulsed laser deposition for organic LEDs [91]. From Aldrich catalogue, Zinc Oxide Hydrate costs £1.009/g, and Aluminium Oxide Hydrate costs £0.00552g. Assuming a 1g/m^2 usage and similar process cost of ITO at £0.30/m^2. Having 98:2 mixture, the approximate cost of TCO is £1.00/m^2 (£0.98882/m^2 + £1.104e-4/m^2). This makes the final estimated cost for AZO-coated flexible substrate as in (4.2):

$$AZO_{\text{cost}} = \pounds 3.00/\text{m}^2 + \pounds 1.00/\text{m}^2 + \pounds 0.30/\text{m}^2 = 4.30\pounds/\text{m}^2 \tag{4.2}$$

As mentioned earlier, organic TC is an economic substitute as an electrode which is also more resistant to cracking on bending and more easily used in printing processing methods. The total material cost for a VPP:PEDOT organic TC is £0.60/m^2, based on the deposition of VPP:PEDOT on glass substrate of 40nm thickness [92]. The cost was derived from Aldich catalogue with Isopropanol at £0.05/ml, Pyridine at £0.06/ml and an assumed Fe(OTs)3 (iron(III)-p-tosylate) at £0.10/ml, having a ratio of 125:1:25 respectively and small drops of EDOT (3,4-ethylenedioxythiophene) at £148.6/g. EDOT price is also expected to go down once demand and supply are scaled up. Considering that process costs are twice as much as basic TCOs, at £0.60/m2, the final estimate for a VPP:PEDOT on a flexible substrate is in (4.3):

$$VPP:PEDOT_{\text{cost}} = £3.00/\text{m}^2 + £0.60/\text{m}^2 + £0.60/\text{m}^2 = 4.2£/\text{m}^2 \tag{4.3}$$

Based on the difference between the industrial minimum cost estimates of TCO on glass and minimum cost estimates on flexible substrates, a factor of 10 is added to estimate the maximum boundary for an organic TC on a flexible substrate which is the minimum cost estimate on glass. Another factor of 10 provides the cost estimate maximum boundary for an organic TC on glass.

There are a number of options for semiconductor materials that can be used in an organic-based solar cell for an OPV or a hybrid-OPV. The active layer costs estimates are based on the most common form of OPV made from P3HT (Poly (3-Hexylthiophene)) and PCBM (Phenyl-C61-butyric acid methylester). These materials have already resulted in reasonable module efficiency of around 3% on commercial scale of OPV modules and are considered as the cheapest polymer materials so far. Today the commercial-grade product for P3HT can be estimated at around £90/g and PCBM at £78/g (€$_{2009}$100/g for C60 derivative) for 10 to 15kg orders [93]. Meanwhile, the active layer for the hybrid solar cell is considered with P3HT polymer and PbS (lead sulphide) QD. As prices for PbS QD are unavailable, CdSe QD prices are assumed. From an industrial communication on CdSe QD, the manufacturer price is currently around £100/g for bulk powder quantity over 25kg. Assuming a mass production scale-up for the above materials in the emerging PV technology market the costs are estimated to go down by one order of magnitude, leading to P3HT at £9/g, PCBM at £7.8/g and QD at £10/g.

The active layer is assumed 1:1 blend of either P3HT with PCBM, for OPV, or a blend of P3HT with PbS QD, for hybrid-OPV. Assuming a plausible 25% material wastage during printing processes for a 200nm thickness of active layer, equivalent to 0.1cm^3 for 1m^2, the active layer cost is estimated in (4.4). The material densities are assumed at 1.5g/cm^3 for P3HT, 1.11g/cm^3 for PCBM and 7.5g/cm^3 for PbS QDs.

$$\left.\begin{aligned} P3HT_{\mathrm{cost}} &= 0.1\mathrm{cm}^3 * \ 1.50\mathrm{g/cm}^3 * \ £9.0/\mathrm{g} \ * \ 1.25 \ = \ £1.688/\mathrm{m}^2 \\ PCBM_{\mathrm{cost}} &= 0.1\mathrm{cm}^3 * \ 1.11\mathrm{g/cm}^3 * £7.8/\mathrm{g} * \ 1.25 \ = £1.082/\mathrm{m}^2 \\ PbS\ QDs_{\mathrm{cost}} &= 0.1\mathrm{cm}^3 * \ 7.50\mathrm{g/cm}^3 * \ £10/\mathrm{g} \ * \ 1.25 \ = \ £9.375/\mathrm{m}^2 \end{aligned}\right\} \qquad (4.4)$$

Hence the total active layer cost estimates are £2.770/m^2 for OPV, and £11.063/m^2 for a hybrid-OPV. These estimates are taken the highest. Thinner active layers of 50nm may reduce the active layer cost by a factor of 4. However this may reduce the efficiency the cell and hence the layer thickness needs to be optimised for the particular process technologies. One should note that these estimates are based on a full scale-up production of materials as stated above and therefore, are significantly lower than current costs.

Similar to TC there are four main potential alternatives for back electrodes. Three of these are based on metals aluminium, silver and gold. The latter is not widely used mainly due to high costs. The other alternative is an organic conductor, such as the PEDOT:PSS or VPP:PEDOT, the latter is the basis for calculation at £0.60/m^2, calculated above. Based on a ratio of 46.4% active area with respect to module size for large-area OPV fabrication [94], and assuming 150nm metal electrode thickness, the maximum total volume required per m^2 is estimated at 0.0696cm^3. Hence, assuming metal density of 2.7g/cm^3 for Aluminium, and 10.49g/cm^3 for Silver, with a cost price at £100/kg and £950/kg respectively, the potential electrode cost estimates are in (4.5):

$$\left.\begin{aligned} \mathrm{Aluminium}_{\mathrm{cost}} &= \ 0.0696\mathrm{cm}^3 * \ 2.70\mathrm{g/cm}^3 * \ £100/\mathrm{kg} \ / \ 1000\mathrm{g} \ = \ £0.019/\mathrm{m}^2 \\ \mathrm{Silver}_{\mathrm{cost}} &= \ 0.0696\mathrm{cm}^3 * \ 10.49\mathrm{g/cm}^3 * \ £950/\mathrm{kg} \ / \ 1000\mathrm{g} \ = \ £0.694/\mathrm{m}^2 \\ \mathrm{Organic}_{\mathrm{cost}} &= \ 46.4\% \ * \ £0.6/\mathrm{m}^2 = \ £0.278/\mathrm{m}^2 \end{aligned}\right\} (4.5)$$

For metal electrodes, thinner layers, approximately half of the estimate, were reported in the literature. Hence, the lower boundary is a factor of 2. One should note that, for the organic electrode, the same thickness was estimated on the TC estimates above. Hence its value was estimated on the percentage of the active layer in one module.

Interlayers match the work functions between the active layer and the electrodes which make the solar cell operate far more efficiently. Though interlayers may not be required for organic conductors, interlayers costs are added for consistency with the schematic structure in Figure 4.2. The interlayer PEDOT:PSS may be useful for planarising or smoothing effect in the device between the active layer and the TC, while calcium (Ca) or lithium fluoride (LiF) interlayer between the active layer and electrode may improve the electrode selectivity. The cost estimate for PEDOT:PSS is based on the HC Starck's Clevios P VP AI 4083 at £999 per litre for small quantities. Assuming large quantities and full scale-up production the PEDOT:PSS is assumed at £9.99. Less than 0.333*l* is required for approximately a 40nm thickness on a 1m^2 substrate. Hence the cost for interlayer between TC and active layer is estimated at £3.33/m^2. An automated industrial process may decrease the amounts required, from spin coating process, by a factor of 2, giving a minimum cost estimate of £1.67/m^2. Meanwhile for Ca or LiF, taken as the lower and higher boundary respectively for this interlayer, the cost estimates in (4.6), are based on Sigma Aldrich Catalogue and 60nm thickness with a 46.4% active area in a 1m^2 module. The maximum total volume required per m^2 is estimated as 0.0276cm^3.

$$\left.\begin{aligned} \mathrm{Ca}_{\mathrm{cost}} &= 0.0276\mathrm{cm}^3 * \ 0.63\mathrm{g/cm}^3 * \ £0.148/\mathrm{g} \ = \ £0.003/\mathrm{m}^2 \\ \mathrm{LiF}_{\mathrm{cost}} &= 0.0276\mathrm{cm}^3 * \ 2.64\mathrm{g/cm}^3 * \ £0.281/\mathrm{g} \ = \ £0.020/\mathrm{m}^2 \end{aligned}\right\} \tag{4.6}$$

An ethylene vinyl acetate (EVA) of 0.5mm thickness encapsulation is estimated between £1.78/m^2 to £3.56/m^2. Special chemicals may be required similar to those used in inorganic thin films, due to the instability problems with respect to degradation of polymer materials, estimated between £1/m^2 to £2/m^2 [33].

A summary of the above estimated costs is given in Figure 4.3. Table 4.1 shows the direct comparison between OPV and hybrid-OPV. All estimates are based on a production scale-up. The active layer for hybrid version constitutes to about 20%-24% of the total cost compared to 5%-6% for OPV. The substrate for these organic-based solar cells is still the largest portion of the device costs. For glass substrate the device cost share is 73%, while for flexible substrate it is 36%. Meanwhile, it is easily noticeable that flexible substrate is less expensive than glass. Therefore, the total device cost for a hybrid-OPV may range between £11.43/m^2 and £53.67/m^2 compared to OPV that may range between £9.36/m^2 and £45.37/m^2. The OPV estimates are comparable

Table 4.1: Comparison of material costs estimates for OPV, hybrid OPV and TF PV

Component	Organic Solar Cell Cost (£/m2)		Hybrid Solar Cell Cost (£/m2)		Thin Film Solar Cost (£$_{2009}$/m2) [95]	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
TCO coated substrate	4.20	33.00	4.20	33.00	6.60	16.51
Interlayer	1.67	3.33	1.67	3.33	1.98	6.60
Active Layer	0.58	2.31	2.77	11.06	1.32	33.01
Interlayer	0.01	0.05	0.01	0.05	1.98	6.60
Back Electrode	0.01	0.69	0.01	0.69	5.28	9.90
Adhesive and Encapsulation	1.78	3.56	1.78	3.56	0.00	5.28
Special Chemicals	1.00	2.00	1.00	2.00	1.32	9.90
Total	9.25	44.94	11.44	53.69	18.49	87.81

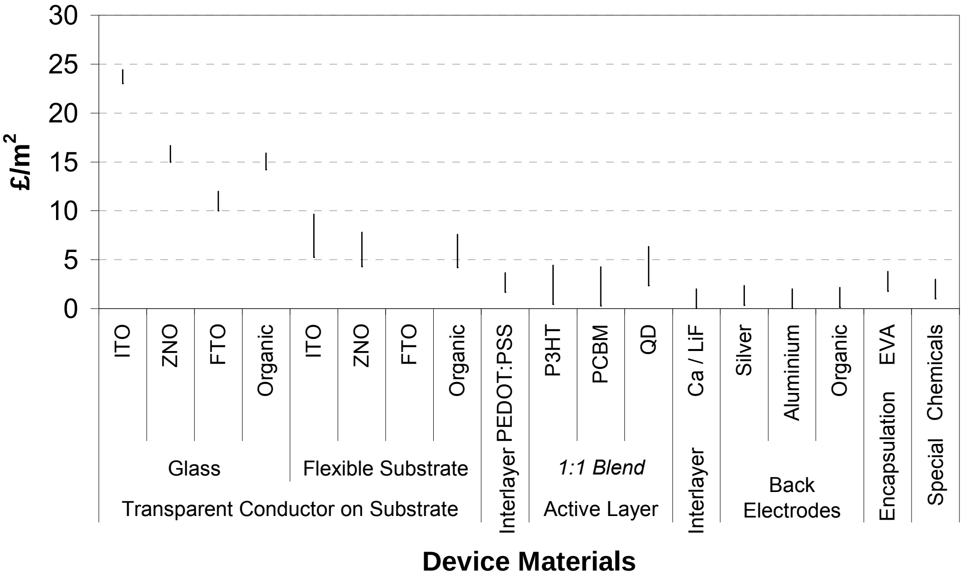

Figure 4.3: Cost estimates indication of all potential materials under investigation

with the basic cost model by Kalowekamo and Baker (2009) [33]. This model estimates OPV device costs between £15.82/m^2 and £16.55/m^2 (\$23.4/m^2 to \$24.48/m^2)[2].

TF PV technologies have several materials in common even though some are used for different purposes such as back contact, interlayer, active layer or TCO. Of interest, Indium (In) is used both as a TCO in ITO or absorber layer in CIGS devices. As discussed above, In appears likely to be scares and hence bears some price concerns. A number of studies have already looked at material constraints issues for PV technologies development, ranging from c-Si and various mature inorganic and emerging organic-based TFs [12-17]. Collectively these studies identify In and tellurium (Te) as the main threat to TF PV deployment technologies, specifically to CdTe and CIGS TF. A recent

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[2] US dollar converted to pounds using OECD 2008/9 Purchasing Power Parity.

study has also compared common materials typical usage figures for each TF PV technology (Figure 4.4). Despite the In future price and/or availability uncertainty, several alternatives like efficiency increase, lower thicknesses and material substitutions are discovered to reduce any impact of any critical materials on TF PV developments [59].

4.2.2 Production and process costs

Apart from low material usage, TF PV technologies have the potential for substantial cost advantage against c-Si due to the potential application of simpler manufacturing process. Commercial mature inorganic TF PV technologies employ a number of different deposition techniques such as physical vapour deposition, chemical vapour deposition, electrochemical deposition, or a combination. All these deposition techniques are less expensive than the ingot-growth techniques required for c-Si.

A simple, low-cost manufacturing process and low-temperature in air process are a common desire in TF PV. Apart from making the process cheaper to operate, it enables the use of less expensive flexible substrates as this may become a major expense for TF technologies. Hence the ideal method of manufacturing may resemble that of printing presses by depositing patterned electrodes and semiconductors on rolls of plastic or metal substrate in a continuous roll-to-roll process. This process does not involve high temperatures and high vacuum depositions. Two of TF commercial providers have

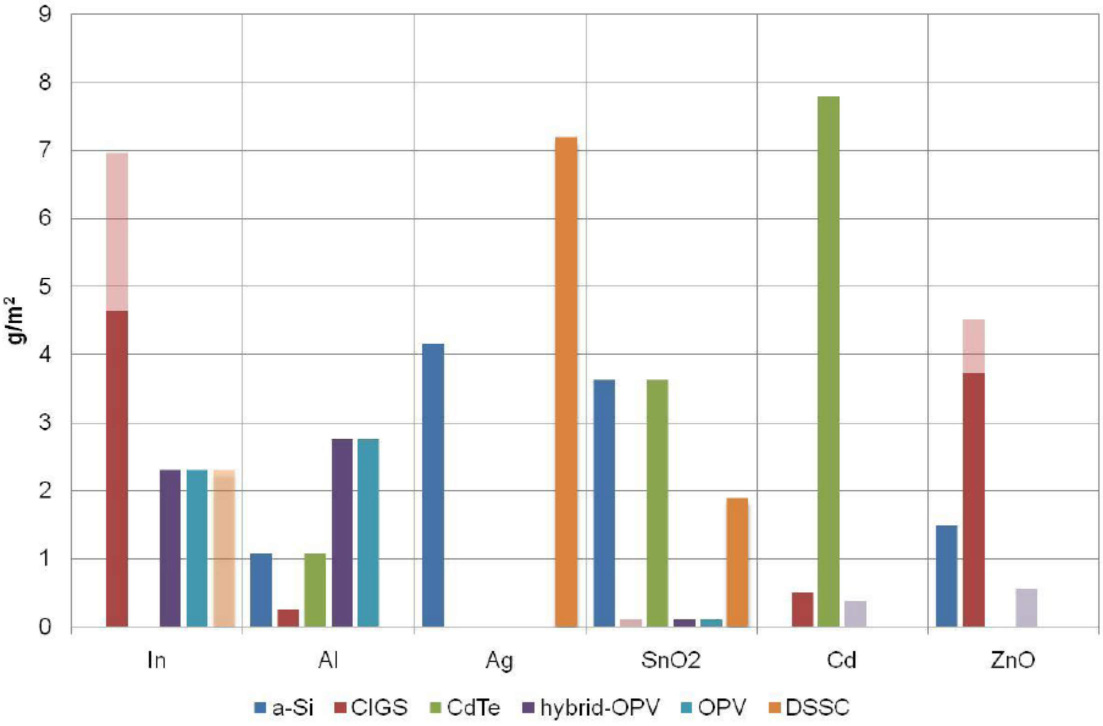

Figure 4.4: TF technology comparison on common material content [59]

already applied this concept in their production processes such as Nanosolar for CIGS [96] and Uni-Solar for a-Si [97]. The latter has provided a-Si flexible modules for a number of years. CdTe is also deposited on low-cost flexible substrates such as stainless steel [98]. Other companies such as Heliovolt are also developing ink-based processes for simpler, higher throughput and low-cost PV manufacturing [99]. Even though today most TF technology companies do not have online roll-to-roll processes, some has already established low manufacturing costs, such as First Solar. PV modules on a flexible substrate may reduce installation / original material costs which bring an added value to the investor.

Organic-based semiconductors already offer the capability to fabricate electronic device at low temperature and on various large area flexible substrates such as plastic and paper. Organic-based PV technologies fabrication and processing on printing and coating techniques are currently being studied [100, 101]. Speeds of up to 1000m per minute can be achievable which has potential of significant manufacturing costs reductions. The advantage that is already realised by industry and research institutions is that organic-based solar cells may be dissolved in ordinary solvents, and sprayed or printed onto substrates from solutions at or near room temperature. However before reasonable market penetration some issues need to be addressed. These include the stability enhancement of conjugate polymers, and higher conversion efficiency, matching the bandgap of suitable blended/composite polymers and dyes.

Hybrid organic-based PV modules may potentially exhibit common process steps as OPV modules. Except the nanoparticles synthesis and annealing, all processes of hybrid solar cells are relatively considered being similar to OPV modules. These nanoparticles synthesis and annealing may require a slightly higher temperature processes. The advantage with flexible substrates, for example roll-to-roll production, is that of a greater output production. At present Konarka is the only company, to the author's knowledge, that has a commercial up-scale for OPV with around 1GW facility [60].

It has already been demonstrated that the slowest roll-to-roll fabrication of OPV is the PEDOT:PSS deposition and slot die coating and layer drying at 18m/h [102]. Hence with a roll width of 305mm 24/7 production, a 2GWp is reachable for 5% module efficiency (131.76m^2/day = 48,092.4m^2/year = 2.4GWp/year). This will bring costs significantly down by a factor of over 200 within the production and process costs, when compared to typical installed thin-film manufacturing 10MW plants, based on glass substrates. Hence a 100 times faster production speed is assumed giving a reasonable ratio of 100.

Currently there are no mass produced hybrid organic-based QD PV. Hence estimates for process costs are based on the available industry equipment and literature on the mass production of TF manufacturing plants, 10MW in size, which mostly produce solar modules on glass substrate. These estimates are then extrapolated, by this factor of 100, to represent the high throughput on flexible substrates.

From the literature, the estimated capital cost of equipment for PV manufacturing can range from \$0.5M to \$5M per megawatt capacity [28]. Assuming a 10MW plant, 5% efficient solar modules, plant lifetime 7 years and discount rate 7%, the annualised cost for a 10MW plant is £0.61M to £6.14M. A yearly production based on 10MW plant is equivalent to 200,000m^2 (10MW / (1000W/m^2 * 5%)). Therefore, the capital costs estimates are £3.05/m^2 (£0.61M/200000m^2) to £30.00/m^2 (£6.14M/200000m^2).

Labour cost estimates are important, though their significance in the whole cost model is minimal. Labour cost in Booming Economies such as China and India can be about 7 times lower than Western Countries in EU and US. There is still an uncertainty on the true amount of labour needed when processes are not well known. Hence based on previous derived labour costs for OPV [33], labour cost estimates 30 people, 8h/day, 350days/year at £11.50/hour (\$17/hour[3]), the estimated labour cost is (£966000/year) / 200000m^2 = £4.83/m^2. While this estimate is the minimum, the maximum estimate is taken based on the 20MW/year First Solar CdTe manufacturing model at £8.10/m^2 (\$12/m^2). Therefore, the labour cost estimates range between £4.83/m^2 to £8.10/m^2.

The overhead costs in production and process costs are based on the simple cost model for OPV which included facility renting, utilities, maintenance, miscellaneous and customer warranty costs [33]. The miscellaneous costs, assumed as research and development costs, and warranty were taken at a high percentage at 5% due to the technical developments and early high prices in the market. The maintenance cost is taken at 4% of capital cost per year. In general, facilities and utilities for both OPV and hybrid organic-based QD PV are expected to have similar manufacturing processes.

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[3] US Dollar converted to Pounds using the OECD 2008/9 Purchasing Power Parity

4.2.3 Estimated cost of PV module

Table 4.2 presents a summary of manufacturing, production, process and device costs. For easy comparability with other PV cost estimates in literature. A 95% cell yield is used. The cost estimates for a hybrid organic-based PV on glass substrate will range between £36.50/m2 and £103.56/m2. Considering a higher throughput when using flexible substrate, the cost estimates will range between £13.37/m2 and £40.84/m2. This is slightly higher from OPV that range between £34.10/m2 and £93.97/m2, and £10.98/m2 to £31.26/m2 for glass and flexible substrate respectively.

For ease of comparability, considering a 98% module yield and a 2012 future OPV target of 5% module efficiency [33, 40, 103], the above organic-based module cost is calculated using (4.7):

$$C_{\text{module}} = \frac{C_{\text{manufacturing}} \cdot 1.02}{H_{STC} \cdot \eta_{PV}} \tag{4.7}$$

Hence the module cost estimates range between £0.22/Wp and £2.11/Wp.

Table 4.2: Summary of total cost estimates for OPV and hybrid OPV

Cost Component	**Estimates of OPV (£/m^2)**				**Estimates of Hybrid OPV (£/m^2)**			
	Glass^		**Flexible^**		**Glass^**		**Flexible^**	
	min	**max**	**min**	**max**	**min**	**max**	**min**	**max**
Device Costs	15.16	32.37	9.36	26.57	17.24	40.67	11.44	34.87
Production and Process Costs								
Capital Costs	3.05	30.00	0.03	0.30	3.05	30.00	0.03	0.30
Labour	4.83	8.10	0.05	0.08	4.83	8.10	0.05	0.08
Facilities	4.90*	6.86*	0.05	0.07	4.90*	6.86*	0.05	0.07
Utilities	1.47*	2.94*	0.01	0.03	1.47*	2.94*	0.01	0.03
Total Manufacturing Costs	29.41	80.27	9.50	27.05	31.49	88.57	11.58	35.35
Maintenance Cost *(4% of Capital)*	0.12	1.20	0.00	0.01	0.12	1.20	0.00	0.01
Warranty Cost *(5% of Manufacturing Costs)*	1.47	4.01	0.48	1.35	1.57	4.43	0.58	1.77
R&D *(5% of Manufacturing Costs)*	1.47	4.01	0.48	1.35	1.57	4.43	0.58	1.77
Total Costs	32.47	89.50	10.46	29.77	34.76	98.63	12.74	38.89
Total Cost *with 95% cell yield*	34.10	93.97	10.98	31.26	36.50	103.56	13.37	40.84

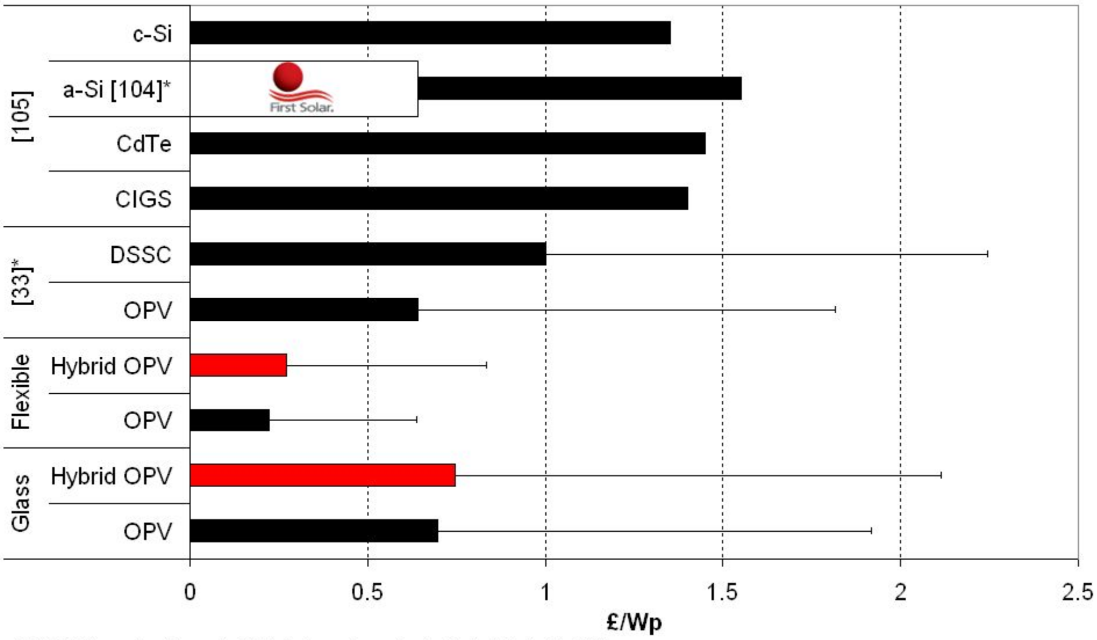
* US Dollar converted to Pounds using the OECD 2009 Purchasing Power Parity

^ 10MW annual production plant is assumed for glass substrate, while on flexible substrate a 1GW annual production plant is assumed

From Table 4.2, it is clear that the device costs constitute the largest part of the total module costs in most cases except for high end cost estimates on glass substrate. Hence, it is also clear that production and process costs will not significantly impact module costs on a flexible substrate.

As described in the previous chapter, cost competitiveness with respect to energy output performance over a system lifetime is critical for on-grid domestic environment PV market penetration. Figure 4.5 compares the cost estimates for different PV technologies in literature. This study investigates four cost estimates of emerging PV technologies, based on glass and flexible substrate, for OPV and potential future hybrid-OPV. The data in the literature is drawn from previous comparable work, assuming cell yield of 95% and module yield of 98% [33].

Commercial TF technology modules are currently cheaper than c-Si to manufacture, with CdTe modules manufactured at 0.98$/Wp by First Solar. Target cost reductions of around 0.5€/Wp are deemed achievable by around 2020, provided that the expected increase in the production facility sizes and improvements in efficiencies are realised [29-31]. The cost estimate in this study is comparable with previous DSSC and OPV cost estimates. On the other hand, flexible substrates offer a significant cost reduction by increasing the throughput in production. However, there is still uncertainty in the process and device costs due to lack of knowledge in the process on industrial scale-up



*$1.5589=£1 as of streling agaist US dollar forward rates by the Bank of England in 2010

Figure 4.5: PV technologies cost estimates comparison [33, 104, 105]

and economics of scale in relation to material costs. This uncertainty is shown by a wide range in the cost estimates.

4.2.4 Estimated cost of PV electricity

The Levelised Electricity Cost (LEC) is estimated on the model in Figure 4.6. The model does not consider operation and maintenance costs. The BOS costs include area and energy related costs for a complete system. In this case system installation costs are considered as part of the BOS costs. On the other hand BOM costs include module costs and overheads. The overheads include the installation or replacement of modules within the system. A cost margin for replacement costs may be considered within the BOM costs as discussed in sections 3.5 and 3.6. This replacement cost is still unknown on the market as this approach has not been realised in a real world application. However one may consider high replacement costs to low replacement costs depending on the module fixing design and procedures. Hence for simplicity in the calculation below the BOM costs is taken as the module estimated cost in section 4.2.3 without profit margins or overhead costs. Equity for capital costs are not considered, in order to have a true picture of the LEC incentives. These BOM and BOS cost indicators on the system level has already been defined in section 1.2.3.

The LEC is calculated by annualising the life cycle investment cost (LCIC) divided by the annual PV energy output as in (4.8). The annualised LCIC is the product of the LCIC which is the total system cost over its life cycle and the capital recovery factor (CRF).

$$LEC = \frac{LCIC \cdot CRF}{E_{PV}} \tag{4.8}$$

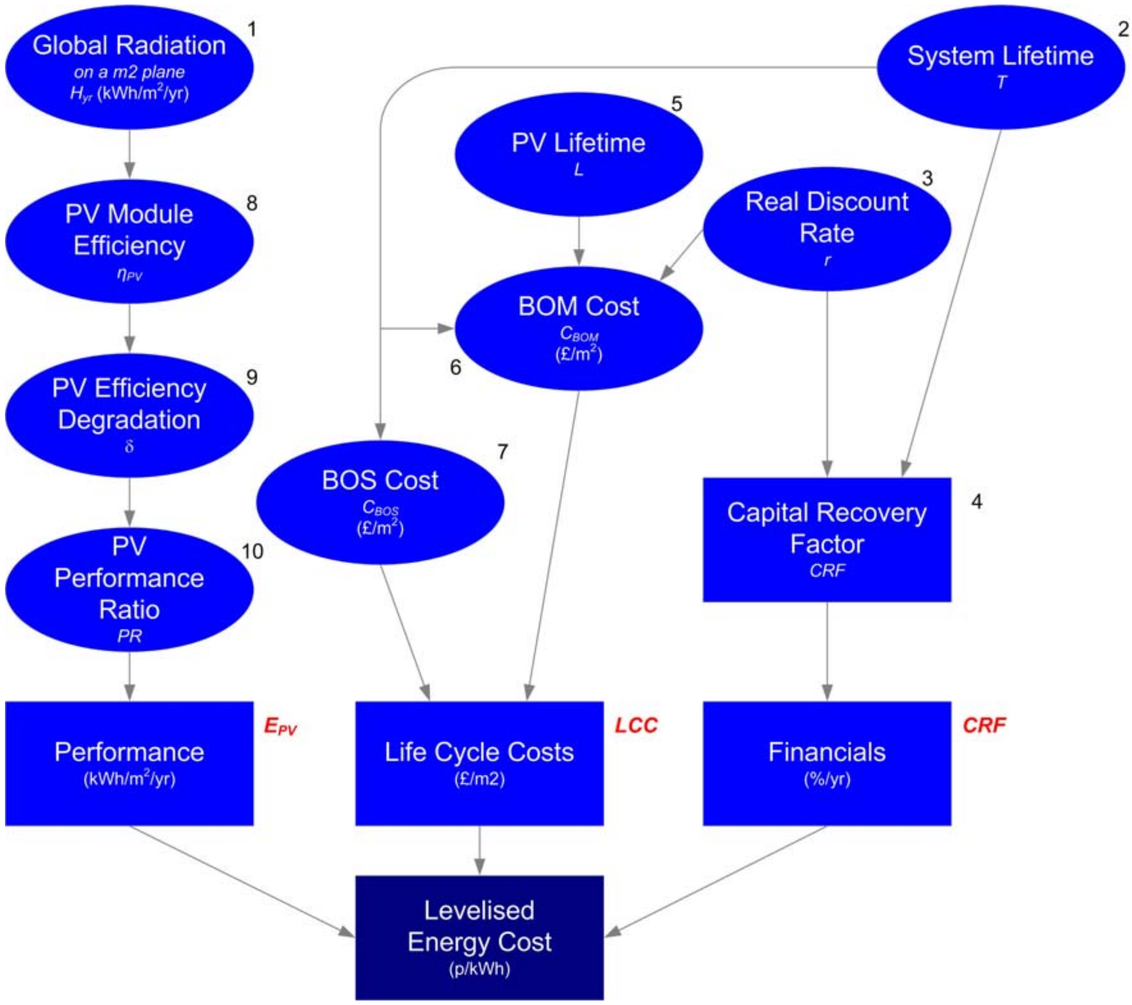
where:

CRF is calculated as in (4.9) using inputs 2 and 3:

$$CRF = \frac{r(1+r)^T}{\left[(1+r)^T - 1\right]} \tag{4.9}$$

E_{PV} is calculated in (4.10) similarly as in section 3.4.1 using inputs 5, 6 and 7 from the model:

$$E_{PV} = H_{yr} \cdot \eta_{PV} \cdot \left(1 - \tfrac{(1-\delta\ )}{2}\right) \cdot PR \cdot 1m^2 \tag{4.10}$$



Oval boxes represent scenario input data and rectangular boxes indicate steps in the calculations.

Figure 4.6: Calculation of the Levelised Energy Cost (LEC)

and, LCIC is calculated in (4.11) similarly as described in section 3.4.1 using inputs 1, 2, 3, 8 and 9 from the model:

$$LCIC = Cost_{BOM} + \sum_{t=0}^{T-1} \frac{\alpha_{PV} \cdot Cost_{BOM}^{ePV}}{\left(1+r\right)^{t}} - Cost_{BOM}^{adj} \tag{4.11}$$

where:

t is studied year

$\alpha_{PV} = 1$ if replacement of PV module is needed, otherwise $\alpha_{PV} = 0$

and,
$$Cost_{BOM}^{adj} = \left[\left(1+r\right)^{-NL} \cdot Cost_{BOM}^{ePV}\right] \times \left(1 - \tfrac{T-NL}{L}\right) \tag{4.12}$$

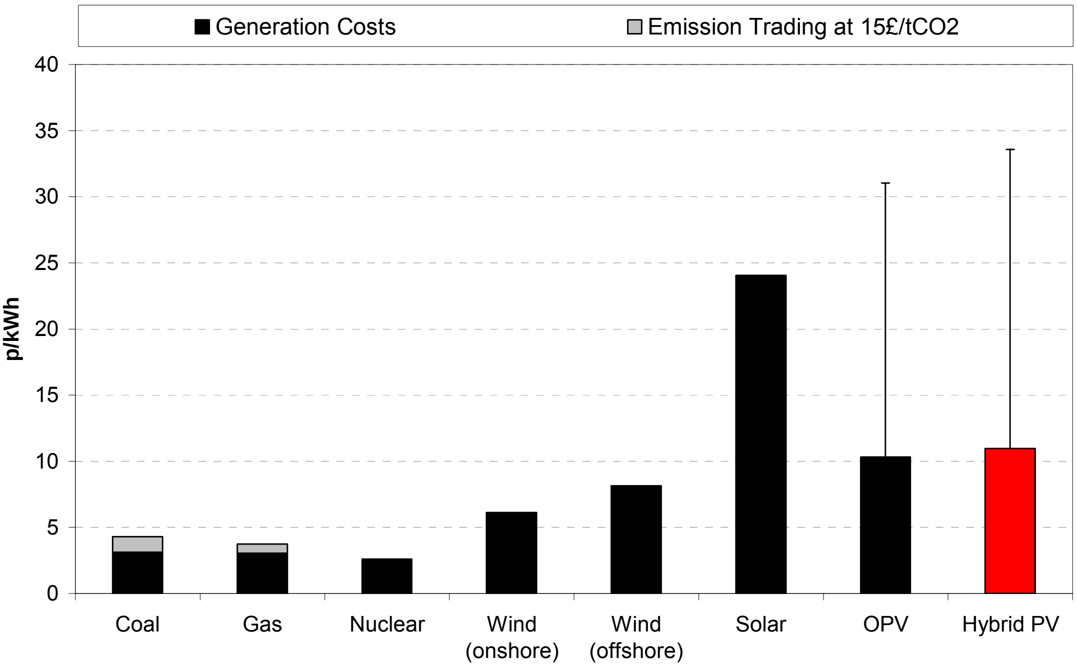
where N is the number of replacement during systems' lifetime, calculated in (4.13):

$$N = \left\lceil \frac{T}{L} \right\rceil \text{-1} \tag{4.13}$$

assuming a 7% discount rate and 30 year system lifetime.

The PV system is assumed to have a PV module degradation of 50% by the end of life, a 5% module efficiency, a performance ratio of 0.85 to estimate the total system energy output with respect to its peak power rating and a low BOS cost estimate of £30/m^2. If we consider lifetime of the PV module same as system lifetime and installed at a site having average annual radiation of 1000kWh/m^2, the LEC estimates for OPV range between 15.42p/kWh and 36.40p/kWh, while for hybrid-OPV range between 16.42p/kWh and 38.82p/kWh.

Figure 4.7 shows the LEC range for the estimated OPV and hybrid-OPV in comparison with other electricity sources. These energy costs are not favourable against current centralised power stations and wind energy. While the lower estimate exhibits a reduction in PV electricity by more than twofold, the upper estimate may be similar to current PV technology status. In addition, these emerging PV technologies may require frequent replacement throughout the system lifetime, making them highly costly if efficiency and lifetime is not increased.

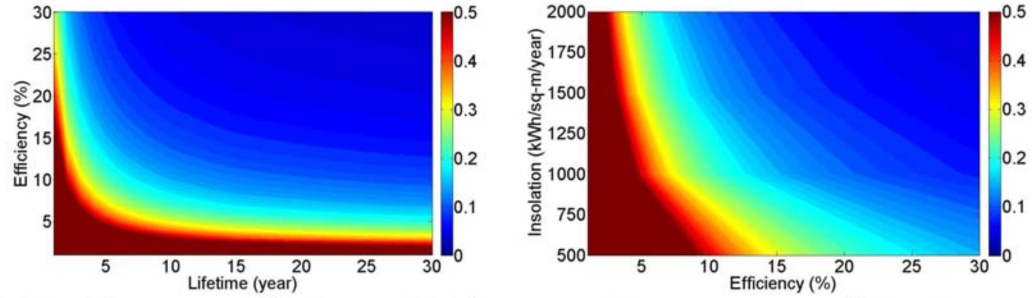


Based on 2004 report [106], for Solar [7] and the Authors' cost estimates for OPV and hybrid PV.

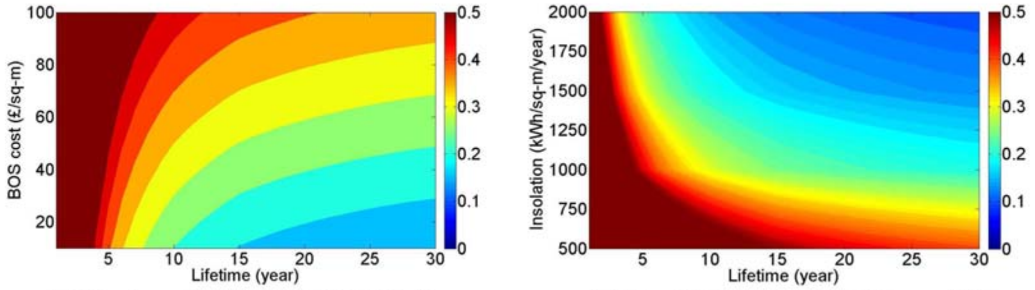
Figure 4.7: The electricity generation costs of the power plants in UK

4.2.4.1 Sensitivity on LEC results

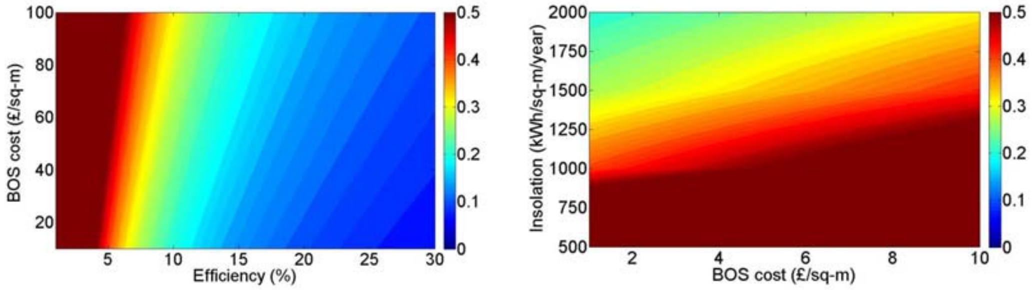
Apart from the module cost, the LEC is sensitive to the module efficiency, lifetime, irradiation and BOS cost. A BOM cost baseline of £50/m^2 is considered for the contours plotted in Figure 4.8. The impact of efficiency and lifetime on the LEC is most noticeable when lifetime is short as seen in Figure 4.8 (a). In fact, for a LEC lower than 10p/kWh, the PV module boundaries for the assumed system are around a 10% module efficiency and 5 year lifetime. As one expects in Figure 4.8 (b, d and f), higher available irradiance reaches competitive LEC even with lower performances of efficiency and lifetime, although greater than 10%, 10 year lifetime seems to reach close to the electricity cost from other electricity sources. Meanwhile, Figure 4.8 (c and e) shows the BOS cost exhibits a fixed impact and is mainly driven by PV module efficiency rather than lifetime.



(a) ***Fixed BOS cost at 30£/m^2 & H at 1000 kWh/m^2/yr*** **(b)** ***Fixed BOS cost at 30£/m^2 & L at 5 years***



(c) ***Fixed η_{PV} at 5% & H at 1000 kWh/m^2/yr*** **(d)** ***Fixed BOS cost at 30£/m^2 & η_{PV} at 5%***



(e) ***Fixed L at 5 years & H at 1000 kWh/m^2/year*** **(f)** ***Fixed η_{PV} at 5% & L at 5 years***

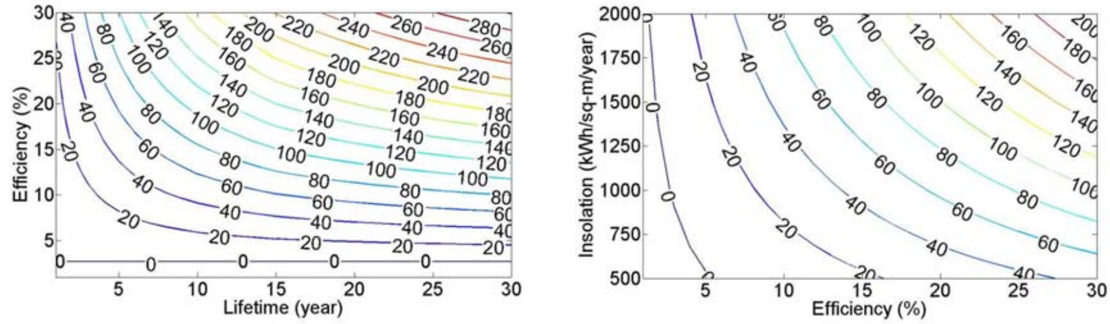
The system lifetime is assumed 30 years, 50% efficiency degradation, 7% actual discount rate.

Figure 4.8: PV levelised electricity cost £/kWh for a BOM cost at £50/m^2.

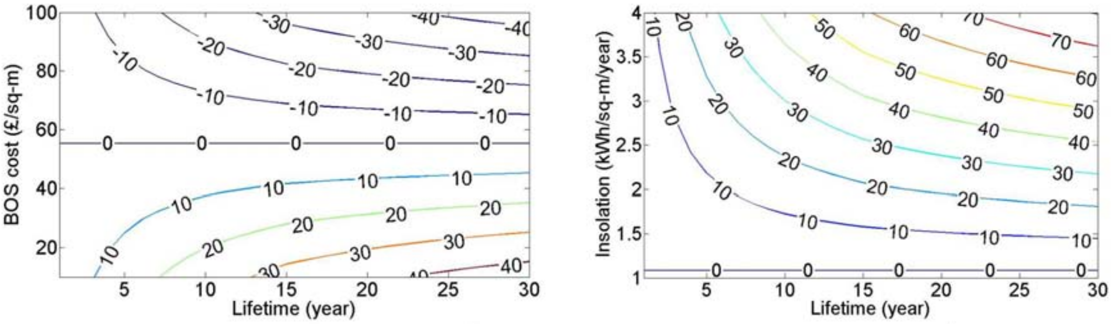
4.3 Discussion on PV LEC grid parity on BOM costs

Similar to the sensitivity on LEC, the BOM cost sensitivity establishes the boundaries for integrating emerging PV technologies by suggesting BOM cost with respect to the module efficiency, lifetime, irradiation and BOS cost. Figure 4.9 illustrates the BOM cost contours in £/m^2. The 0 contour indicates the lower boundary. The baseline for grid parity was taken at 13.97p/kWh based on the 2009 Energy Statistics [107]. The average annual domestic electricity bill was £461 based on annual consumption of 3,300kWh.

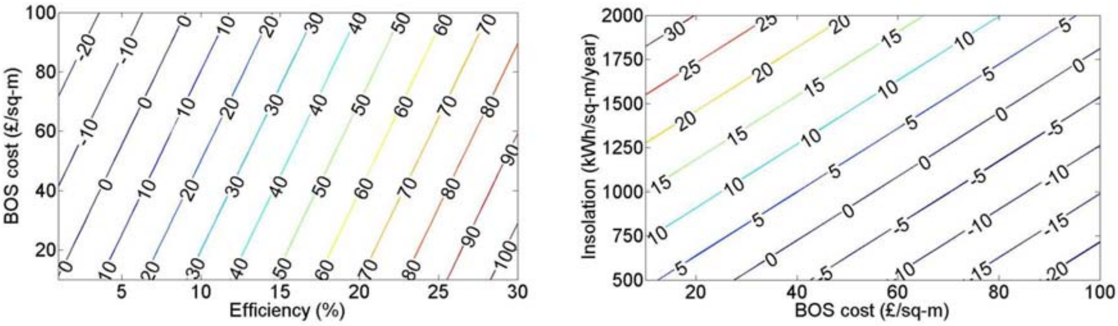
The impact of efficiency and lifetime on BOM cost is again most important. Lower efficiency, lower lifetime require low BOM cost for grid parity as seen in Figure 4.9 (a).



(a) Fixed BOS cost at 30£/m^2 & H at 1000 kWh/m^2/yr ***(b) Fixed BOS cost at 30£/m^2 & L at 5 years***



(c) Fixed η_{PV} at 5% & H at 1000 kWh/m^2/yr ***(d) Fixed BOS cost at 30£/m^2 & η_{PV} at 5%***



(e) Fixed L at 5 years & H at 1000 kWh/m^2/yr ***(f) Fixed η_{PV} at 5% & L at 5 years***

The system lifetime is assumed 30 years, 50% efficiency degradation, 7% actual discount rate.

Figure 4.9: BOM cost contours in £/m^2

On the other hand, as shown in Figure 4.9 (c), BOS cost higher than £50/m^2 cannot reach grid parity with 5% efficiency modules, while this boundary is relaxed as module efficiency is improved as seen in Figure 4.9 (e). Meanwhile, the available solar irradiance also impact BOM cost with respect to efficiency, lifetime and BOS costs; as illustrated in Figure 4.9 (b, d and f).

4.4 Future development promise discussion

Moving forward, the debate of whether or not emerging organic-based PV technologies require a same lifetime of over 20 years as current mature PV technologies is ongoing. Certainly amongst emerging organic-based PV technologies similar lifetime and performance levels may be necessary. Hence for very low-cost modules, short lifetime is deemed acceptable as seen in previous sections. In fact, this is the direction taken by some companies such as Konarka. On the other hand, investors may be less likely to support technology with low efficiency and low lifetime.

The target for OPV technology is to increase from a lifetime of 5 years in 2012 to almost three times as much in 2020, around 13 years [40, 103, 108]. This target is the reference scenario. Hence in Figure 4.10:

- The reference scenario depicts the targets of OPV and uses them as boundaries for the case which settles at around 25 years after 40 years
- The optimistic scenario follows the optimistic targets and continues to improve at a rate which settles at around 30 years in 40 years time, and
- The pessimistic scenario follows a growth rate from 1 year lifetime and settles at around 15 year lifetime in 40 years.

The overall efficiency of conversion of irradiance into electrical energy of a system could be minimum 60% of the efficiency of a laboratory cell [109]. Figure 4.11 illustrates the progress achieved in the efficiencies of c-Si and TF PV modules respectively in the past.

The progress gradient of a-Si between 1981 and 1990 was 0.33. Currently, OPV efficiencies are increasing at about 1 percent per year. The goal is to improve device efficiency to 14% for solar cells and 10% for modules by 2020 [40, 103]. As in the previous section, the goal for these devices is to increase cell efficiency and lifetime / stability levels from 5% for 2,000 hours to 10% per 10,000 hours by 2020. This means a PV module life expectancy of more than five years in 2012 and 13 year lifetime in 2020 [108].

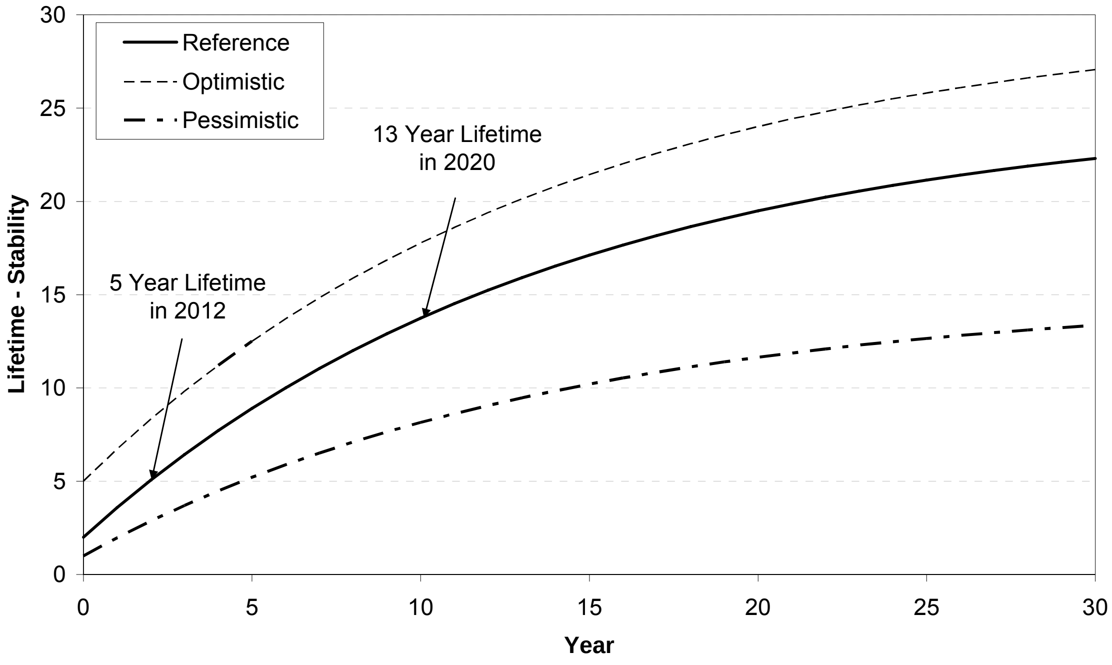


Figure 4.10: Lifetime trends scenario entails stability of emerging PV technologies

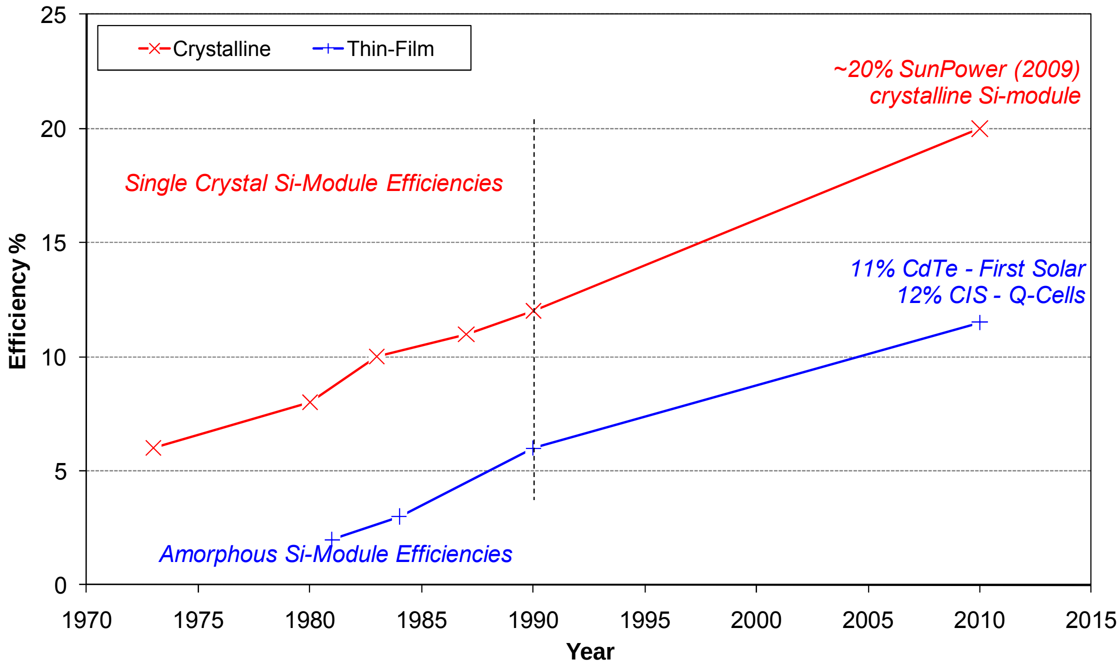


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Figure 4.11: The progress achieved in PV module efficiencies [109]

Hence in Figure 4.12:

- The reference scenario depicts the targets of OPV,

- The optimistic scenario follows the relation between lab-cells efficiency and commercial module efficiency and assumes lab-cell efficiencies to reach theoretical maximum efficiency in 40 years time, and
- The pessimistic scenario follows a linear increase from 1 percent efficiency in anticipation of a steady growth in efficiency as predecessor a-Si modules.

A model to predict the price of emerging PV technologies is based on coupling the exponential growth rate in PV production and the learning curve for PV technologies. Most forecast studies use an exponential growth which is in the form as in (4.14):

$$m = m_O\left(1+g\right)^t = m_O e^{t\ln(1+g)} \tag{4.14}$$

where m is the annual market, t the time in years and g is the annual growth rate.

Figure 4.13 shows the exponential growth rate at 25%, 30% and 40% on the actual annual production. The current best fit, minimum least square error, is at 37%.

Future market expectations are assumed to have a 25% growth in PV after 2010 [110]. Starting from 10GW in 2010, one may expect 8TW in 2040, about half the estimated 14TW of carbon free energy needed by 2050 [111].

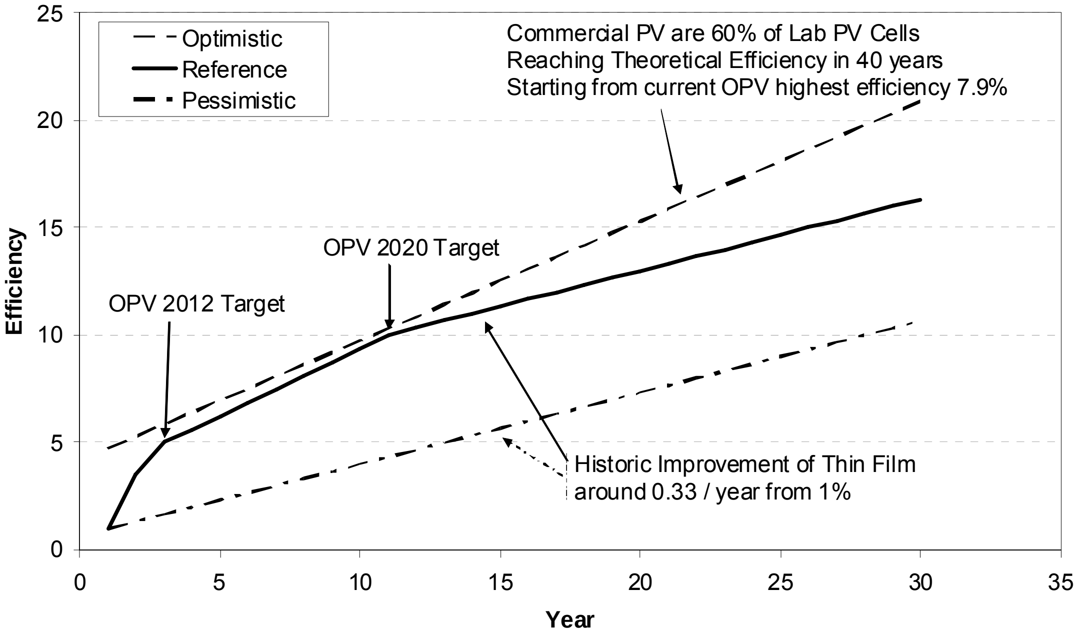
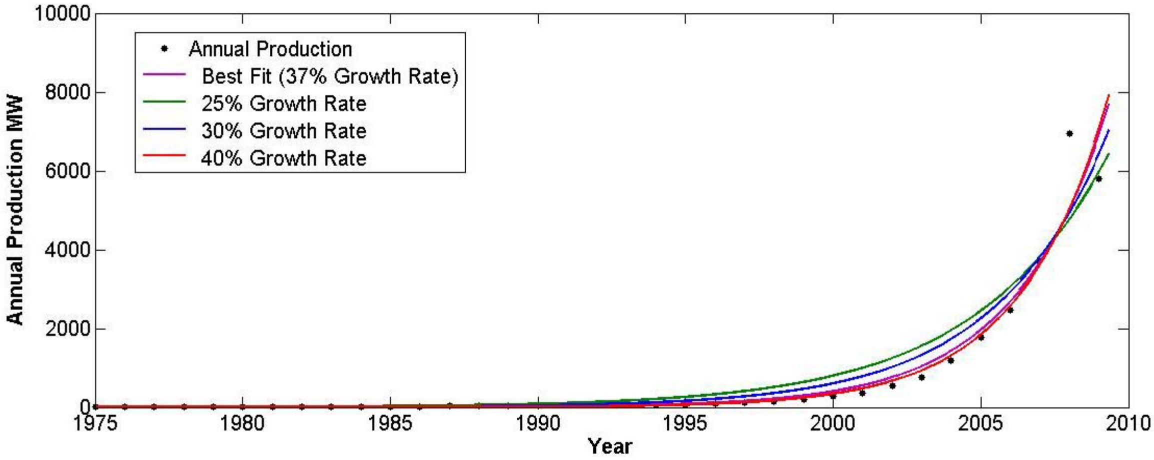


Figure 4.12: Emerging PV efficiency trends scenario entails technology progress



Up to the third quarter figure for 2009

Figure 4.13: The historic growth rate of PV production

The historic development of module prices shows an experience factor of around 20% [112]. This means a 20% price reduction for each doubling of cumulated volume of sold modules globally. This is in analogy to the learning factor derived from cost learning curves as in (4.15):

$$\left.\begin{aligned} &p = aM^{-b} \\ &pr = 2^{-b} = 1 - f \\ &b = -\frac{\ln(1-f)}{\ln(2)} \\ &a = \frac{p_O}{M_O^{-b}} \\ &\Rightarrow \frac{p}{p_O} = \left[1 + \frac{M - M_O}{M_O}\right]^{-b} \end{aligned}\right\} \tag{4.15}$$

where p is the price at a given M cumulative sale; and p_O and M_O are the price and cumulative sales (referring as the production) at the initial moment; and pr is the progress ratio and f is the learning curve (experience curve)

So far the progress ratio of 80% has been more or less constant, even though there have been an increasing favourable number in the PV support scheme contributions from a number of countries. However as the contribution of material cost relative to the total manufacturing cost will increase with economy of scale, the experience factor will most probably decrease.

The recent interest in new product ideas and additional market segments was illustrated on one possible scenario. The three main PV technology categories c-Si, TF and new concept (NC) for emerging technologies, could grow in parallel, and contribute to the overall expected market increase, with an approximate 25% growth rate, as shown in Figure 4.14 [110]. A growth rate of over 30% is depicted for both TF and NC. In fact, a recent study shows that with a growth rate greater than 30%, a TF PV system reaches the break-even point of 1$/Wp before c-Si. Also the cost gap and social investment will be lower with TF PV systems [95].

As seen in the previous section, for a scale-up approach, OPV will range between £10.98/m^2 and 93.97/m^2, while a hybrid-PV module may cost between £13.37/m^2 and 103.56/m^2.

Figure 4.15 displays the three progress ratio scenarios under consideration, assuming commercialisation emerging PV module price at baseline cost price of 50£/m^2:

- The reference scenario depicts a realistic scenario for a complete price-cost cycle for market introduction of a new product. In fact, a viable technology has four phases in this cycle as seen in Figure 4.16:
  i. Development - initial producer setting prices below cost to establish market. A typical progress ratio at this stage is 90% or more.

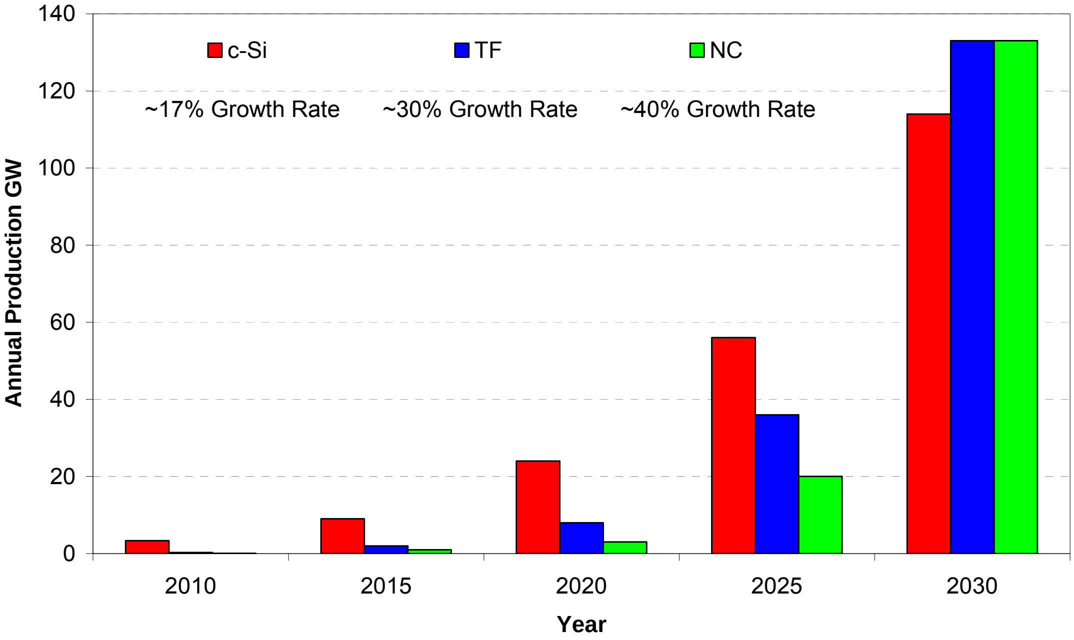


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Figure 4.14: One possible scenario of different PV technologies growth rates [110]

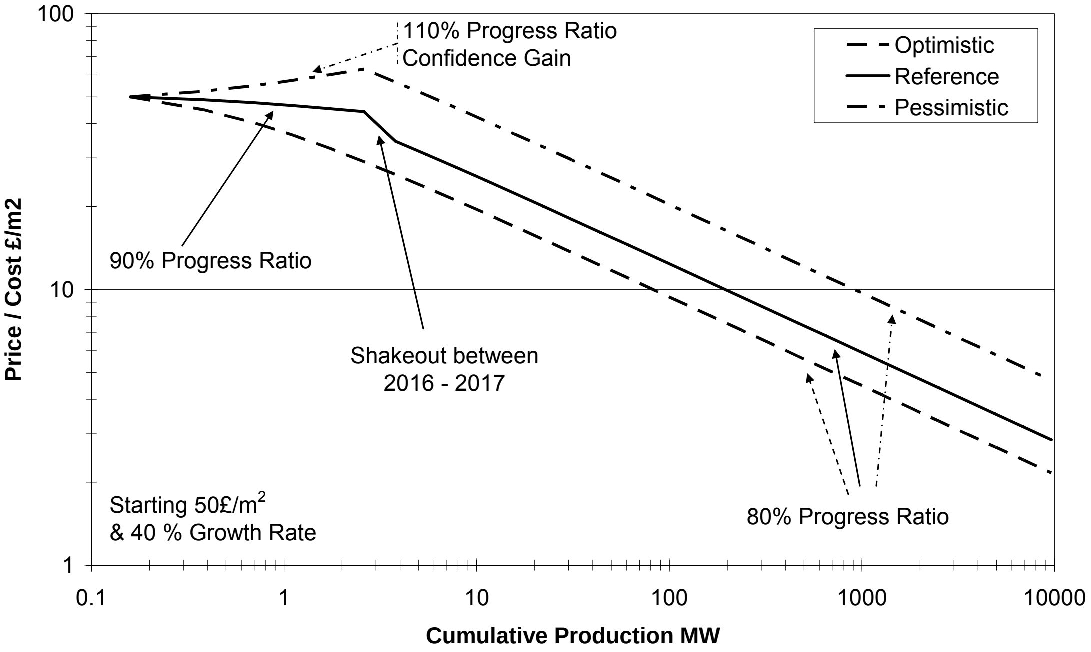


Figure 4.15: Emerging PV experience curve projections

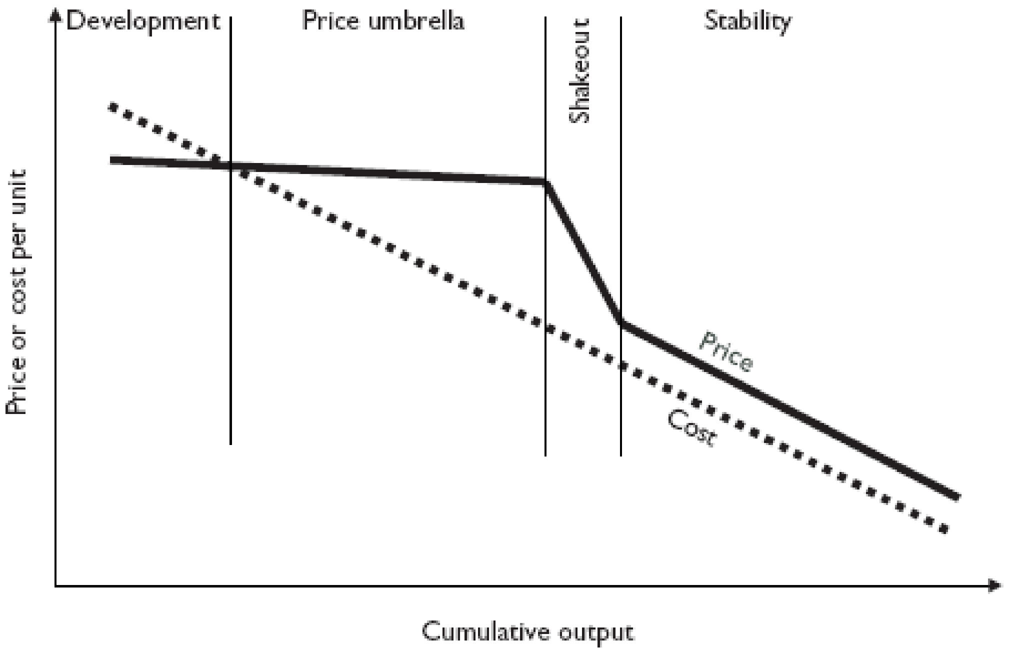


Figure 4.16: Price-cost relations for a new product [113]

ii. Price Umbrella – learning by doing, cost reduces. In this stage, more competitors may enter the market with lower costs, while the difference between price and cost becomes larger.

iii. The Shakeout - when prices fall faster than the cost. A typical progress ratio is around 60%. This may be assumed following a target, such as 5 year lifetime or market growth doubles. In the case of the reference scenario in this research, this shakeout is assumed after 5 years.

iv. Stability – is reached when the price and cost stabilise with the same progress ratio, and defines a stable market. An 80% progress ratio on cost may be assumed.

- The optimistic scenario follows the progress ratio of 80% on price of PV immediately at market entry-point. A PV module price extrapolation study shows the overall learning curve of PV technologies discontinues when the advantages of TF and NC technologies are realised, and their deployment increase heavily. Though this breakthrough is suggested to be noticed beyond 2020, TF and NC technologies can accumulate the experience learned from c-Si technology. Hence this experience will not affect the learning curve of the individual PV technologies [114]
- The pessimistic scenario follows a price increase to provide for the first market entrants with an opportunity to recover development costs, as well as efficiency improvements. This reflects the market power of the first producers of these emerging PV technologies. It also increases the customer valuation of the product due to increased technical performance such as efficiency and lifetime.

4.5 Conclusion

This chapter has estimated the costs on a scale up production for OPV compared to hybrid organic-based QD PV, depicting the two emerging PV technologies. Although cost estimates for hybrid organic-based QD PV will range a bit higher than OPV, these advanced TF technologies using QD are expected to have better performance than OPV ones as discussed in section 2.6.4. The cost estimates for these organic-based PV modules range between £10.98/m^2 and £103.56/m^2. Considering a 5% module efficiency, 98% module yield under STC, the module costs between £0.22/Wp and £2.11/Wp. Translating this for a system with over 30 years module lifetime will result between 15.42p/kWh and 38.82p/kWh under 1000kWh/m^2/yr average solar irradiance, with insignificant difference between the two types of technologies.

Although this is a preliminary cost estimate for these emerging technologies, the potential of cost reduction for PV electricity from the current status was highlighted. The most significant factor in the cost estimates is mainly the substrate costs and process. The lower end estimates consider flexible substrates and a faster process by a factor of 100 from glass modules. So far, there was no full-scale industrial example, such as the roll-to roll process. Hence, there is still need to understand this significant change in PV production that will eventually lead to competitive electricity prices with other energy sources.

On the other hand, the LEC does not only depend on the manufacturing cost but also on module performance, location and BOS costs. The module performance, efficiency and lifetime require improvement for competitive integration. The BOS costs, which are likely to reach module costs, will also require to be minimised as much as possible. These factors are also important as not to lose the competitiveness with other mature PV technologies already in the market.

Future potential developments on efficiency, lifetime and ultimately module cost have illustrated future possible trends. The current historical learning curve is mainly based on a more mature PV technology that is mainly c-Si. Though, this technology has been on the market for a number of years, a number of cost reduction factors still remain. On the other hand, TF technologies are likely to reach higher levels of cost reduction than c-Si given production capacity expansion. Hence one may anticipate steeper learning curves than the current one. Besides, emerging PV technologies may lead to even higher learning pace. The baseline of the learning curve for the emerging PV considered matches the historical one for the illustrated future anticipated learning rates. In order to achieve similar or steeper learning rates, bottlenecks in the production processes need to be properly addressed, to achieve the promising manufacturing cost reductions.

Therefore, innovation both at the material and device level can help in addressing possible future materials concerns and cost reduction in delivering TF technologies. These PV developments may have a decisive role in defining future relative cost level and market penetration for the two groups of TF technologies, mature inorganic TF and emerging organic-based TF [59].

5

Life Cycle Assessment for Hybrid Organic-Based PV Module

The environmental aspects of typical hybrid organic-based QD PV modules are explored. In this chapter, LCA studies on PV energy generation are reviewed. The standardised Life Cycle Assessment (LCA) methodology is then introduced, and discussed LCA interpretation metrics used for sustainable evaluation. The assumptions and boundaries are given followed by the results, comparison with other PV technologies. Comparable criteria for sustainability of electricity-generating systems namely net energy ratio (NER), energy pay-back time (EPB-T) and electricity carbon footprint (ECF) are found to be lower than mature PV technologies. In addition, PV module lifetime and efficiency boundaries are found for the sustainability of emerging PV technologies.

5.1 Overview of PV LCA studies

In support of sustainable source of energy, an overall evaluation of the product/system's environmental impacts and benefits is required. This environmental evaluation is assessed by the use of the well-known standardised LCA methodology. Current commercially available PV technologies have undergone these environmental evaluations. Most of the studies were performed from cradle to gate, investigating manufacture processes but excluding transportation. However, the usage phase of the PV technology within a PV system was sometimes included because environmental burdens during production are compensated during the utilisation phase, due to low environmental impacts of renewable electricity generation. However, the end-of-life management is usually neglected in preliminary studies as it normally results in negligible environmental burdens. Wambach et al. [115] indicate a reduction of the energy pay-back time (EPB-T) by half when using recyclable material for wafer-based

PV modules. Comparison between PV studies is difficult since investigations employ different methods, use various data sources, replace unknown data with similar ones and take into account different levels of irradiation, operational periods and other assumptions for future technology enhancement.

Table 5.1 summarises the results of the most cited PV LCA studies since 1976 [32, 63, 64, 102, 115-138]. Substantial silicon wafer-based (c-Si) PV LCA studies were presented in the scientific literature. In part, LCA studies were also approached on thin film (TF) PV technologies. Recent studies have also reported LCA studies on the

Table 5.1: Summary of PV LCA studies as published.

Author	REF	Year	PV Technology	Assumptions				E-PBT	GHG	LCEin*
				PR	L	BOS	η	years	gCO_2/kWh	MJ/m^2
Hunt	[116]	1976	Si					12.00		
Palz et al.	[117]	1991	mc-Si	0.65			12.0	2.10		
			a-Si				6.0	1.20		
Hyne et al.	[118]	1994	CIS		15		20-10	10-4		
Phylipsen et al.	[119]	1995	mc-Si		30-15		18-13	3.8-0.5	167-9.8	
Alsema	[120]	1996	mc-Si	0.85-0.75	30-15		16-10	2.3-0.3		
			a-Si+				14-6	2.7-0.4		
			CdTe				18-10	0.9-0.2		
			CIS					1.5-0.4		
Keoleian et al.	[121]	1997	a-Si		10	✓	5.0	7.4		1359
Kato et al.	[122]	1997	c-Si	0.81	20	✓		15.5-4	91-21	
Dones et al.	[123]	1998	mc-Si		30	✓	14.0		189	
			sc-Si				16.5		114	
Kato et al.	[124]	1998	sc-Si	0.81	20	✓	12.2	11.8-3.3	83-25	15524-4159
			mc-Si				11.6	2.4-1.5	20-13	3534-2267
			a-Si				8.0	2.1-1.1	17-9	1643-1178
Frankl et al.	[125]	1998	sc-Si	0.85	25	✓	11.2	9.00	200	
Alsema et al.	[126]	2000	mc-Si	0.75	30	✓	13.0	3.0-4.0	60	4200
			a-Si				7.0	2.5-4.0	50	1190
Greijer et al.	[127]	2001	DSSC		20		12-7		47-19	
Kato et al.	[128]	2001	CdS/CdTe				13-11	1.7-1.1	14-8.9	1802-1272
Knapp et al.	[129]	2001	sc-Si	0.80	30		11.9	4.10		6829
			CIS				8.9	2.20		2823

Table 5.1: Summary of PV LCA studies with LCIA results as published (continue)

Author	REF	Year	PV Technology	Assumptions				E-PBT	GHG	LCEin*
				PR	L	BOS	η	years	gCO_2/kWh	MJ/m^2
Meijer et al.	[130]	2003	InGaP/mc-Si				25.0	5.30		13000
			mc-Si				14.5	3.50		4928
			InGaP				15.5	6.30		9612
Jungbluth et al.	[131]	2005	c-Si		30		17-14	6.0-3.0		
Peharz et al.	[132]	2005	III-V (con.)			✓	26.0	0.67		
Wambach et al.	[115]	2005	c-Si(recycled)	0.75	20			1.60		
Alsema et al.	[133]	2006	sc-Si	0.75	30	✓	14.0	2.70	40	5240
			mc-Si				13.2	2.20	35	3800
			r-Si				11.5	1.70	30	2650
Fthenakis et al.	[134]	2006	mc-Si	0.75	30	✓	13.2	2.20	37	
			CdTe [EU]	0.75			8.0	1.00	21	
			CdTe [US]	0.80			9.0	1.10	25	
Veltkamp et al.	[63]	2006	DSSC	0.75		✓	8.0	1.4-0.6	120-20	430
Mohr et al.	[135]	2007	GaAs	0.75	30		21.2	5.00		6989
			GaInP/GaAs				25.9	4.60		7772
			mc-Si				13.5	4.20		3800
Pacca et al.	[136]	2007	a-Si	0.95		✓	6.3	3.20	34.3	869
			mc-Si				12.9	7.50	72.4	4444
Raugei et al.	[137]	2007	CdTe	0.75	20	✓	9.0	1.50	48	2031
			CIS				11.0	2.80	95	3107
			mc-Si				14.0	5.5-2.4	167-57	9720-3585
Jungbluth	[138]	2008	sc-Si	0.75	30	✓	14.0	3.30		3449
			mc-Si				13.2	2.90		2632
			r-Si				12.0	2.70		2136
			a-Si				6.5	3.00		1142
			CdTe				7.1	2.70		1031
			CIS				10.7	2.80		1986
Roes et al.	[32]	2009	OPV	0.75	25	✓	5.0	1.3-0.2		805-120
Espinosa et al.	[102]	2010	OPV	0.80	15		3-2	2.0-1.4		379
Garcia-Valverde	[64]	2010	OPV-lab	0.80	15		5/10	4 / 2		2801

con. - concentrated

* LCEin is for module only (BOS not Included)

emerging organic-based PV technologies namely dye-sensitised solar cells (DSSC) and organic-organic (OPV) technology. Some of these studies have added inventory data to this field of emerging organic-based PV technology.

So far, LCA studies on organic-based PV modules, especially hybrid organic-based QD PV, are limited because no industrial fabrication processes have lead to stable, long lifetime solar cells. This chapter is based on a preliminary LCA study developed by the author on PV systems using hybrid organic-based QD PV technology [4]. For the purpose of analysis, the chapter will further update this initial LCA study on the hybrid organic-based QD solar cell within a PV system. Sustainability criteria results, including energy payback time (EPB-T), electricity carbon footprint (ECF) and net energy ratio (NER), are compared with previous LCA studies. At the same time, initial characteristics such as minimum viable efficiency and lifetime for potential hybrid organic-based QD solar cell are suggested for a sustainable energy source within a PV system.

5.2 LCA methodology

The LCA was performed in accordance with EN ISO14040 and updates [139]. The LCA methodology is divided into 4 steps, as shown in Figure 5.1. The LCA

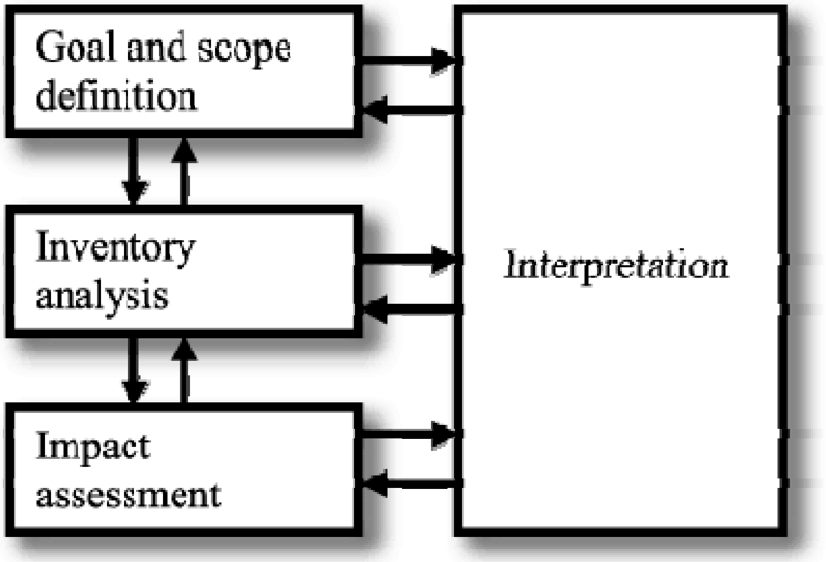


Figure 5.1: LCA framework within EN ISO 1404

methodology offers an excellent foundation for conducting other analyses such as life cycle energy analysis (LCEA) and life cycle costing analysis (LCCA), where the results can be compared and integrated in the evaluation. Please note that in the case of the previous chapter there may have been some inconsistency with assumptions and data of this chapter. This is due to the time of studies and for easy comparability with previous studies in the literature.

The software tool for LCA was the openLCA version 1 open source [140]. Two impact assessment methods were used to access the potential impacts of the environmental flows collected in the inventory stage. The equivalent Green House Gas (GHG) emissions are evaluated with IPCC 2007 data for a timeframe of 100 years, while the equivalent primary energy was calculated by the Cumulative Energy Demand (CED) LCIA method [141].

Important parameters for LCA interpretation of PV systems and other RE production technologies are the NER, the EPB-T and ECF, here referred to the sustainable metrics. Despite the PV technology, these three sustainable metrics are strongly affected by the model being used for irradiation level, orientation, energy for fabrication, system performance, lifetime and system design. NER is suggested to be the metric of choice when comparing electricity generating systems. The NER of a PV system is a function of its useful life, so this metric may assess the lifetime energy performance of an electricity generating system [121].

The system NER described by Pacca et al. [136] or the electricity production efficiency referred to by Keoleian and Lewis [121] compares the total life cycle energy inputs with outputs. Hence the calculation is the life cycle energy output (LCE_{out}) which is the energy produced from PV electricity generation, over its life cycle energy input (LCE_{in}), which stipulate the RE obtained from each energy input source, most likely to be from non-RE sources, as described in (5.1):

$$\boldsymbol{NER = \frac{LCE_{out}}{LCE_{in}}} \tag{5.1}$$

The ECF is the calculation of the total emitted GHGs during a system's life cycle divided by the electricity generated over the PV system lifetime as described in (5.2):

$$\boldsymbol{ECF = \frac{CO_2 - eq^{in}}{LCE_{out}}} \tag{5.2}$$

The EPB-T, in (5.3), determines the amount of years needed so that the system compensates for the energy during production. This sustainable metric does not distinguish the energy source, such as nuclear or fossil, or quality differences, that is electricity or heat use. Jungbluth et al. describes EPB-T as the time until environmental impacts from the production of the plant are levelled out [142].

$$EPB-T = \frac{LCE_{in}}{AEO} \tag{5.3}$$

5.2.1 Goal and scope definition

The assumptions within the utilisation phase influence the lifetime energy generation and thereby the sustainable matrices. Krebs and Spanggaard define polymer solar cell lifetime as the time it takes for the efficiency to decay to half its initial value [14]. On the other hand, most commercially available PV technologies have an 80% power guarantee from the initial manufacturer efficiency after 25 years. However, PV LCA studies have neglected efficiency degradation, and different lifetime periods were considered. Therefore for easy comparability the initial analysis is based on 10% conversion efficiency without degradation, and 30 year lifetime assumptions as shown in Table 5.2. Other conversion efficiencies and lifetimes are also discussed further in this paper.

For the purpose of this study, a 1 cm^2 glass substrate laboratory-scale was considered. The process is then scalable to a 1m^2, size for a single module. Parallel analyses of two types of hybrid organic-based QD solar cells, as described in section 2.6.2, were

Table 5.2: Comparable assumed characteristics for solar cells [32, 63, 142]

	Efficiency (%)	**cm^2/Wp**	**Lifetime /years**
Hybrid QD-based Solar Cells	***10***	***100***	***30***
OPV	5.0	200	25
DSSC	8.0	125	30
sc-Si	13.6	71	30
mc-Si	12.8	76	30
r-Si	11.7	83	30
a-Si	6.3	154	30
CdTe	8.7	141	30
CIS	10.4	93	30

performed. The results were compared with other PV LCA studies with recent datasets from ecoinvent by Jungbluth [143] on wafer-based c-Si and mature inorganic TF technologies, considering the detailed inventory for BOS components for laminated BIPV system on a slated roof. In addition, recent LCA studies on emerging organic-based PV technologies were also compared and modelled [32, 63, 64, 102].

The amount of solar radiation absorbed by a PV system establishes the annual electricity output (AEO) as described in section 2.5 and defined in equation (2.1). Hence for the system utilisation phase the following assumptions are a common basis for comparability with other PV LCA studies:

i. The average southern European yearly radiation at 1700 kWh/m^2.
ii. Performance ratio (PR) of 0.75 (25% system losses) which is due to PV system losses caused by the balance of system components (BOS) and other indirect losses. Other PR in PV LCA studies ranged from 0.65 to 0.95.

5.2.2 Inventory analysis

The main input flows of the inventory shown in Table 5.3 were based and modelled on the available datasets from ecoinvent version 2.01 [143].

CdTe is the first PV technology to reach a cost below \$1/Wp as illustrated in the previous chapter. This was mainly due to the efficient throughput that First Solar has established within the fabrication of TF CdTe modules on glass substrate. Hence considering glass substrate modules, the assembly of the solar cell module is based on TF CdTe vapour deposition fabrication processes of a laminate module in ecoinvent datasets [143]. This fabrication process energy, 58.12kWh/m^2, is the highest boundary for emerging PV technologies. It has already been demonstrated that roll-to-roll fabrication of OPV requires less fabrication process energy, about 7.48kWh [102]. Also the processing energy consumption for glass-to-glass DSSC was also considered at 12kWh [63] instead of a range between 100kWh/m^2 to 200kWh/m^2 [127]. The energy mix considered is based on the European Union for co-ordination of transmission of electricity system. This energy mix includes coal, gas, oil, nuclear, hydro, biomass and wind energy.

Recent LCA studies on OPV have included new inventory data [32, 64]. These inventories were remodelled by ecoinvent datasets, and their equivalent primary energy results were found to be similar. On the other hand, inventory data on nanoparticles

Table 5.3: Main input inventory flows for hybrid QD solar cells production

Life Cycle Inventory data	Blend Type	Variant Type	Units	Comments
Electricity				
Electricity,UCTE,grid	58.1200	58.1200	kWh/m^2	Consumption
Materials				
Glass Substrate				
solar glass, low-iron	7000.0000	7000.0000	g/m^2	x1 3mm glass
ITO on glass [88]	1.0000	1.0000	m^2	ITO-fabrication
Interlayer (40nm)				
PEDOT:PSS [88]	29.9700	-	g/m^2	40nm lab-production
ZnO Nanorods by VLS [109]				
zinc oxide, at plant		2000.0000	g/m^2	ZnO powder
carbon black, at plant		2000.0000	g/m^2	carbon powder
argon, liquid at plant		7.4556	g/m^2	for VLS chamber
oxygen, liquid at plant		0.1219	g/m^2	for VLS chamber
Active Layer (200nm)				
P3HT [88]	0.1875	0.0938	g/m^2	lab-production
QD PbS [107]	0.9625	0.4813	g/m^2	lab-production
Clorobenzene	156.2500	78.1250	g/m^2	solvent
Interlayer (60nm & 46.4% active area)				
lithium flouride, at plant	0.0735	0.0735	g/m^2	interlayer
Back Electrode (46.4% active area)				
aluminium primary at plant	0.1879	0.1879	g/m^2	back electrode
Encapsulation				
EVA copolymer, at plant	465.0000	465.0000	g/m^2	EVA encapsulant

does not exist. Hence, for QD, an inventory dataset was drawn up from a ‘greener’ lab-production synthesis approach [144]. Meanwhile, ZnO nanorods growth was assumed part of the production process and only material data is included in the input flows. The data and approach was extrapolated from an assumed vapour-liquid-solid (VLS) process for the growth of the nanostructures, due to its potential simplicity and efficiency for large scale manufacturing [145, 146]. All other module processes are assumed to be taken place in ambient conditions. Some input flows are lab-based productions as there is still no commercial data available and hence do not include transportation.

Some PV LCA studies have omitted BOS. Keoleian and Lewis argue that, if the scope of the analysis is to evaluate the total energy requirements for electricity generation and distribution, the product system would also include the additional necessary components to connect the PV module to the electricity grid and from the grid to a building's distribution [121]. Emerging organic-based PV modules are likely to be manufactured for building integrated products. Hence the BOS inventory may consist of frameless laminated modules. Structure for BIPV module based system is included, since glass substrate is considered for this study. The inventory of a typical BOS for a BIPV grid-connected slanted rooftop installation using laminated modules, inventoried in detail in ecoinvent datasets by Jungbluth [138], is taken as the basis for BOS during comparison. However, one can keep in mind that BOS components for emerging building integrated PV (BIPV) may differ, most likely decrease in content, from other module based PV systems due to better integration aspect.

End-of-life management and recycling alternatives were not included due to lack of data for similar solar cells. However, such investigations may assume that glass and metals are recycled, offering reduction of mineral resources. Inorganic substances may be disposed in landfills potentially offering energy recovery and the rest of polymers may be incinerated.

5.2.2.1 Processing of PbS Nanoparticles

PbS is a key direct band gap semiconductor material, having a small band gap (0.41 eV), large Bohr radius, high dielectric constant and very high carrier mobility which fit well for optical and photonic devices. These properties make optical response significantly better than GaAs and CdS nanoparticles [147-149]. MEG, as introduced in section 1.2.2, is exhibited by PbS nanoparticles, where the impact of a single photon generates two or more excitons [150, 151].

Several PbS nanoparticles synthesis were reported [152-155]. The lab-production synthesis of PbS nanoparticles in olive oil, illustrated in Figure 5.2 and inventoried in Table 5.4, was taken as the process for producing 0.882g in a dry state PbS QDs. Olive oil is used as a capping agent and solvent which do away with air-sensitive, toxic and expensive chemicals. This method also reports low temperature synthesis, at 60^{o}C, for PbS nanoparticles [144].

PbO was dissolved in olive oil, octadecene and oleic acid to make lead oleate at 150^{o}C under vacuum for two hours. Then temperature was brought down to 60^{o}C for reaction.

TMS solution was prepared in octadecne and olive oil without using heat at room temperature. Nitrogen gas was used to provide inert reaction conditions for TMS solution. The reaction process involved TMS injection into Pb-oleate at 60°C. The growth time may only take around 10-180 seconds. Purification of nanoparticles was carried out by dissolving the reaction in toluene and acetone before putting the solution into a centrifuge machine for 2 to 10 minutes, but for smaller nanoparticles such as QDs an hour may be required. The latter is repeated for 2 or 3 times but does not require any heating process [144].

LCI of Olive Oil production was documented in Cyprus [156]. This was remodelled with ecoinvent database only. The LCIA results were found similar at 3.6kgCO_2-eq per litre of olive oil, using openLCA and ecoinvent database for Intergovernmental Panel on Climate Change(IPCC) at 100 Global Warming Potential (GWP). Meanwhile, lead oxide LCI was taken from best available manufacturing technique documented [157].

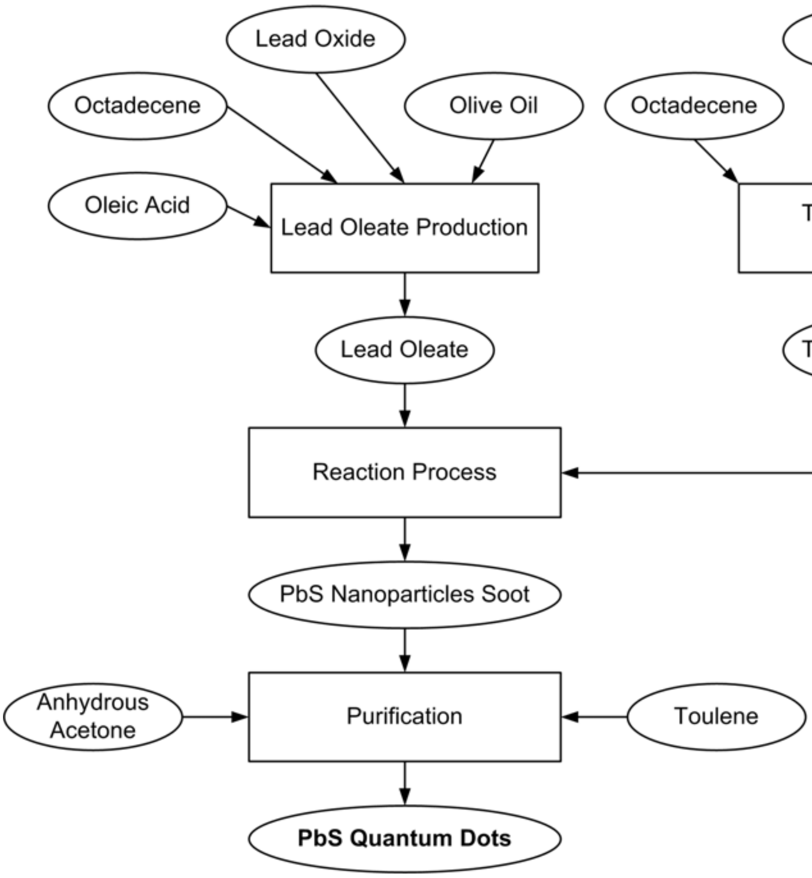


Figure 5.2: PbS QD processing route in olive oil

Table 5.4: LCI for producing 0.882g in dry state of PbS QDs

Life Cycle Inventory data	Units	Comments
lead oxide [120]	0.9000 g	
olive oil [119]	14.5000 ml	
fatty acid from vegetable oil, at plant	0.8950 g	oleic acid
n-olefins, at plant	1.1835 g	octadecene
sulfur, in ground	0.5640 g	tetramethylsilane (TMS)
acetic anhydride, at plant	1.5600 g	anhydrous acitone
toluene, liquid, at plant	13.0035 g	
Lead Oleate Production	0.2800 kWh	
TMS Solution Preperation	0.0075 kWh	
Reaction Process	0.0040 kWh	
Purification of Nanoparticles	0.1706 kWh	

5.2.3 Impact assessment

Table 5.5 summarises the LCIA results and evaluations. The calculated impact indicators for the analysed PV systems using hybrid organic-based QD solar cells are presented in Figure 5.3 along with comparable results from previous PV LCA studies. These are the updated results for typical hybrid organic-based QD solar cells, using recent datasets and other available datasets. Therefore, the results may be subject to change in the future as technology matures, and more datasets and scaled-up processes become available.

5.2.4 Interpretation

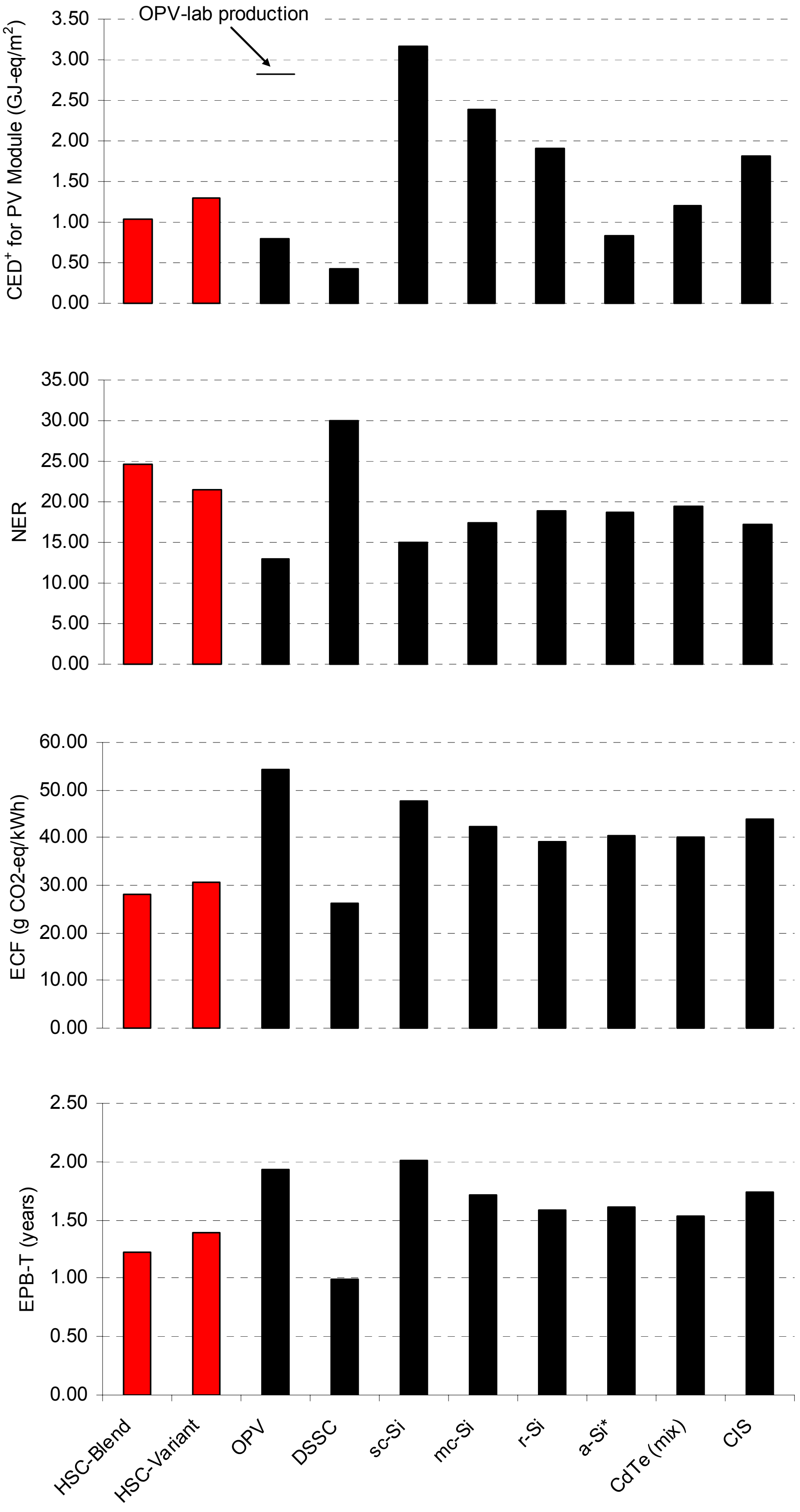
From the LCIA results and evaluations in Table 5.5 and Figure 5.3, a PV system with hybrid organic-based QD solar cells compare favourably with other PV technologies. The results can be taken as boundary for commercial production. A real commercial production, not based on lab-production extrapolations, may significantly reduce the burden of process energy. This process energy was the main contributor for non-RE sources in CED and GWP impacts. Glass substrates can also be replaced with flexible ones. This will further reduce the impact on energy and environment, while also contributing to a replace building material in case of BIPV. Meanwhile, the BOS components contribute nearly to half the energy required of a PV system using hybrid organic-based QD PV modules. Again, the impact associated with BOS can be reduced significantly by using BIPV systems. In addition, the laboratory scale sub-processes tend to be less efficient than commercial processes, even though, the already very small amounts of chemical compounds required contribute to low environmental impacts. Despite a number of alternatives discussed above to further reduce the energy and environment impacts, hybrid organic-based QD solar cells are a sustainable alternative for electricity generation within the PV technology arena. Assuming a 10% module efficiency and 30 year lifetime these PV cells may have the potential to generate at least 20 times the amount of energy received during their production. These assumptions are plausible in the long-term. However, in the short and medium term, the main uncertainties are the electrical energy used in the solar cell production process as well as the lifetime and performance of future PV systems using organic-based PV technologies. Hence further detailed LCA studies extrapolated to commercial scale production of a commercial available module are required, to minimise uncertainties.

Table 5.5: LCA results for the studied hybrid organic-based QD solar cells.

	Blend Type	Variant Type	Units	
H	1700	1700	kWh/m^2	Assumptions
PR	0.75	0.75		
η	10	10	%	
L	30	30	years	
$AEO^{\#}$	127.50	127.50	kWh/m^2	Calculations
	1517.25	1517.25	$MJ\text{-}eq/m^2$	
$LCE_{out}^{\#}$	3825.00	3825.00	kWh/m^2	
	45517.50	45517.50	$MJ\text{-}eq/m^2$	
CED^{+} for PV module	1030.01	1296.00	$MJ\text{-}eq/m^2$	Impacts
CED^{+} for BOS	820.00	817.34	$MJ\text{-}eq/m^2$	
GWP for PV module	52.80	62.80	kg $CO_2\text{-}eq/m^2$	
GWP for BOS	54.87	54.87	kg $CO_2\text{-}eq/m^2$	
NER	24.60	21.54		Evaluation
ECF	28.15	30.76	g $CO_2\text{-}eq/m^2$	
EPB-T	1.22	1.39	years	

[#] The efficiency electricity supply is assumed 11.9MJ-eq/kWhel

* Non-renewable energy sources



*a-Si on flexible substrate not glass

sc-Si, mc-Si, r-Si, a-Si, CdTe(mix) & CIS are datasets from ecoinvent v2.2

BOS was based on ecoinvent v2.2 for 3kWp slanted roof BIPV laminated modules.

Figure 5.3: Comparable LCIA results and evaluations

5.3 Boundaries for sustainability

Emerging organic-based PV technologies are likely to bring short lifetimes and low efficiencies at the initial stage of commercialisation, nevertheless, low cost PV modules. Sensitivity analysis was performed to assess the impact of variations in module efficiency and lifetime on the NER and ECF metrics. Figure 5.4 and Figure 5.5 show the sensitivity analyses in contour plots for NER and ECF metrics respectively. The dark blue shaded area shows NER values less than one. Similarly, the thresholds for efficiency and lifetime with respect to 50 CO_2-eq/kWh are indicated with dark red shaded area.

NER value greater than one signifies a sustainable product, which has potential to generate more RE during its lifetime than the energy required in producing the product. The results show that PV modules require high efficiency levels for short lifetimes to become sustainable.

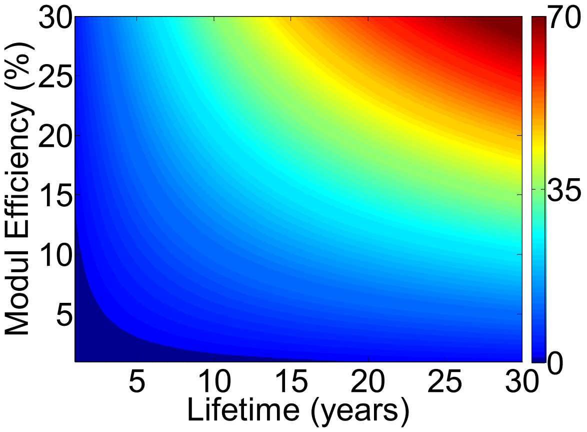


Figure 5.4: Sensitivity contours for NER evaluations

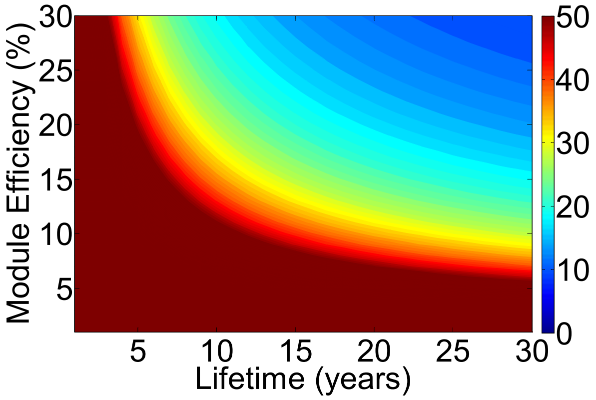


Figure 5.5: Sensitivity contours for ECF evaluations

5.4 Conclusion

This chapter updated the preliminary laboratory-based LCA, on future potentially low cost PV systems using emerging hybrid organic-based hybrid PV modules. Initial commercialisation of these PV modules is likely to come at the expense of efficiency and durability. Comparable sustainability metrics were calculated, and boundaries for efficiency and lifetime related to environmental issues are estimated and suggested. On the basis, of the data presented in this chapter, which is consistent with previous organic-based PV LCA studies [32, 64], it is shown that future potentially low-cost PV systems using hybrid organic-based QD PV modules is favourable.

The LCIA and evaluation metrics are significantly less than that of c-Si technologies. On the other hand, the LCIA and evaluation metrics for mature inorganic TF technologies are more competitive. However, preliminary indications show that a compromise between module lifetime and efficiency is required, for the PV system using hybrid organic-based QD solar cells, to be sustainable. LCA studies are important for potential low-cost PV systems, such as hybrid organic-based QD PV modules, to penetrate the PV market as another sustainable electricity technology. The focus of this chapter has been on environmental boundaries of PV systems using hybrid organic-based QD PV modules for a sustainable source of energy. However further improvements in data quality on mass production are needed for emerging organic-based PV technologies.

6

PV System Optimisation Within a Domestic Environment

This chapter sets the two system configurations namely with and without energy storage, and their mathematical models to formulate the mixed integer program (MIP). The general scenario is a PV system optimisation problem within a domestic environment which is investigated under no financial support schemes. Two case studies, with fixed and dynamic electricity tariffs, are presented to provide optimal characteristics of a PV module on a system level analysis followed by a discussion on PV module lifetime with respect to BOM costs and a sensitivity analysis of system parameters. Finally, the optimal sizing of PV system using emerging PV technologies is also investigated based on the technology and price development trends discussed in Chapter 4.

6.1 Introduction

Understanding the way PV systems integrate into the domestic household scenario is important, as emerging PV technology may lead to low-cost PV systems. Hence, in this chapter, the objective of optimising the domestic household energy value, without PV incentive schemes, has two separate aims:

i. to determine the suggested optimal efficiency of the PV module within a given available area, or
ii. to determine the optimal system sizing.

The problem may be considered as discrete optimisation, consisting of integer programming together with combinatorial optimization, due to the system configuration. Therefore in achieving these aims, the most feasible operation for a domestic household is established by a Mixed Integer Program (MIP).

6.2 Overview of grid-connected PV system optimisation

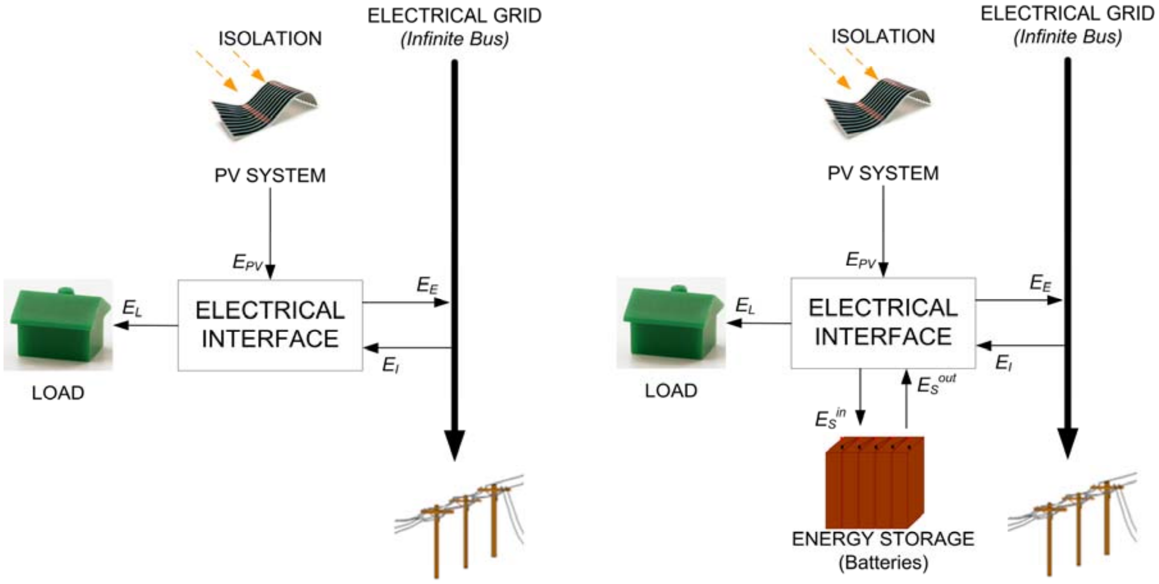
As PV system costs decline to parity with fossil fuel generated electricity, grid parity, the solar market will see tremendous growth. In this financial situation, ‘green washing’ investments through subsidies are no longer required and only the most economic feasible projects will progress. While most studies focuses on PV project as investment opportunities through favourable conditions such as feed-in tariffs (FITs) and subsidised investment, it is timely to study the optimal PV integration within a domestic environment once subsidies run out.

Previous studies on sizing a grid-connected PV system optimise the PV/inverter ratio to increase system efficiency and reduce energy losses [158], profitability and amortisation of system [159] while, on the other hand, pre-defined systems were evaluated with respect to some parameters variation [160]. In fact, studies based on simulations have evaluated PV system performance. Some performance evaluation studies have been carried out on grid-connected PV systems [161-165]. Then again a number of studies have optimised the integration of PV systems in rural, stand alone hybrid systems [166-169].

The optimal PV module integration has not yet been considered in sizing problem for the most feasible PV module efficiency and price. The use of emerging PV technologies within the domestic environment requires further investigation on the PV modules frequent replacement. The main objective is to maximise the economic benefit of the system by maximising the Net Present Value (NPV) or minimising the Annualised Life Cycle Cost (ALCC). Within a domestic environment, the system includes local load, PV and energy storage, if the latter is available. Once developed, this framework will provide a tool for optimal PV module integration characteristics at a specific PV LEC, as well as PV system sizing and economic viability under different scenarios.

6.3 The system configuration

The two system configurations are shown in Figure 6.1, namely (a) without energy storage and (b) with energy storage. The configuration components are all assumed on system level. The PV system is connected to the grid within the domestic environment consisting of the typical components such as inverters, power control units and PV modules. The load is the respective local load of the household itself. The increasing



(a) (b)

Figure 6.1: Configuration of domestic PV micro-generator system

use of PV systems may require amalgamation of demand response, grid energy storage, and spot pricing. Intermittent energy sources, such as PV, are limited to at most 20 to 30% of the electricity generated for the grid without such instruments [111]. Hence systems with energy storage may be a future configuration. The energy storage is considered an electrochemical secondary battery.

The Electrical Interface is the decision making component that decides whether to import or export energy, or even charge or discharge energy storage. Hence the local load is firstly satisfied by a PV system that generates electricity from solar irradiance. Any excess of the energy generated is either stored or exported to the grid while, on the other hand, any energy deficit from the PV system or storage is imported from the grid.

Hence due to the system configuration, the problem may be considered as discrete optimisation that consists of integer programming together with combinatorial optimisation. The most feasible operation for a domestic household is established by a MIP which optimises the time-series model.

The MIP was implemented using Fico-Xpress optimisation suite. The time-series data inputs and outputs are hourly based. Therefore, the energy flows are calculated in kWh.

6.4 Problem formulation

This section describes the mathematical formulation, objective functions and constraints for the calculation in the MIP formulation. The MIP algorithm is expressed in standard form as in (6.1):

$$\left.\begin{array}{r l} \text{minimise: } & f(x) \\ & Ax < b \\ \text{subject to: } & A_{eq} \cdot x = b_{eq} \\ & lb \leq x \leq ub \\ \text{with: } & x \text{ are the variables (continuous, binary or integer)} \\ & A, A_{eq} \text{ are matrixes} \\ & f, b, b_{eq} \text{ are vectors} \end{array}\right\} \tag{6.1}$$

where A, b, A_{eq}, b_{eq} are the inequality and equality equation constraints of x, and f is the vector of the objective function. The unknown variables in vector x are limited by lower (lb) and upper (ub) bounds, and comprise of:

- the design independent variables: the PV module efficiency (η_{PV}) or the PV module area (A), capacity of energy storage, ($S_{SOC}^{\max}$) and the grid connection rating ($E_{grid}^{\max}$).
- hourly operation dependent variables: the energy fed into the energy storage facility (E_S^{in}), the energy consumed from the energy storage facility (E_S^{out}), the grid imported energy (E_{in}) and the grid exported energy (E_{out}); and
- decision binary variables: the hourly λ_S^{in} and λ_S^{out} define charging and discharge state for energy storage while the hourly λ_e^I and λ_e^E distinguish the import and export mode with the grid.

6.4.1 Objective function

The main objective of PV integration into a domestic environment described in this section is to maximise the value of the complete system. Similar to other studies, the NPV is used for sizing problem, whereas the ALCC is used, for PV integration, to determine PV module efficiencies and costs at a certain PV LEC. These two methods are described separately in this section. Both methods value the system as a net economic benefit.

6.4.1.1 Analysis based on the Net Present Value

The NPV is the sum of discounted single and annual cash flows over the system lifetime less the initial capital investment cost. As described in section 3.2, NPV is the present worth of the system. A positive value indicates that the accumulated benefits will exceed costs over the system's economic life. A high NPV indicates a good economic financial benefit.

This method is very useful to evaluate project viability through profitability and hence compare different project scenarios. Using this method, the objective of the problem is to maximise the system NPV over the PV system lifetime. The yearly cash flow (CF) is discounted to the initial year, and the initial investment is subtracted as shown in (6.2):

$$\text{maximise: } Z_1^{NPV} = -I_0 + \sum_{y=1}^{T} \frac{CF_y}{\left(1+r\right)^y} \tag{6.2}$$

where: y is the cash flow year , d is the annual discount rate, I_0 is the initial investment in (6.3):

$$I_0 = C_y^{BOM} \cdot A + C_y^{BOS} \cdot A + C^S \cdot S_{SOC}^{\max} \qquad y = 0 \tag{6.3}$$

where *y = 0 (Year is 0)* is the base date.

CF is the cash flow calculated on the yearly total benefit (B_y^{tot}) less the yearly total costs (C_y^{tot}). For simplification, the operation and maintenance costs are neglected, since most domestic grid-connected PV systems have no moving parts, and current PV systems show that little maintenance is needed. However, it may be suggested that due to regular replacement in the case of emerging PV technologies, maintenance cost margin can be taken as part of the BOM replacement investment cost. Hence a small margin in the suggested BOM cost for emerging PV modules may be left for any system upgrades and maintenance required.

The *CF* in (6.4) considers the grid energy transfer of buy and sell, the replacement of equipment and the grid connection rating.

$$\left.\begin{aligned}
CF_y &= B_y^{tot} - C_y^{tot} \\
B_y^{tot} &= \sum_{j=1}^{N+1} \alpha_E(y,j) \begin{bmatrix} \sum_{t=1}^{8760}\left[\left(E_{LOAD}(t) - E_{in}(t,j)\right)\times\sigma_{in}\right] + \\ \sum_{t=1}^{8760}\left[E_{out}(t,j)\times\sigma_{out}\right] + \\ \left[\left(\max_{t\in 8760}\left(E_{LOAD}(t)\right) - E_{grid}^{\max}(j)\right)\times\sigma_{grid}\right] + \\ \sum_{t=1}^{8760}\left[E_{PV}(t,j)\times\sigma_{FIT}\right] \end{bmatrix} \\
C_y^{tot} &= \sum_{j=1}^{N+1}\begin{bmatrix} \alpha_{PV}(y,j)\times C_{PV}(j)\times A_{PV} + \alpha_S(y,j)\times C_S(y,j)\times S_{SOC}^{\max} \\ -\alpha_{PV}^{r}(y,j)\times C_{PV}^{adj}\times A_{PV} + \alpha_S^{r}(y,j)\times C_S^{adj}(y,j)\times S_{SOC}^{\max} \end{bmatrix}
\end{aligned}\right\} \tag{6.4}$$

where:

N is the number of replacements of PV module

$\alpha_E = 1$ if energy flows correspond to the system in j, otherwise $\alpha_E = 0$

$\alpha_{PV} = 1$ if PV modules require replacement that corresponds with the system in j, otherwise $\alpha_{PV} = 0$

$\alpha_S = 1$ if Storage System requires replacement that corresponds with the system in j, otherwise $\alpha_S = 0$, and

$$C_{PV}^{adj} = \frac{C_{PV}(N+1)}{L(N+1)}\times\left(L - \sum_{j=1}^{N} L(j)\right) \text{ and } C_S^{adj}(j) = \frac{C_S}{T}\times\left(T - L(j)\right)$$

where:

$\alpha_{PV}^{r}(y,j) = 1$, at y=T, j=N+1, and

$\alpha_S^{r}(y,j) = 1$, when $\alpha_S = 1$ and y=T, j=N+1 except at y=0.

The first term for the total revenue stands for savings in energy consumption from the grid. The second term corresponds to the revenues from grid energy exports. Finally, the third term is the benefit / loss for the fixed grid connection cost. The last term simulates the FITs scheme revenue, if available.

Since maintenance and operation costs are neglected, the terms for total costs are the cost increase in investment due to equipment replacements, PV modules and energy storage respectively. BOS costs are set to be fixed throughout the whole system lifetime. The cost adjustment for unutilised equipment before end-of-life is deducted, considering no salvage value after useful lifetime.

The NPV is a useful method to indicate the time investment is profitable and also the level of profitability. However, this system NPV cannot explicitly show the PV LEC to integrate in a competitive market. Therefore, ALCC is analysed in the next section.

6.4.1.2 Analysis based on the Annualised Life Cycle Cost

In order to maximise the benefit of the system, the Annualised Life Cycle Cost (ALCC) needs to be minimised. For 'pure' PV cost integration evaluation, no support schemes are considered. The cost is the sum of the annualised investment cost (C_I) and yearly operational costs (C_o) which the latter includes the levelised electricity cost for the PV system as in (6.5) and

$$\text{minimise: } Z_1^{YC} = C_I + C_O \qquad (6.5)$$

where annualised investment cost for energy storage is given in (6.6):

$$C_I = \left(\sum_{t=0}^{T-1} \frac{\alpha_S \cdot C_S \cdot S_{SOC}^{\max}}{(1+d)^t} \right) \cdot CRF \tag{6.6}$$

and similarly C_o is given in (6.7)

$$\left. \begin{aligned} C_O &= C - B \\ B &= \sum_{t=1}^{8760} \left[E_E(t,j) \cdot \sigma_E \right] \\ C &= \left[\sum_{t=1}^{8760} \left[E_I(t) \cdot \sigma_I \right] + E_{grid}^{\max} \cdot \sigma_{grid} \right] + \sum_{t=1}^{8760} \left[E_{PV}(t) \cdot \sigma_{PV} \right] \end{aligned} \right\} \tag{6.7}$$

The benefit term (B) is the revenue from exports. The FIT term is not included as it is not required for this analysis as stated earlier. Meanwhile, the first two terms of the cost equation (C) correspond to grid running costs: fixed cost for grid connection and variable costs for energy imported. The grid cost / benefit is interchanged from the ALCC to the NPV as cost and benefit respectively. At the end, results from these two analyses can verify the working model on same assumptions. On the other hand, the last term is the cost of PV system based on the LEC.

6.4.2 Models' details and constraints

6.4.2.1 PV system model

The PV energy production is calculated on a system level. As in section 2.5, the electric power generated by the PV system is related with solar radiation. Using solar irradiance received each hour on every square meter of the PV array surface, H; the PV array efficiency, η_{PV}; the efficiency degradation limit, δ_{PV}; the total PV surface area, A; and system performance, PR; the total electric energy generated by the PV system E_{PV} is obtained from (6.8):

$$E_{PV}(t) = H(t) \times \eta_{PV} \times \left(1 - \tfrac{(1-\delta_{PV})}{2}\right) \times A \times PR \tag{6.8}$$

where t is the hourly time sample.

6.4.2.2 *Energy storage facility model*

PV systems with energy storage facilities have always been a question of cost versus supply reliability. Energy storage in future PV systems may not only be required to even out irregularities in the electricity production and load demand but, in addition, storage facilities may provide the option of using the energy when it is the most cost effective such as in spot pricing, or smart grids interface. On top, energy storage may reduce the power rating of the electrical interface from DC to AC, hence its cost. However, additional energy storage investment may increase the complexity and overall cost of the system. Today, battery technologies commonly used in PV systems are lead-acid and nickel cadmium. These technologies are still at the very high end price, around \$1 per kWh of energy storage, to become attractive to PV grid-connected systems. To simplify the calculations, these extra cost/saving efforts are not considered in the analysis and similar system costs are considered as those without energy storage facilities. Despite current energy storage technology costs are significantly high, some investigated scenarios may postulate the importance of small energy storage requirements.

An energy storage technology facility has efficiency in relation to the energy stored and energy re-delivered. The assumption of 90% efficiency in energy stored or delivered is taken with a total overall efficiency for energy storage of 81%. The model also assumes that the depth of discharge is not more than 20% of the maximum energy storage. Electrochemical secondary storage battery dissipation losses are negligible, around 3% per month. Lead Antimony batteries have a higher self discharge rate of 2% to 10% per week compared with the 1% to 5% per month for Lead Calcium batteries. A 1% per month self discharge (99.9986% for every hour) is considered. This is a decision factor for energy storage. The rate of energy discharged or charged per hour is also restricted to 50% of the maximum energy storage.

Therefore, the relationship between the energy storage level S_{SOC}, the electrical energy charge E_S^{in} and the electrical energy discharge E_S^{out} is expressed in (6.9). The charging and discharging choices and efficiencies are later resolved in the energy flow management in the next section 6.4.2.3.

$$\left.\begin{array}{c} S_{SOC}(t+1) = S_{SOC}(t)\cdot 0.999986 + E_S^{in}(t) - E_S^{out}(t) \\ 0.2\cdot S_{SOC}^{\max} \le S_{SOC}(t+1) \le S_{SOC}^{\max} \\ E_S^{in}(t) \le 0.5\cdot S_{SOC}^{\max} \\ E_S^{out}(t) \le 0.5\cdot S_{SOC}^{\max} \\ S_{SOC}^{\max} = 0, \text{ if system is without energy storage} \end{array}\right\} \tag{6.9}$$

where the energy flows E and $S_{SOC}^{\max}$ are determined corresponding to the system design at each replacement stage.

6.4.2.3 *The energy flow management*

The energy generated by the PV system may be greater, smaller or equal to the energy required by the load. The excess energy from PV was either exported to the grid or stored for a later beneficial use, if energy storage facilities are available within the system. The optimal energy balance has to be achieved for every hourly time sample. Therefore, the electrical interface in Figure 6.1 is modelled on the energy balance, described in (6.10).

$$\left.\begin{array}{c} E_{PV}(t) - \dfrac{\lambda_S^{in}(t)\kappa(t)}{\eta_S^{in}} + \eta_S^{out}\cdot\lambda_S^{out}(t)\kappa(t) = E_L(t) - \lambda_e^I(t)\kappa(t) + \lambda_e^E(t)\kappa(t) \\ \lambda_S^{in}(t),\ \lambda_S^{out}(t),\ \lambda_e^I(t),\ \lambda_e^E(t) \ge 0 \\ \lambda_S^{in}(t),\ \lambda_S^{out}(t),\ \lambda_e^I(t),\ \lambda_e^E(t) \in \{0,1\} \\ \lambda_S^{in}(t) \ne \lambda_S^{out}(t),\ \lambda_e^I(t) \ne \lambda_e^E(t) \\ \lambda_S^{in}(t)\kappa(t) = E_S^{in}(t) \\ \lambda_S^{out}(t)\kappa(t) = E_S^{out}(t) \\ \lambda_e^I(t)\kappa(t) = E_I(t) \\ \lambda_e^E(t)\kappa(t) = E_E(t) \end{array}\right\} \tag{6.10}$$

where η_S^{in} and η_S^{out} are the efficiencies (90%) when charging and discharging respectively and energy flows E and E_{PV} are determined corresponding to the system design at each replacement stage.

The combinatorial electrical interface model consists of two decisions: first decision is defined by $\lambda_e^I(t)$ and $\lambda_e^E(t)$ as energy deficit from PV system or storage, or excess energy respectively. The other second decision is defined by $\lambda_S^{in}(t)$ and $\lambda_S^{out}(t)$ as charging or discharging to / from energy storage. Since both decisions have two processes independently and cannot be carried out simultaneously, the optimal procedure for assessing energy flow operation was defined using the λ-form separable programming [170], as defined in detail in (6.10) with respect to the energy balance. This λ is a real valued decision variable that forms a Special Ordered Set (SOS) first introduced by Beale et al [171, 172]. The stipulation of SOS1 is that at most one variable λ can be non-zero at an integer feasible solution.

6.4.2.4 Electricity grid model

As the system is a grid-connected system, the grid energy transfer is limited to the grid connection rating $E_{grid}^{\max}$ as in (6.11). In the previous section, the selectivity between import and export was explained. The exports are only the surplus from the PV generation.

$$\left.\begin{aligned} 0 \le \boldsymbol{E}_{in}(\boldsymbol{t}) \le \boldsymbol{E}_{grid}^{\max} \\ 0 \le \boldsymbol{E}_{out}(\boldsymbol{t}) \le \boldsymbol{E}_{grid}^{\max} \\ 0 \le \boldsymbol{E}_{out}(\boldsymbol{t}) \le \boldsymbol{E}_{PV}(\boldsymbol{t}) \end{aligned}\right\} \tag{6.11}$$

6.4.2.5 PV contribution evaluation

The PV performance can be defined by the term Solar Fraction (SF), the fraction of load met directly by a PV system, given in (6.12):

$$SF_{PV} = 1 - \sum_{t=1}^{8760} \frac{E_{in}(t)}{E_{LOAD}(t)} \tag{6.12}$$

where $\sum_{t=1}^{8760} E_{in}(t) / E_{LOAD}(t)$ is also known as the 'loss of load probability', 'deficit of energy' or 'loss of power probability'. The SF is also known as 'autonomy' or 'load coverage rate'. These terms are usually used for stand-alone systems. However, such term also quantifies the reliability in grid-connected PV systems in respect to a thorough techno-economic analysis. A negative factor implies imported energy is stored for later use, while a positive factor implies the fraction that the system contributes directly to the local load.

6.5 Numerical studies

Numerical studies were performed for the validity and effectiveness of the two objective functions evaluation presented in this chapter, and to evaluate the domestic environment that is willing to adopt a PV system. For these studies, the problem is solved using Fico-Xpress solver interfaced with Matlab. Firstly the ALLC for a pre-determined PV LEC is evaluated followed by the NPV evaluation of several scenarios.

6.5.1 Input data

The two time-series input data is solar radiation and load profile. For the numerical studies, the yearly solar radiation assumed as a typical meteorological year was obtained from SoDa while the yearly load profile was taken from UK Energy Research Centre (UKERC).

The HelioClim-3 is a database of solar radiation from minute to month of Europe and Africa. The database HelioClim-3 irradiance values are calculated from the Meteosat satellites images. The data taken in this case is the available 2005 sample data. The data is based on flat surfaces. Data for south faced tilts and south faced facades were adjusted accordingly, refer to Appendix A. For easy comparability in the numerical studies, the calculated Manchester irradiance at optimal tilt angle is considered.

There is a lack of monitoring data for domestic energy consumption. Hence the yearly electrical energy demand data was based on the average data of the monitoring work for 94 low-energy homes in Milton Keynes Energy Park between 1989 and 1991, in which their design corresponds with Government's Standard Assessment Procedure for Energy Rating of Dwellings (SAP) values, having 75 to 90 rating [173]. These load profiles were filtered, sorted and averaged in hourly time steps under four different categories described in APPENDIX A. A typical total annual energy usage of a UK dwelling is around 15708.4 kWh-eq [174], while electricity annual average consumption is 3,300kWh. For easy comparability in the numerical studies, the load data for a four bedroom dwelling using electricity and gas energy sources is considered. Only mitigation of the electricity energy sources is assessed throughout the numerical studies.

6.5.2 Assumptions

Table 6.1 lists the assumed parameters under one case study. A 4 bedroom tarraced house is considered. The PV area is tilted at the optimal south facing angle for latitude at Manchester, UK. Fixed electricity tariff at 13.97p/kWh average UK 2009 domestic electricity cost for imports and 3p/kWh for export were considered. In addition, the model was also modelled with dynamic tariffs from 2009 data, to show the impact of PV systems within an opened electricity market to private domestic users, refer to APPENDIX A for electricity tariffs.

6.5.3 Results

The optimisation results, for the ALLC as defined in (6.5), of the grid-connected PV system in this domestic environment include the PV module efficiency η_{PV} and the capacity of energy storage, $S_{SOC}^{\max}$ and the maximum grid connection $E_{grid}^{\max}$. Meanwhile, the optimisation results, for the NPV as defined in (6.2), include the PV module area A_{PV} the capacity of energy storage, $S_{SOC}^{\max}$ and the maximum grid connection $E_{grid}^{\max}$.

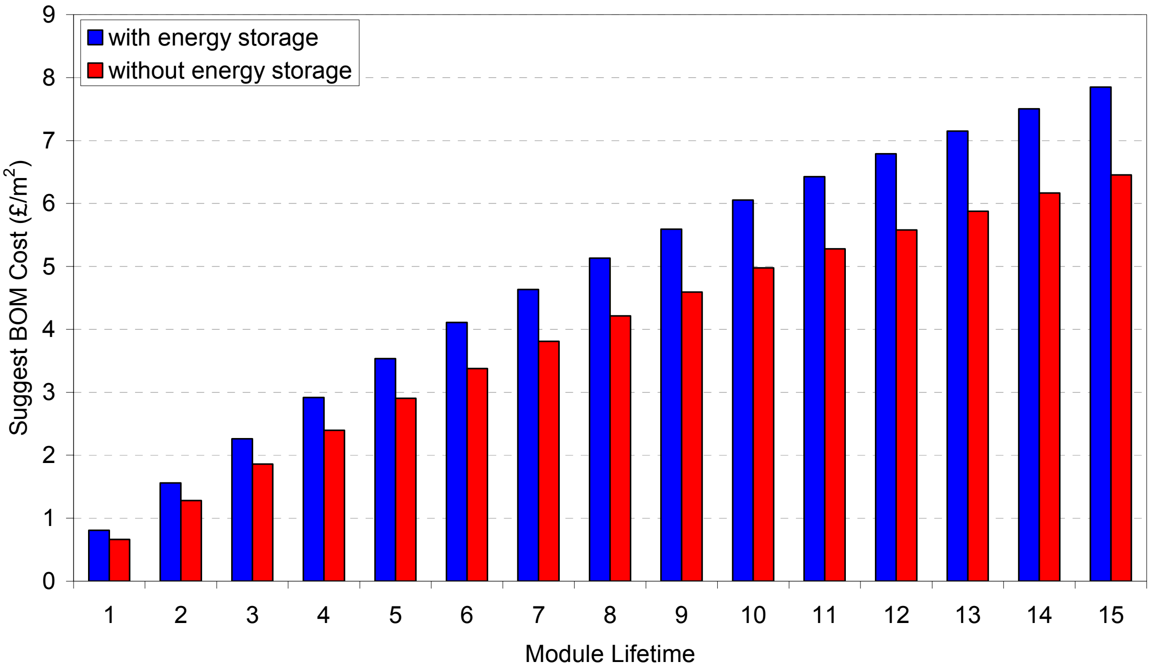
Table 6.1: Assumed parameters for PV systems optimisation studies

	Item	Abbrev.	Value	Units
PV System	Lifetime	T	30	years
	Performance Ratio	PR	0.85	
	Available Area	A_{PV}	25	m^2
	PV Module Degradation	$_{PV}$	50	%
Energy Storage System	Storage Charge	η_S^{in}	90	%
	Storage Discharge	η_S^{out}	90	%
	Maximum Charging	$\max E_S^{in}$	$0.5 S_{soc}^{max}$	kWh
	Minimum Discharging	$\max E_S^{out}$	$0.5 S_{soc}^{max}$	kWh
	Minimum SOC	S_{soc}^{min}	$0.2 S_{soc}^{max}$	kWh
	Self-Discharge		1	%-month
	Investment Costs	C_S	150	£/kWh
	Lifetime	L_S	10	years
Financial Parameters	Actual Discount Rate	t_n	7	%
Capital Unit Costs	Balance of System	C_{BOS}	30	£/m^2
Rates of Electrcity	Imported Electricity	$_I$	*13.97 / Dynamic (2009)*	p/kWh
	Exported Electrcity	$_E$	*3.00 / Dynamic (2009)*	p/kWh
	PV Levelised Electrcity Cost	$_{PV}$	*10 / 4*	p/kWh
	Grid Connection Cost	$_{grid}$	*25*	£/kW-year

6.5.3.1 *Fixed tariff system*

Integrating a PV system at 10p/kWh under fixed tariffs, the cost objective for grid-connected PV system with storage result is £581.73/year. This saves only 19.8p/year when compared to a grid-connected PV system without storage and £22.55/year better off than without any system. The optimal PV module efficiency, for this 25m^2 PV system, is 4.12% with energy storage and 3.93% without energy storage. Hence, the suggested BOM costs, with respect to a fixed lifetime of the PV modules throughout 30 years system lifetime, are shown in Figure 6.2. For systems with energy storage, equal increases in capital cost, every 10 years, are considered. This suggests that low BOM costs, less than £10/m^2, are required for optimal integration of PV modules at 10p/kWh. The results were confirmed with the NPV objective formulation which resulted in a NPV of £279.802 and £277.34 for systems with and without energy storage respectively.

Figure 6.3 shows a sample day profile of the optimised energy flows. Jointly with energy storage, PV generation and the local load consumption, the optimal energy flow management ensures the optimal operation for minimum costs. Since PV energy and storage may be cheaper than grid imports, energy is stored during peak sun-hours for later

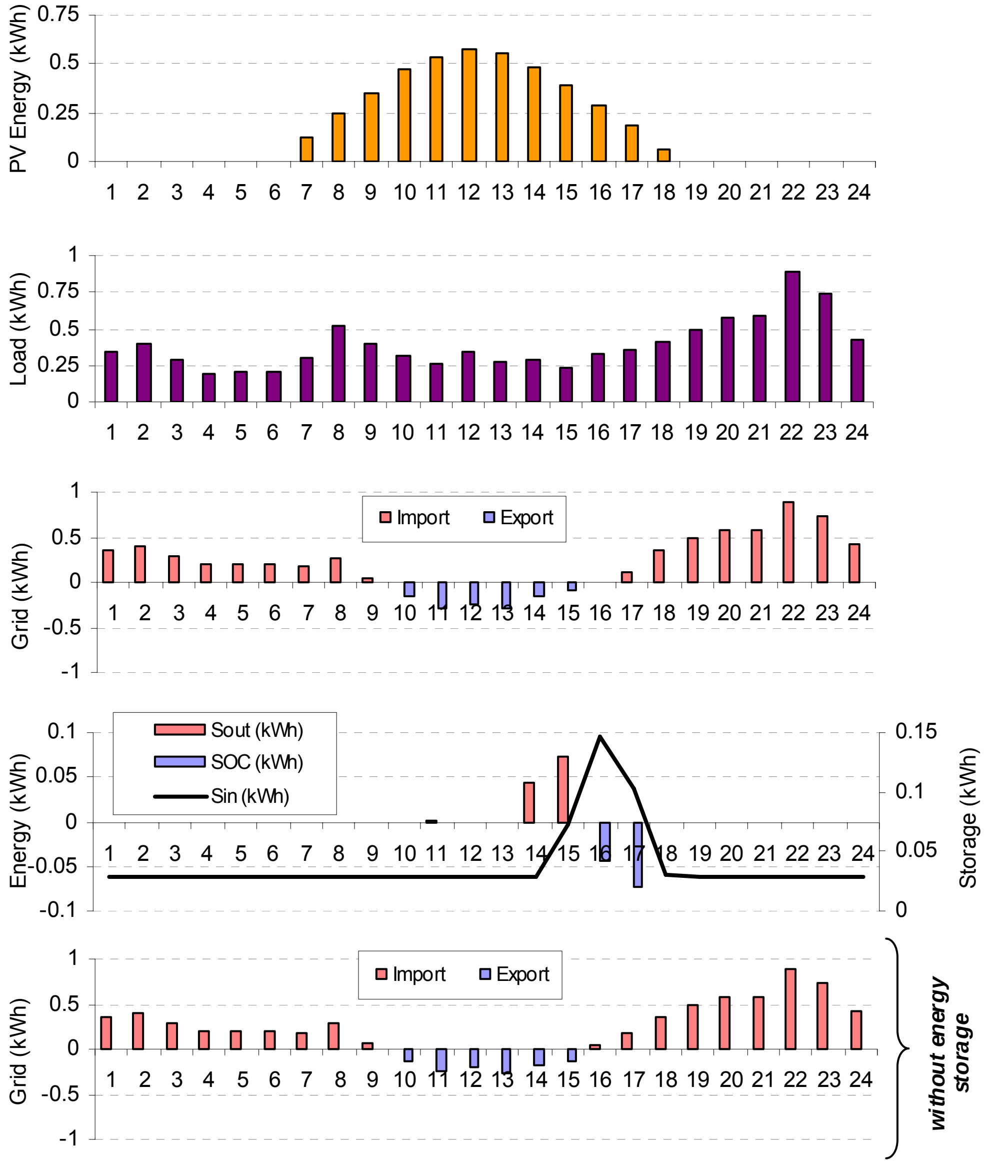


Systems with and without energy storage at 4.12% and 3.93% PV module efficiency respectively, at regular replacement periods / lifetime.

Figure 6.2: Suggested BOM cost boundary under fixed tariff system

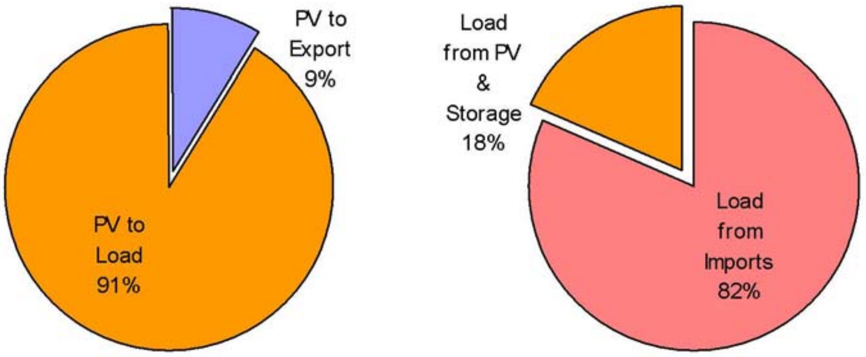
local load demand, and load is supplied by grid power if PV energy is not available. The excess PV energy can be stored and exported depending on the most economic state. Therefore, in this way, the domestic household can save both from the grid connection cost, by flattening the household load profile, as well as the energy consumption costs. In this case, the grid-connection rating is limited to 1.48kW from 1.55kW with an optimal energy storage size of 0.15kWh. On the other hand, the systems without energy storage may not necessary reduce the grid-connection rating, while it may increase it due to excessive exports. In this case, grid-connection rating holds at 1.55kW.

As shown in Figure 6.4, for a system with energy storage facilities 91% of the PV

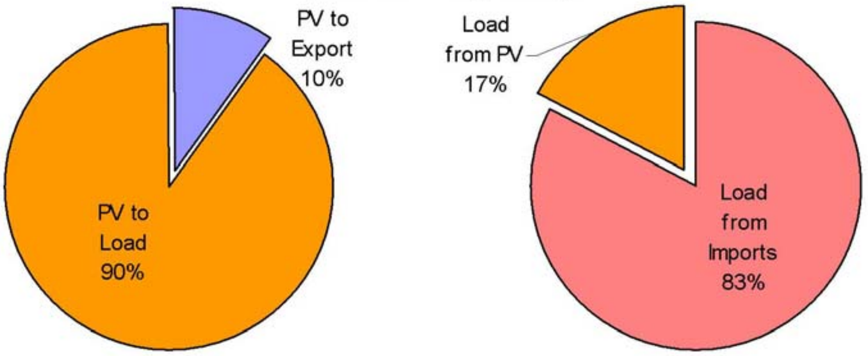


Sample day profile (21st May)

Figure 6.3: Day sample of optimised energy flows under fixed tariff system



System with Energy Storage



System without Energy Storage

PV energy (left) and Load supply (right)

Figure 6.4: Optimal energy share under fixed tariff system

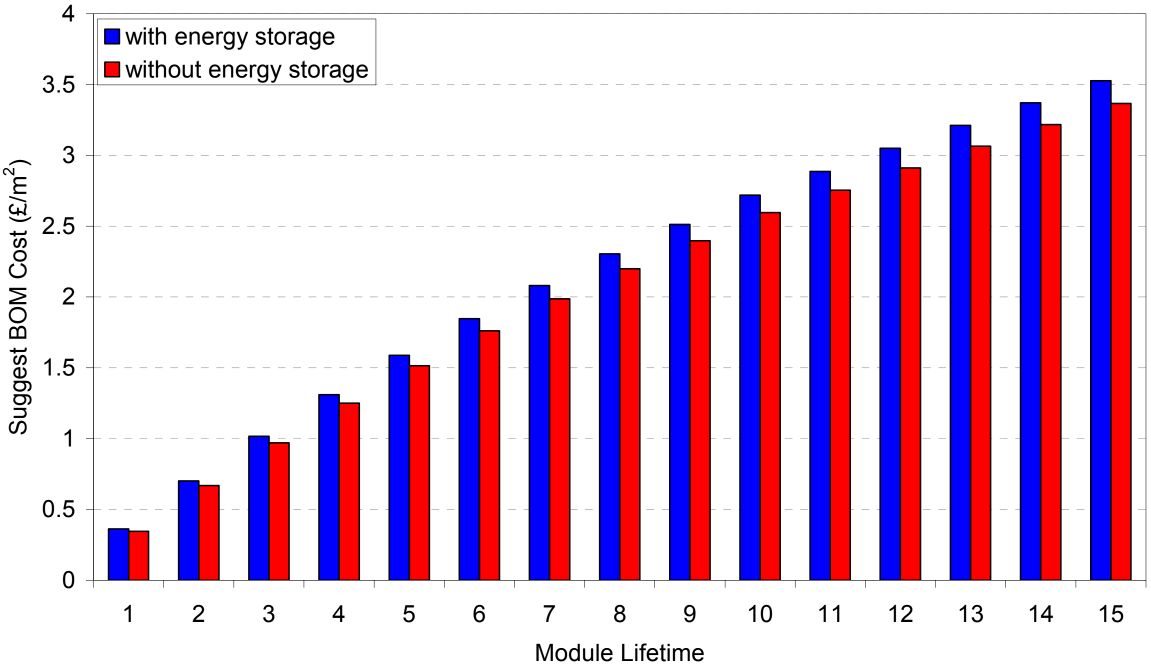
energy is consumed by the local load while 9% is excess exported energy to the grid. On the other hand, only 18% of the local load is supplied by the PV and Storage, and the remaining 82% is imported from the electricity grid. For the grid connected system without energy storage, the difference is marginal, 90% of the PV energy is consumed by the local load while 83% is imported from the electricity grid. Although storage may help reduce dependency on the grid by lower grid imports and exports, and increase the local energy sources contribution to the local load, energy storage investment costs requires a significant reduction for an increase in PV applications.

6.5.3.2 Dynamic tariff system

Integrating a PV system at 4p/kWh under dynamic tariffs, to participate in the electricity market, the objective for grid-connected PV system with and without storage result is £194.922/year costs. This is £3.287/year better off than without any system. The system does not suggest storage. Only with low PV LEC, 80% less at 3.2p/kWh, storage makes a better contribution for the ALLC. The optimal PV module efficiency for this 25m^2 system is 10.94%, having an NPV value of £32.10.

The suggested BOM costs, with respect to a fixed lifetime of the PV modules throughout 30 years system lifetime, are shown in Figure 6.5 at PV LEC of 3.2p/kWh. For systems with energy storage, an equal increase in capital cost, every 10 years, is also considered. This suggests that low BOM costs, less than £4/m^2, are required for optimal integration of PV modules at 3.2p/kWh, to participate in the electricity market. The results were confirmed with the NPV objective formulation which resulted in a NPV of £248.31 and £248.266 for systems with and without energy storage respectively.

Figure 6.6 shows a sample day profile of the optimised energy flows at an LEC PV integration of 3.2p/kWh, to participate in the electricity market. In compliment with energy storage, PV generation and the local load consumption, the optimal energy flow management ensures the optimal operation for minimum costs. Hence, when grid energy is cheap, energy might be stored for later use during peak-hours. Therefore, the local load is supplied by grid power, if PV energy is not available. The excess PV energy can be stored and exported depending on the most economic state. Therefore, in this way, the domestic household can save both from the grid connection cost, by flattening the household load profile, as well as the energy consumption costs.

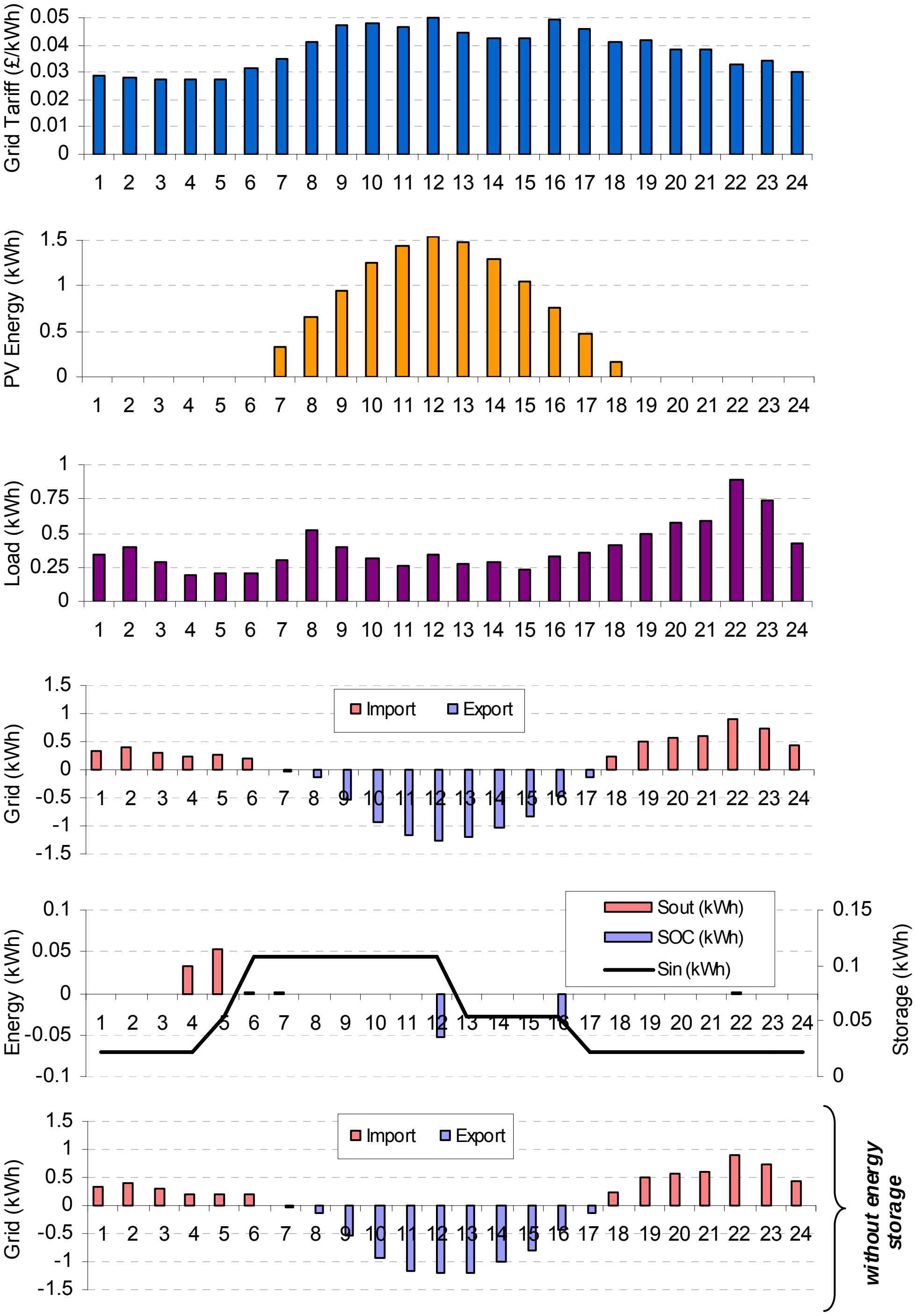


Systems with and without energy storage at 11.01% and 10.94% PV module efficiency respectively, at regular replacement periods / lifetime, participating in the electricity market

Figure 6.5: Suggested BOM cost boundary under dynamic tariff system

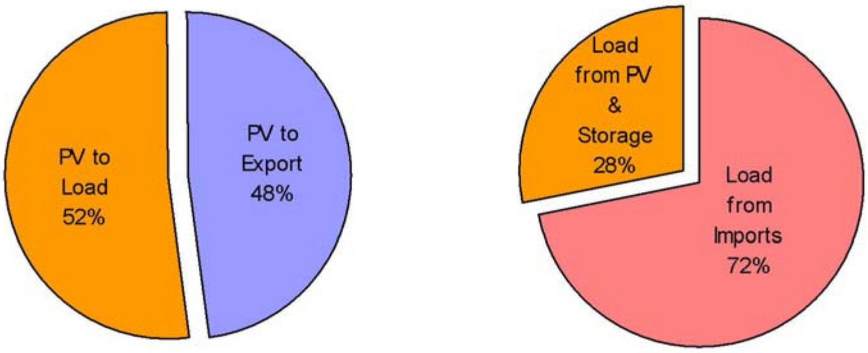
In this case, the grid-connection rating is limited to 1.50kW from 1.55kW with an optimal energy storage size of 0.28kWh.

Participating in the electricity market increases the PV source importance as a micro-generator to the grid exports, nearly 50% exported energy. As shown in Figure 6.7, the difference in PV contribution is minimal, while the ratio of the supply source to load is the same. The PV contribution to the load has increased from around 20% under fixed

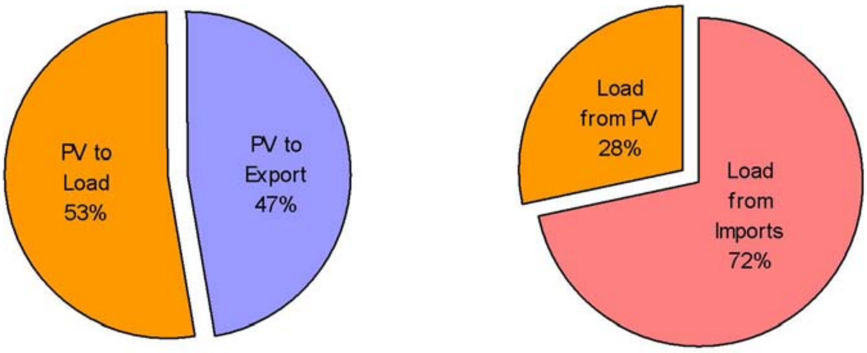


Sample day profile (21st May)

Figure 6.6: Day sample of optimised energy flows, under dynamic tariff system



System with Energy Storage



System without Energy Storage

PV energy (left) and Load supply (right)

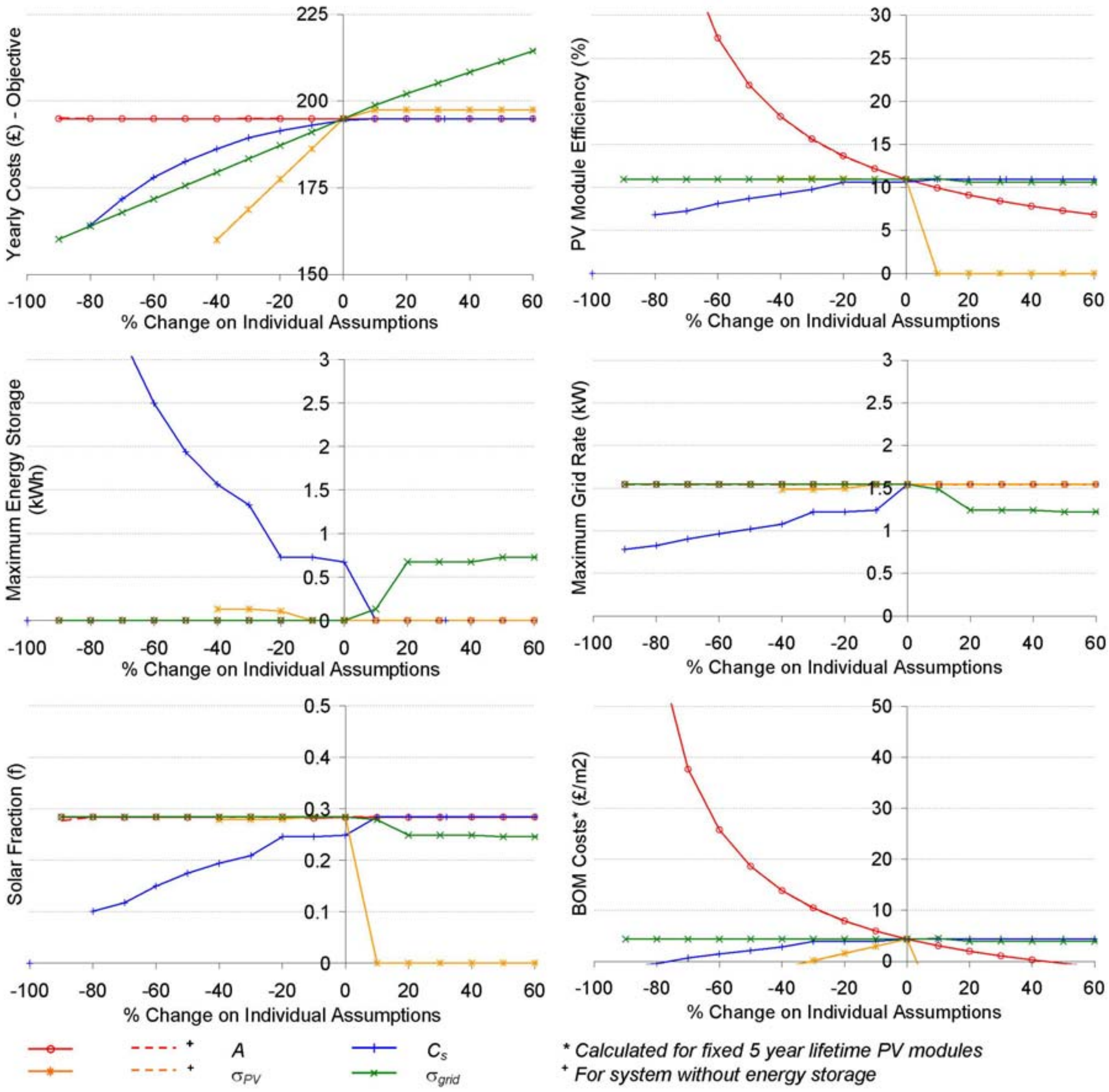
Figure 6.7: Optimal energy share, participating in the electricity market

tariffs to around 30% under dynamic tariffs. Similarly, though storage may help reduce dependency on the grid by lower grid imports and exports, and increase the local energy sources contribution to the local load, its price requires a significant reduction for an increase in PV applications such as these.

6.5.4 Sensitivity analysis

The sensitivity analysis was performed on the impact of the variation in the LEC for PV integration, energy storage cost, grid-connection cost and available area; taking as a baseline the assumptions in Table 6.1. As shown in Figure 6.8, under fixed tariffs, the LEC of PV at which one opts for integration significantly affects the objective function. Meanwhile, the objective problem design variable, the PV module efficiency η_{PV}, has an exponential relation with the Area and LEC of PV, and slightly with the storage cost. Meanwhile as expected the energy storage cost and grid-connection costs considerably affect the contrary of the design variables, that is the capacity of energy storage, $S_{SOC}^{\max}$ and the maximum grid connection $E_{grid}^{\max}$ respectively. As a result, the LEC of PV significantly affects the solar contribution, represented by the SF, while there is an optimal maximum suggested BOM cost for a specific LEC of PV. The latter also distinguish where a PV system with the assumed parameters is still viable, by suggesting positive BOM cost. Meanwhile, the available area and storage costs also notably affect the suggested BOM cost.

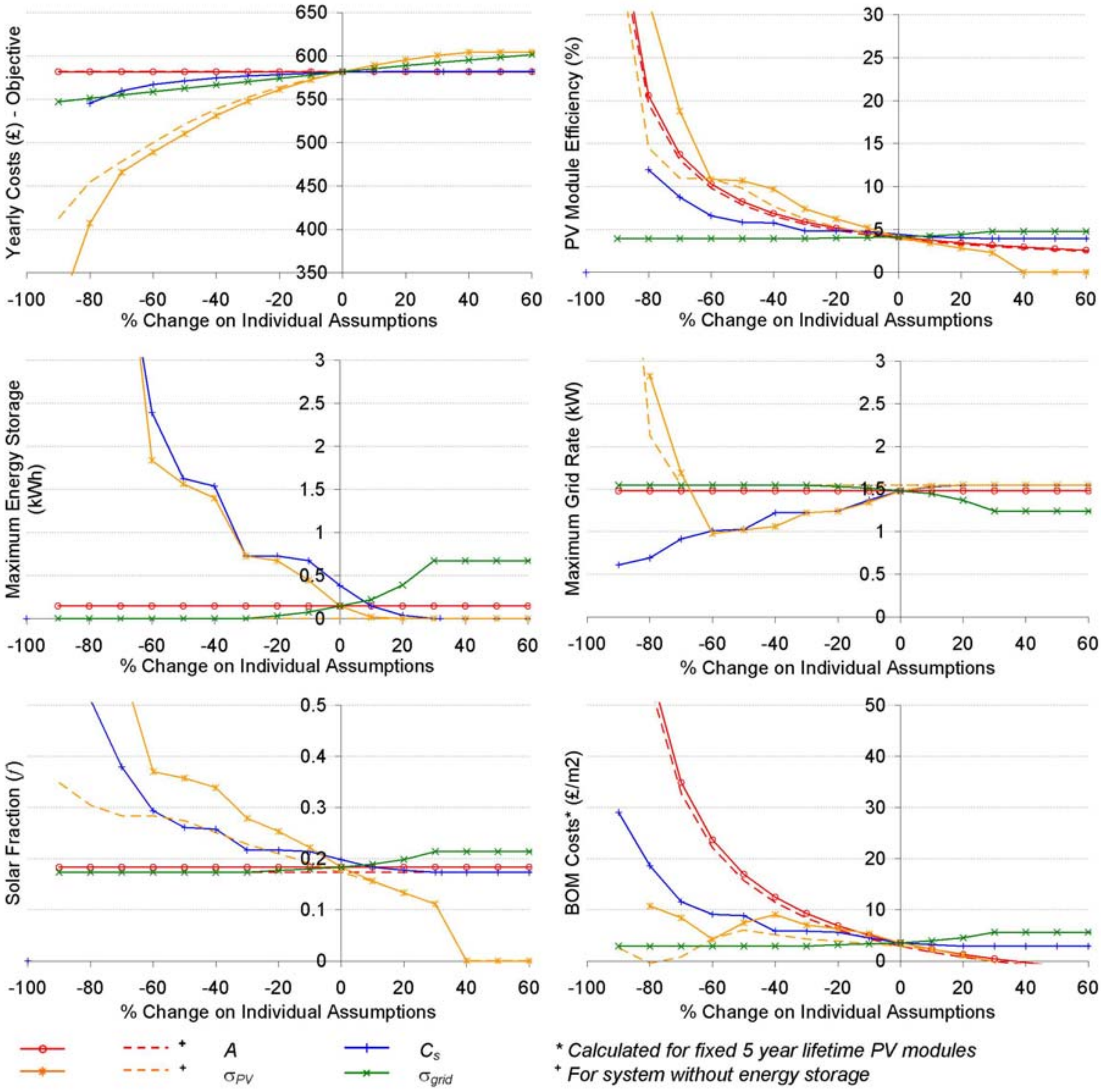
Similar conclusion can be drawn from sensitivity analysis under dynamic tariffs. The baseline for Figure 6.9 is LEC for PV at 4p/kWh, in which case no storage facility is required.



** Calculated for fixed 5 year lifetime PV modules*

$^+$ For system without energy storage

Figure 6.8: Optimal variables sensitivity analysis under fixed tariff system



* Calculated for fixed 5 year lifetime PV modules

+ For system without energy storage

Figure 6.9: Optimal variables sensitivity analysis, under dynamic tariff system

6.5.5 Results: optimising Net Present Value (NPV)

The optimisation results for the NPV as described in (6.2) of the grid-connected PV system in this domestic environment include the PV module Area A_{PV} throughout the system lifetime; and the capacity of energy storage, $S_{SOC}^{\max}$ and the maximum grid connection $E_{grid}^{\max}$, for each module replacement.

In the investigated cases, the investment cost is later increased due to replacement of PV modules. The investment upgrade of energy storage or module replacements is indicated, most of the time, by downward or sideways jumps. The breaking point (NPV=0) indicates the amortisation of investment, the point of profitability and the pay-back period (PBT).

Figure 6.10 shows the discounted cash-flows, for the systems under investigation in previous analysis and the optimistic scenario described in section 4.4, with respect to lifetime, efficiency and price. It can be seen that there is no big difference under the cases considered being with and without storage. Both systems have a payback time of 16 years under no support schemes. On the other hand, if emerging PV technologies where to follow the optimistic path, described in section 4.4, the optimal system sizing result is 5.42m^2 of PV active area without energy storage. The payback time is 28 years, which is still too high to consider as an investment considering the unclear state of these technologies. Under other scenarios, reference and pessimistic trends, discussed in the same section, no other investment is considered profitable. Meanwhile with dynamic tariffs, participating in the electricity market, the payback time is similar to fixed tariffs, if the PV system is integrated at 3.2p/kWh while 28 years payback time if integrated at a PV LEC of 4p/kWh.

6.6 Conclusion

In the context of integration a PV system within a domestic environment there is an optimisation problem to achieve the optimal size or characteristics for the net benefit of the system configuration. The main assumption is that PV support schemes are non-

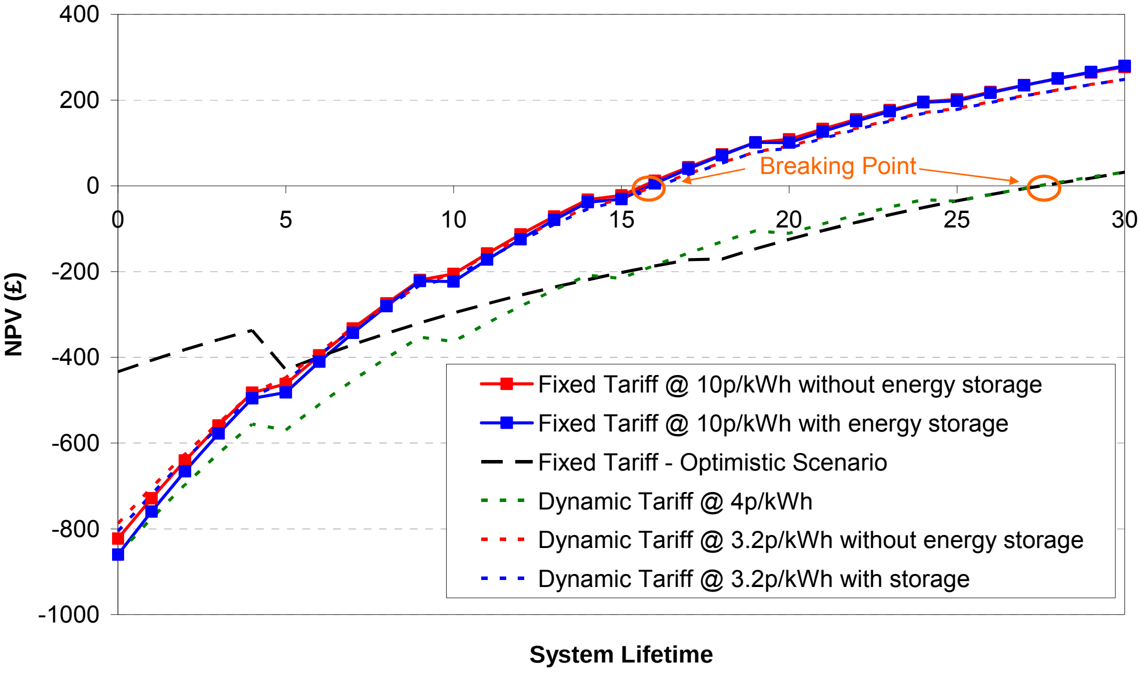


Figure 6.10: Optimal discounted net cash flows for the investigated studies

existing. Hence all PV generation is consumed locally by the local load or exported to the grid. The grid electricity is either charged or paid using fixed tariffs or market electricity prices. The objective is to demonstrate the framework developed for optimal sizing and energy flow management within the domestic household environment, with investment upgrades during system lifetime.

Therefore, the main purpose of this developed framework is:

- To be economic beneficial with respect to energy sources, load profile and grid imports / exports. This is performed by optimising the operation of the system and PV use to the local load.
- To suggest the acceptable PV module characteristics: efficiency and price target, for a given lifetime, within a domestic environment, and
- To provide a metric, based on NPV of the system, for the feasibility and viability to invest within different possible future scenarios.

The focus of this chapter was to investigate the integration of PV systems under no support schemes at a system level analysis. The framework is beneficial in determining system cost boundaries for PV technologies at grid parity integration. A PV system requires a positive NPV, so the owner is better off investing than not investing. On the other hand, incentives should be structures for a £0 NPV at the time systems are projected to be economically viable in that location without incentives. This is further discussed in the next chapter.

7

Multi-Objective Optimisation of a PV System

This chapter describes the proposed multi-objective (MO) approach as a basis of PV deployment support schemes. The MIP developed in chapter 6 is used to investigate another conflicting objective with the economic objective on a micro-level, which describes the end-user interests by minimising grid consumption, or macro-level, describes the public interests by minimising the carbon footprint. The application of three suggested MO methods is demonstrated on the two system configurations. Hence, the chapter firstly reviews MO studies for PV systems, which show the gap in studies related to on-grid systems. Then three suggested MO methods are explained, followed by the objectives definitions for the applied model. The trade-off results of 16 scenarios are illustrated, and discussions on their compromise solution set are provided. Finally, the chapter highlights the use of MO approach PV system integration framework that draws attention to the optimal and compromise characteristics of PV modules in a PV system and also the optimal and compromise sizing of a PV system.

7.1 Introduction

Global energy and environmental problems are at the top agenda for most countries. PV systems have the advantage of reducing fossil fuels consumption and mitigate Green House Gas (GHG) emissions. Despite their current, expensive price, residential PV systems may be an attractive investment especially when a support scheme is in place, such as the ones reviewed in section 2.3. In the near future, emerging PV technologies may also open to commercial markets for micro-generation. However, these PV technologies may initially have limitations in efficiency and durability, making the penetration process into the micro-generation PV market unclear.

7.2 Overview of grid-connected PV systems MO approach

MO optimisation approach is used to satisfy two or more conflicting objectives. The objective functions are discussed later in the next section. This approach will lead to trade-offs between the objective functions, and a possible compromised solution is suggested.

MO studies have been extensively performed on stand-alone hybrid PV systems [166, 175], optimising the economic benefit (ALCC or NPV) and environmental benefit (CO_2 avoided). Grid-connected PV systems studies are not significantly studied within a multi-objective approach. Two studies, a deterministic and a probabilistic approach, considered the economic benefit (ALCC) [176, 177].

The optimal integration of PV systems at a LEC higher than grid-parity using MO approach, is a contribution by the author [178]. This is discussed in this chapter. In addition, grid-connected PV systems considering the economic benefit (ALCC or NPV) and environmental impact / benefit have not been considered. This approach provides further understanding for future PV support schemes especially related to the integration of emerging PV technologies for micro-generation.

7.3 Multi-objective optimisation theory

The field of MO optimisation defines the science of making decisions based on trade-offs between conflicting objectives. The general accepted solution of an MO problem is a Pareto Optimal solution. A Pareto Optimal Solution is one for which any improvement in one objective worsens at least one of the other objectives [179-182]. Normally non-Pareto efficient solutions are neglected while Pareto efficiency is an important criterion for economic evaluation and public policies. There are several approaches to obtain such solutions. This section describes the generic mathematical formulation of the three MO methods, based on two objectives (bi-objective cases) which belong to the so-called second class methods [183], namely:

i. The Weighted Sum (WS) Method
ii. The Compromise Programming (CP) Method
iii. The Normalised Normal Constraint (NNC) Method

The methods were chosen on the grounds of their easy application and verification of the Pareto solutions, to overcome the drawbacks of other methods, and for an insight to a comprised solution within the MO formulation.

7.3.1 The Weighted Sum (WS) method

This is the simplest way to formulate a MO function, by associating weights to the objective function and then, do a weighted sum of the objective functions. Therefore, a new objective function is formed in (7.1):

$$\left.\begin{array}{c} f_{eq}(x) = w_1 f_1(x) + w_2 f_2(x) \\ \text{subject to: } w_1 + w_2 = 1 \\ w_1, w_2 \geq 0 \end{array}\right\} \tag{7.1}$$

The thick line in Figure 7.1 illustrates the Pareto optimum solution for the objective functions, $f_1(x)$ and $f_2(x)$. The optimum solution which, in this case, minimises varies along the thick line in the figure as the weight values of w_1 and w_2. If the space of the objective function is a convex, changing the value of the weights approximates the trade-off surface. The weights have the significance of importance of each objective function.

7.3.2 The Compromise Programming (CP) method

Based on the geometrical definition of best, close to ideal solution, this method is used to obtain a satisfactory compromise set. This method has two weaknesses the extreme efficient points have already been established, and the best compromises could not be the interior points. However, these weaknesses do not affect this developed model. The extreme efficient points, determined from the WS method, give a convex pareto solution.

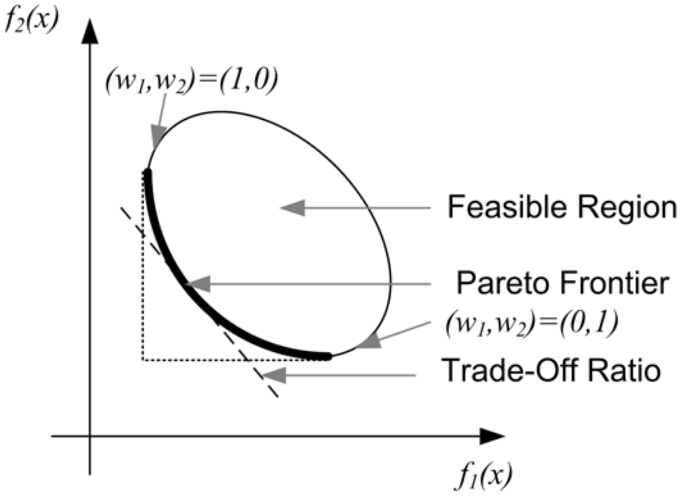


Figure 7.1: Pareto optimal solution with WS method

Thus, for the L_1 metric the best-compromise (closest to the ideal point) can be obtained by solving the following LP problem in (7.2):

$$\left.\begin{array}{ll} \min L_1 = \sum_{z=1}^{2} \frac{f_z^* - f_z(x)}{f_z^* - f_{*z}} & \forall f_z^* \geq f_z(x) \\ + & \\ \min L_1 = \sum_{z=1}^{2} \frac{f_z(x) - f_z^*}{f_{*z} - f_z^*} & \forall f_z^* \leq f_z(x) \end{array}\right\} \tag{7.2}$$

where: f_z^* is the component of the ideal solution (Utopia point) and

f_{*z} is the component of the non-ideal solution

For the L_∞ metric, the maximum deviation (*d*) from among the individual deviation is minimised. Hence this metric is obtained by solving the following LP problem as in (7.3)

$$\left.\begin{array}{ll} & \min L_\infty = d \\ \frac{f_z^* - f_z(x)}{f_z^* - f_{*z}} \leq d & \forall f_z^* \geq f_z(x), z = 1,2 \\ \frac{f_z(x) - f_z^*}{f_{*z} - f_z^*} \leq d & \forall f_z^* \leq f_z(x), z = 1,2 \end{array}\right\} \tag{7.3}$$

The metrics L_1 and L_∞ are a subset of the efficient set, called the compromise set. The next best-compromise set falls between these two metrics. This CP method is called the displaced ideal. The compromise set is reduced to a convenient size, suggesting a compromise solution. The method of the displaced ideal repeats the two LP problems above iteratively, taking the new result as the ideal, until a satisfactory compromise set is found [184].

7.3.3 The Normalised Normal Constraint (NNC) method [183]

The NNC method is a follow-up of the Normal Constraint method for generating a set of evenly spaced solutions on a Pareto frontier. The method was used to verify the Pareto frontier results using the WS and CP method. These methods do not generate even spread optimal solutions and the WS method may not generate all the available Pareto points.

The graphical representation of the method is shown in Figure 7.2. Figure 7.2 (a) is the generic design space which is not normalised, similar to the result obtained by the WS method. Figure 7.2 (b) illustrates the same design space but this time, normalised, with the ideal solution set at the origin (0, 0) and the extreme efficient points set at one unit away from the ideal solution. A line is drawn between the two extreme efficient points, called the Utopia Line as indicated in Figure 7.2 (c). The Utopia line is further divided into m_1-1 segments, which will lead to m_1 points. Figure 7.2 (d) shows a normal line (Line NU) to the Utopia Line which reduces the feasible space. Hence minimising $\overline{f_2}(x)$, the optimal point $\overline{f_1 f_2}$ results. The solutions are generated by translating this Line NU to each space point on the Utopia Line, which are equally distributed.

The graphical representation procedure in Figure 7.2 is given in seven step process that formulates this NNC method:

Step 1: *Anchor Points* - Two anchor points are the two extreme efficient points of the pareto solution, which can be obtained by solving each objective separately. Each anchor point contains the most ideal and the non-ideal solution (i.e. f^1 is (f_{*1},f^*_2) and f^2 is (f^*_1,f_{*2}). The line joining these two anchor points is called the Utopia Line.

Step 2: Normalisation of the Design Space – Normalisation is performed to avoid scaling deficiencies and hence the optimisation is performed on a normalised design space. The normalisation of a variable is signified by a bar on top. The Utopia point is the ideal solution is (f^*_1,f^*_2). The lengths l_1 and l_2, between the extreme points and the ideal solution, are calculated in (7.4):

$$\left.\begin{aligned} l_1 &= f_{*1} - f_1^* \\ l_2 &= f_{*2} - f_2^* \end{aligned}\right\} \qquad (7.4)$$

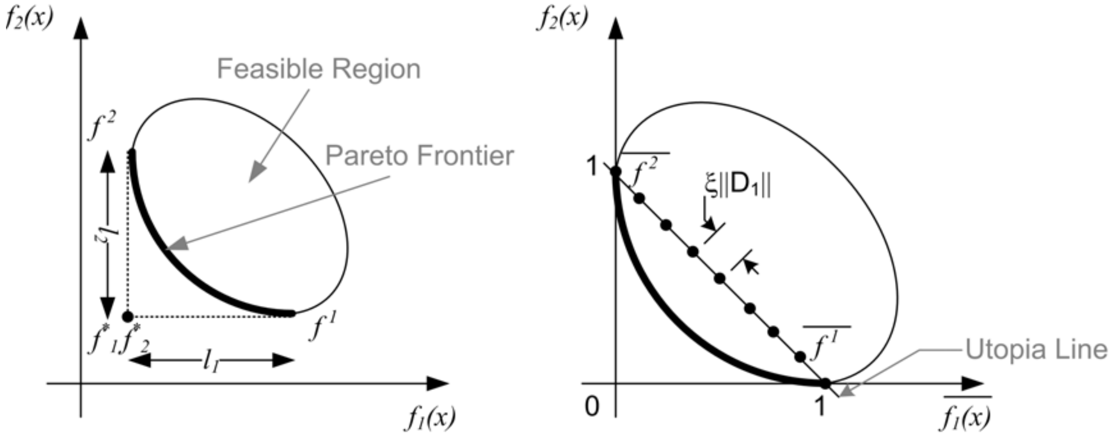
Hence using the above lengths, the normalisation of the design space is given in (7.5):

$$\overline{f_1 f_2} = \left[\frac{f_1(x) - f_1^*}{l_1} \quad \frac{f_2(x) - f_2^*}{l_2} \right]^T \qquad (7.5)$$

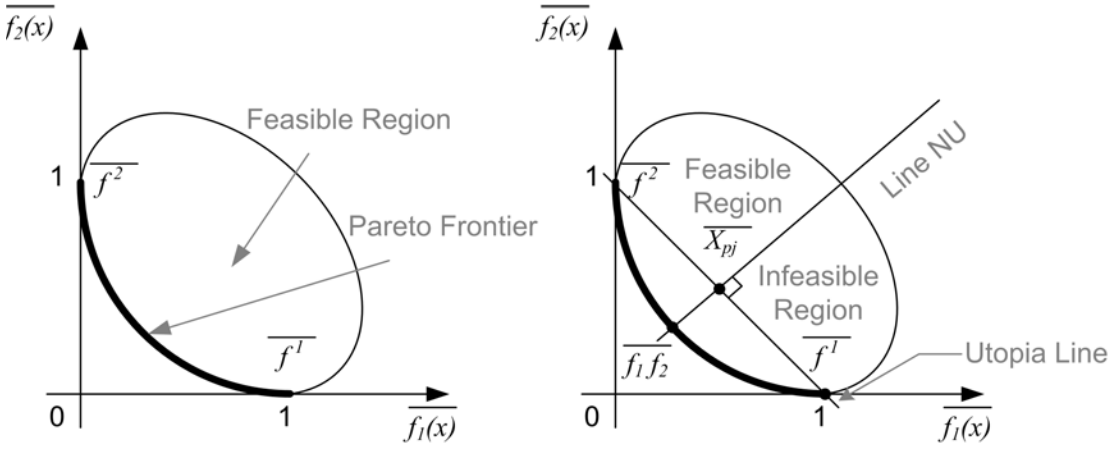
Step 3: Utopia Line Vector - is the direction from f^1 to f^2 in (7.6):

$$\overline{N_1} = \overline{f^2} - \overline{f^1} \qquad (7.6)$$

Step 4: Normalised Increments – for a number of solutions (m_1), the equal increments ξ_1 are computed in (7.7):



(a) General Design Metric Space (c) A set of evenly spaced points on the Utopia line



(b) Normalised Design Metric Space (d) Graphical representation of the NNC method

Figure 7.2: Graphical representation of the NNC method [183]

$$\xi_1 = \frac{1}{m_1 - 1} \tag{7.7}$$

Step 5: Generating Utopia Line Points - generating a set of equally distributed points on the Utopia line as shown in Figure 7.2 (c) follows the mathematical formulation in (7.8)

$$\left.\begin{array}{c} \overline{X_{pj}} = \varepsilon_{1j}\overline{f^1} + \varepsilon_{2j}\overline{f^2} \\ \text{where } 0 \le \varepsilon_1 \le 1 \\ \sum_{k=1}^{2} \varepsilon_{kj} = 1 \end{array}\right\} \tag{7.8}$$

where ε_{kj} is increased by ξ_1, between 0 and 1, and j is a member of $1, 2, \ldots m_1$.

Step 6: Pareto Points Generation – For each evenly distributed point (*j*) on the Utopia line an optimisation for *f₂(x)*, the optimisation problem is defined in (7.9):

$$\left.\begin{array}{ll} \min \overline{f_2(x)} & \\ & Ax < b \\ & A_{eq} \cdot x = b_{eq} \\ \text{subject to:} & lb \le x \le ub \\ & \overline{N_1}\left(\overline{f_1 f_2} - \overline{X_{pj}}\right)^T \\ & \overline{f_1 f_2} = \left[\overline{f_1(x)} \quad \overline{f_2(x)}\right]^T \end{array}\right\} \tag{7.9}$$

Step 7: Pareto Design Metrics Values – The non-normalised design metrics can be obtained from an inverse mapping of (7.10):

$$f_1(x) f_2(x) = \left[\overline{f_1(x)} l_2 - f_1^* \quad \overline{f_2(x)} l_2 - f_2^*\right] \tag{7.10}$$

Some part of the Pareto frontier may not be captured by the WS or CP. In WS, some points may be captured through iterative process by the appropriate scaling of the weights.

7.4 The objective functions

The conflicting objectives of PV integration into a domestic environment described in this section are to maximise the value of the complete system while at the same time trying to maximise the contribution either to the local load (micro-level: customer perspective) or environmental benefits (macro-level: public perspective).

7.4.1 Maximising the economic value of the complete system

As described in sections 6.3.3.1 and 6.3.3.2, the net economic benefit for the customer (micro-level) is found either by maximising the NPV of the system, or minimising the ALCC. The two methods for optimal sizing and optimal integration respectively are used in this chapter. The objective functions have the general form as in equations (7.11) and (7.12) respectively:

$$\text{minimise: } Z_1^{NPV} = -\left[I_0 + \sum_{y=1}^{T} \frac{CF_y}{(1+r)^y}\right] \tag{7.11}$$

$$\text{minimise: } Z_1^{ALLC} = C_I - C_0 \tag{7.12}$$

where in (7.11), the NPV is maximised. The first term is the initial investment, referring to BOS component costs, initial energy storage and PV modules, and the second term is all the discounted cash flows throughout the system lifetime, which includes an increase of investment due to replacements, benefits from not importing electricity and any revenue from selling electricity into the grid; and
in (7.12), the ALLC is minimised. The first term is the annualised costs for any energy storage including regular replacements every ten years, and the second term is the operational costs which include the LEC for PV system, which includes BOS and BOM costs, energy import costs and any revenue from exported energy to the grid.

7.4.2 Maximise the contribution to the local load

At the micro-level, customer perspective, the contribution to the local load is preferred to be maximised. Therefore minimising the energy grid imports will lead to maximising the contribution of the PV micro-generator system in (7.13).

$$\text{minimise: } Z_2^E = \sum_{t=1}^{8760} E_{in}(t) \tag{7.13}$$

where the energy flows E_{in} is imported energy from the grid, corresponding to the system design at each replacement stage.

7.4.3 Maximising the environmental benefits

On the macro-level scenario, renewable energy systems, such as PV systems, are welcome due to a sustainable energy source. Hence these systems can mitigate GHG emissions, expressed in CO_2-equivalent. Similar to the economic objective above, the net environmental benefit is found by either maximising the CO_2 benefit of the system, or minimising the annual CO_2 emissions. The two methods for optimal sizing and optimal integration respectively are used in this chapter. The objective functions have the general form as in equations and respectively:

$$\text{maximise: } Z_2^{CO_2-Benefit} = -CO_2^{Component-Initial} + \sum_{y=1}^{T} CO_2^{Mitigated-y} \tag{7.14}$$

$$\text{minimise: } Z_2^{CO_2-emitted} = CO_2^{LCIA} + CO_2^{Operation} \tag{7.15}$$

where in (7.14), the CO_2 benefit of the system is maximised. The first term is the initial investment CO_2-equivalent emissions for system components, such as BOS, energy storage and PV modules. The second term is all the yearly CO_2-equivalent net benefit throughout the system lifetime, which includes the increase in investment CO_2-

equivalent emissions due to investment replacements, the CO_2-eq emissions mitigated from energy produced / saved (generated) and grid CO_2-eq of the consumed energy.

In (7.15), the annual CO_2 emission is minimised: the first term is the annualised CO_2 equivalent for any energy storage, BOS components and PV modules including fixed regular replacements, and the second term is the operational CO_2-eq emissions for energy consumed less energy produced / saved (generated).

Note there are differing opinions on the appropriate value for the CO_2 emission intensity of grid import and export electricity due to the grid inefficiencies. The SAP 2009 CO_2 conversion factors are taken during the case studies. Hence the CO_2-equivalent for consumed energy is 0.517 kg/kWh and the CO_2-equivalent for energy mitigated either by grid exports or savings from the grid is 0.529 kg/kWh [185].

Similarly, depending on the model objective, the PV and energy storage CO_2 in the objective can also be expressed in terms of the system's CO_2 impact factor as described in chapter 5, per unit such as m^2, Wp or kWh. The baselines for CO_2-eq impact are 30kg-eqCO_2/m^2 for BOM, 15kg-eqCO_2/m^2 for BOS and 60kg-eqCO_2/kWh for energy storage. The BOM and BOS CO_2 impact are general assumed figures close to literature in chapter 5 while the CO_2 impact for energy storage is that for a battery (0.06kg-CO_2 /Wh capacity) [186].

7.4.3.1 The abatement cost

The abatement cost is the cost borne by a policy support scheme or individual for the elimination and/or decrease of an unwanted item that the society / individual has created. There are two main concepts. At the micro-level, the consumer would like to reduce the energy consumption from the grid. On the other hand, at the macro level carbon-free domestic environment is supported. If the NPV is positive, or ALCC are less than without PV system, then there is no abatement cost, as the system is already profitable. However, if ALCC are higher than without PV system, that implies a negative NPV, the abatement cost is the negative NPV of the complete system divided by the electricity consumption or CO_2 avoided. Hence the abatement cost determines the amount of funding required to make an investment economically viable.

7.5 Results

The following scenarios in Table 7.1 and Table 7.2 are compared to analyse the influence of some assumptions taken, as well as future anticipated developments.

Table 7.1: Scenarios for integrating a PV system at a PV LEC

Scenario	Colour	PV LEC (p/kWh)	Typical Radiation	Typical Load	Grid Tariff	Energy Storage
1	⬛	10	Manchester (MAN)	4 Bed G & E	Fixed	✗
2	🟦	41.3	Manchester (MAN)	4 Bed G & E	Fixed	✗
3	🟪	41.3	Malta (MLT)	4 Bed G & E	Fixed	✗
4	🟥	41.3	Manchester (MAN)	2 Bed G & E	Fixed	✗
5	🟦	41.3	Manchester (MAN)	4 Bed G & E	Fixed	✓
6	🟫	41.3	Manchester (MAN)	4 Bed G & E	Variable	✗
7	◼	4	Manchester (MAN)	4 Bed G & E	Variable	✗
8	🟨	41.3	Manchester (MAN)	4 Bed G & E	Variable	✓

Table 7.2: Scenarios for optimal sizing a PV system at a PV LEC

Scenario	Colour	Description	Typical Radiation	Typical Load	Grid Tariff	Energy Storage
1	⬛	Reference	Manchester (MAN)	4 Bed G & E	Fixed	✗
2	🟨	Optimistic	Manchester (MAN)	4 Bed G & E	Fixed	✗
3	◼	Pessimistic	Manchester (MAN)	4 Bed G & E	Fixed	✗
4	🟩	Fixed Replacement	Manchester (MAN)	4 Bed G & E	Fixed	✗
5	🟩	Fixed Replacement	Manchester (MAN)	4 Bed G & E	Fixed	✓
6	🟦	Fixed Replacement	Manchester (MAN)	4 Bed G & E	Variable	✗
7	🟦	Fixed Replacement	Manchester (MAN)	4 Bed G & E	Variable	✓
8	🟪	m-Si Module	Manchester (MAN)	4 Bed G & E	Fixed	✗

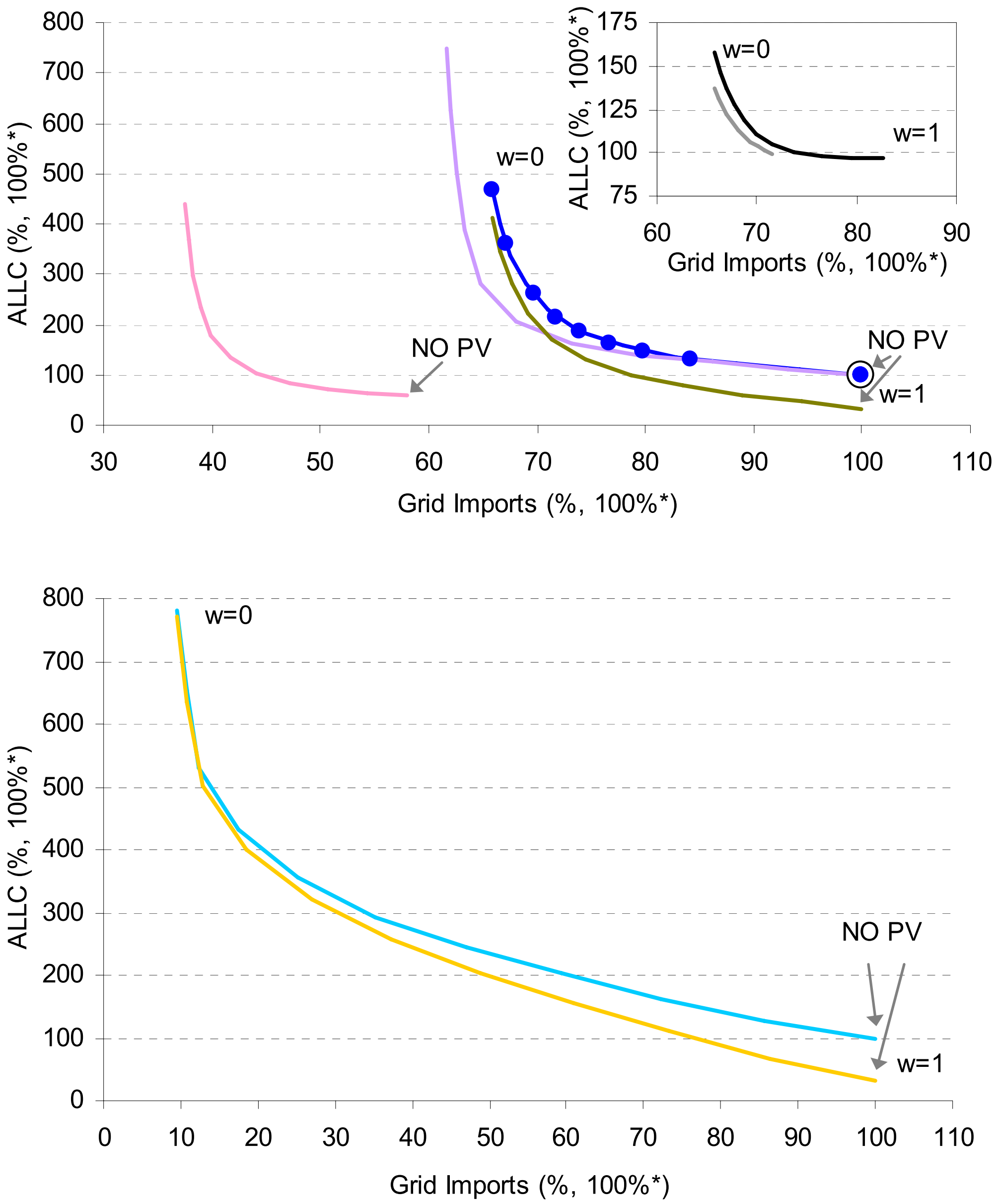
Reference, Optimistic and Pessimistic scenarios were described in section 4.4

Fixed Replacement refers to an emerging PV module (5% efficiency, 5 year lifetime and £50/m^2 BOM costs at year zero).

m-Si Module describes a mature PV module (17% efficiency, 30 year lifetime and £396/m^2 BOM costs at year zero).

7.5.1 Micro-level analysis – economic objective vs consumption

The trade-off relationships, region of the non-inferior points, between the two conflicting objectives the economic objective (Z_1^{ALLC}) and the energy consumed from grid (Z_2^E), are shown in Figure 7.3 under various scenarios as in Table 7.1. The ALLC is decreased as the PV contribution is lessened. 100% is the reference without PV system for a 4 Bed gas and electricity load profile category. When having a higher LEC than grid, the trade-off shifts accordingly to the original electricity cost of household without PV system. With energy storage, the trade-off extends to higher cost to

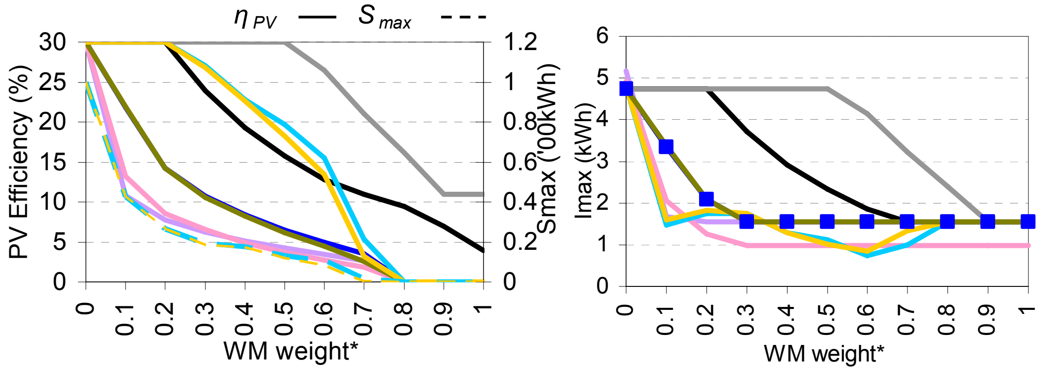


**100% is the baseline for a 4 Bed G & E without PV system under fixed electricity tariffs. Plots are plotted with the NNC method. Dotted points represent the WM results.*

Figure 7.3: Trade-off relationships between Z_1^{ALLC} and the Z_2^{E}

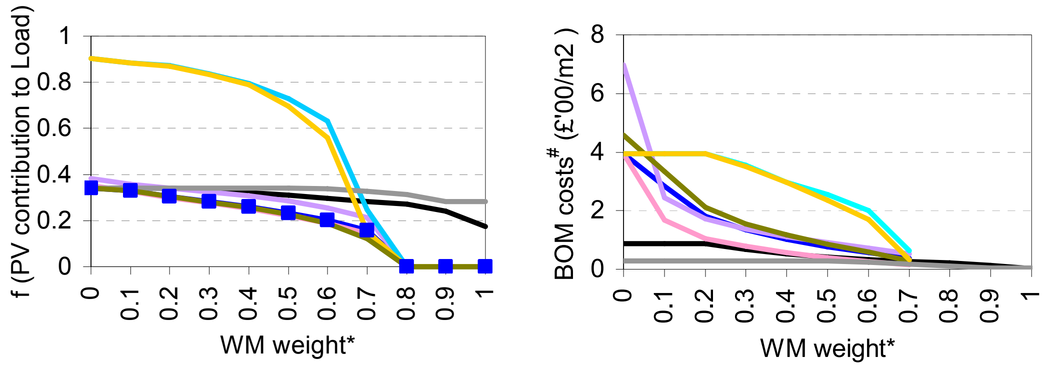
mitigate the energy consumed from the grid. The MO optimisation formulation considers any PV module efficiency between 0% and 30%, the latter is a likely reachable efficiency for commercial modules by mature PV technology or future emerging ones. The formulation also assumes a threshold in energy storage of up to 100kWh.

Figure 7.4 (a) and (b) show the optimal values of efficiency (η_{PV}) and energy storage ($S_{SOC}^{\max}$ - where available) and Grid Rating ($E_{grid}^{\max}$) respectively, in relation to the weight, *w,* which measures the importance to the economic objective (ALCC).



(a) PV Efficiency & Storage Capacity
η_{PV}<=30%, S_{max}<=100kWh

(b) Suggested Grid Rating @ £25/kWh



(c) Calculated PV Contribution

(d) Suggested BOM Costs
5 year lifetime

* Significance of the economic benefit

Figure 7.4: Optimal values of design variables for multi-objective Z_1^{ALLC} vs Z_2^{E}

In Figure 7.4 (a), by setting $w = 0.8$ to 1.0, the optimal value of efficiency becomes zero in most cases except where the PV LEC is lower than the grid tariff. On the other hand, η_{PV} increases as the importance to the economic objective is lessened. For systems with energy storage, this increase is more abrupt to make the most out of the energy storage facilities. The energy storage capacity is kept to the minimum until the economic objective is of no longer importance $w = 0.0$. This increase in η_{PV} and $S_{SOC}^{\max}$ is disadvantageous economically to the domestic user as this requires higher annual costs as shown in Figure 7.3.

As shown in Figure 7.4 (b), at grid fixed rating cost at £25/kWh/yr, the optimal value for grid connection ($E_{grid}^{\max}$) increases due to access PV energy production exported to the grid. However, it is shown that systems with energy storage reduces the grid rating mid-range ($w = 0.4$ to 0.8).

Figure 7.4 (c) and (d) are derived calculations of PV contribution to the local load (f_{PV}) and BOM costs (C_{BOM}) for a 5 year lifetime module, in relation to the weight, *w,* which measures the importance to the economic objective (ALCC).

As shown in Figure 7.4 (c), for PV LEC lower than grid, the PV contribution cost does not improve significantly, while, for systems with energy storage, the PV contribution to local load is much higher. In Figure 7.4 (d), the BOM costs, which may include a margin for module replacement costs, was a wider range for systems with energy storage at $w = 0.2$ to 0.6 for a LEC at 41.3p/kWh. If integrating PV system at a lower LEC than grid tariff, the suggested BOM cost, is lower than £100/m^2.

Table 7.3 summarises the compromise solution sets of the above analysis between the two conflicting objectives the economic objective (Z_1^{ALLC}) and the energy consumed from grid (Z_2^E). The compromise solution sets' optimal values for efficiency lie in between 5% to 19%. These efficiencies can be found in commercial PV modules. The Trade-Off cost of saving a kWh from energy imports is much higher for systems with LEC greater than grid tariff at 41.3p/kWh.

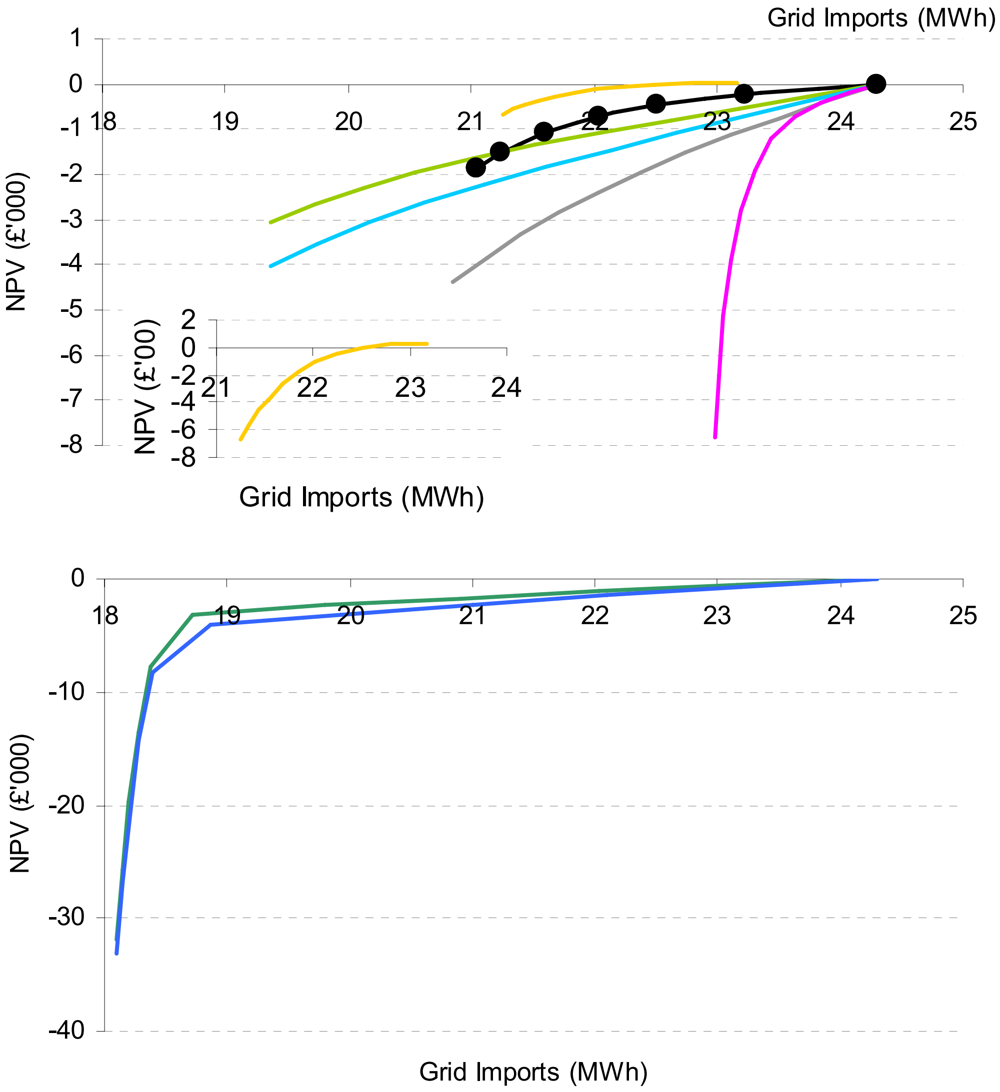
The above analysis was based on the additional annual cost required by minimising 1kWh from the electricity grid (trade-off). In this part of the analysis, the domestic environment economic benefit / loss is expressed with NPV of the system. Hence the trade-off relationships between the two conflicting objectives the economic objective (Z_1^{NPV}) and the energy consumed from grid (Z_2^E) are shown in Figure 7.5 under various scenarios in Table 7.2. The NPV is increased as the PV contribution is lessened. NPV greater than zero represents profitable investment. Having a higher LEC than grid, investment is not profitable at any point and hence the trade-off begins from 0. With energy storage, the trade-off extends to lower NPV to mitigate the energy consumed from the grid. The MO optimisation formulation considers a maximum available area of 25m^2, the latter is considered a typical household roof area. Similarly, the formulation also assumes a threshold in energy storage of up to 100kWh.

Figure 7.6 shows the optimal values of the PV module sizing (A), in relation to the weight, *w,* which measures the importance to the economic objective (NPV). It is shown that, for emerging PV technologies, the increase in the area / sizing is more than for current PV technologies. Fixed replacement emerging PV technology was assumed at 5 year lifetime, 5% efficiency and 50% degradation limit. While, for m-Si module, a system lifetime, 17% module efficiency and 80% degradation limit were assumed.

Table 7.3: Summary of the compromise solution sets for the scenarios in Table 7.1

CS metrics	Obj1 (*ALCC*) £	Obj2 (E_I) kWh	η_{PV} %	*f*	S_{max} kWh	I_{max} kWh	C_{BOM} £/m^2	Trade-off at £/kWh
Scenario 1:								
L_1	654.26	2857.24	12.51	0.29	n/a	1.80	30.93	-0.62
L_∞	654.17	2857.39	12.51	0.29		1.80	30.91	
Scenario 2:								
L_1	1152.50	2980.03	8.73	0.26	n/a	1.55	107.78	-2.08
L_∞	1129.84	2994.74	8.41	0.26		1.55	103.49	
Scenario 3:								
L_1	1312.92	2727.50	6.41	0.33	n/a	1.55	141.05	-3.57
L_∞	1250.53	2754.97	5.91	0.32		1.55	129.49	
Scenario 4:								
L_1	818.71	1682.24	7.06	0.28	n/a	1.02	85.26	-3.89
L_∞	807.69	1686.29	6.92	0.28		1.00	83.34	
Scenario 5:								
L_1	1939.21	1224.02	18.26	0.70	12.00	1.01	194.88	-0.91
L_∞	1965.79	1195.58	18.52	0.70	12.45	1.02	197.73	
Scenario 6:								
L_1	845.39	2978.93	8.76	0.26	n/a	1.55	89.21	-1.92
L_∞	783.66	3019.05	7.92	0.25		1.55	79.93	
Scenario 7:								
L_1	223.49	2755.91	18.36	0.32	n/a	2.76	14.06	-0.29
L_∞	223.69	2755.29	18.41	0.32		2.77	11.65	
Scenario 8:								
L_1	1792.70	1234.83	18.16	0.70	11.85	1.00	234.86	-0.94
L_∞	1803.70	1224.04	18.27	0.70	11.95	1.02	236.38	

Table 7.4 summarises the compromise solution sets of the above analysis between the two conflicting objectives the economic objective (Z_1^{NPV}) and the energy consumed from grid (Z_2^E). The compromise solution sets' optimal values for area lie in between 8 to 25 m^2, which is a typical available area in domestic household. The abatement cost to mitigate energy from the grid is lower for emerging technologies than for mature technology at the compromise solution set.



Plots are plotted with the NNC method. Dotted points represent the WM results.

Figure 7.5: Trade-off relationships between Z_1^{NPV} and Z_2^{E}

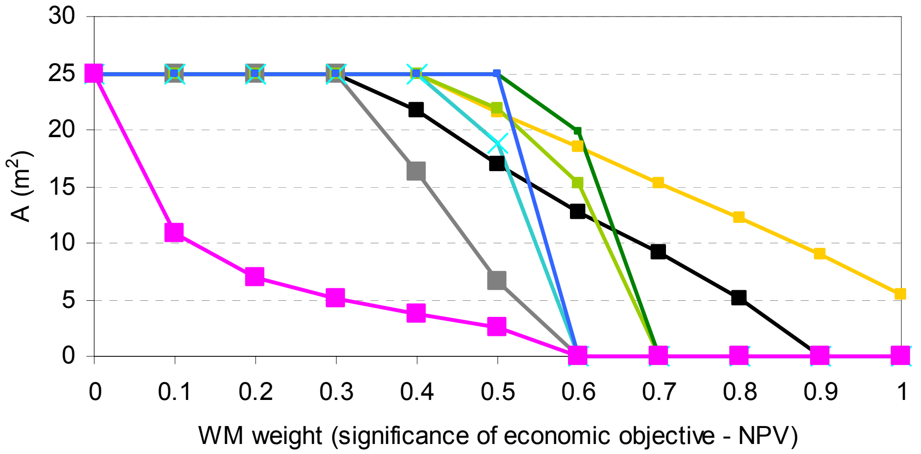


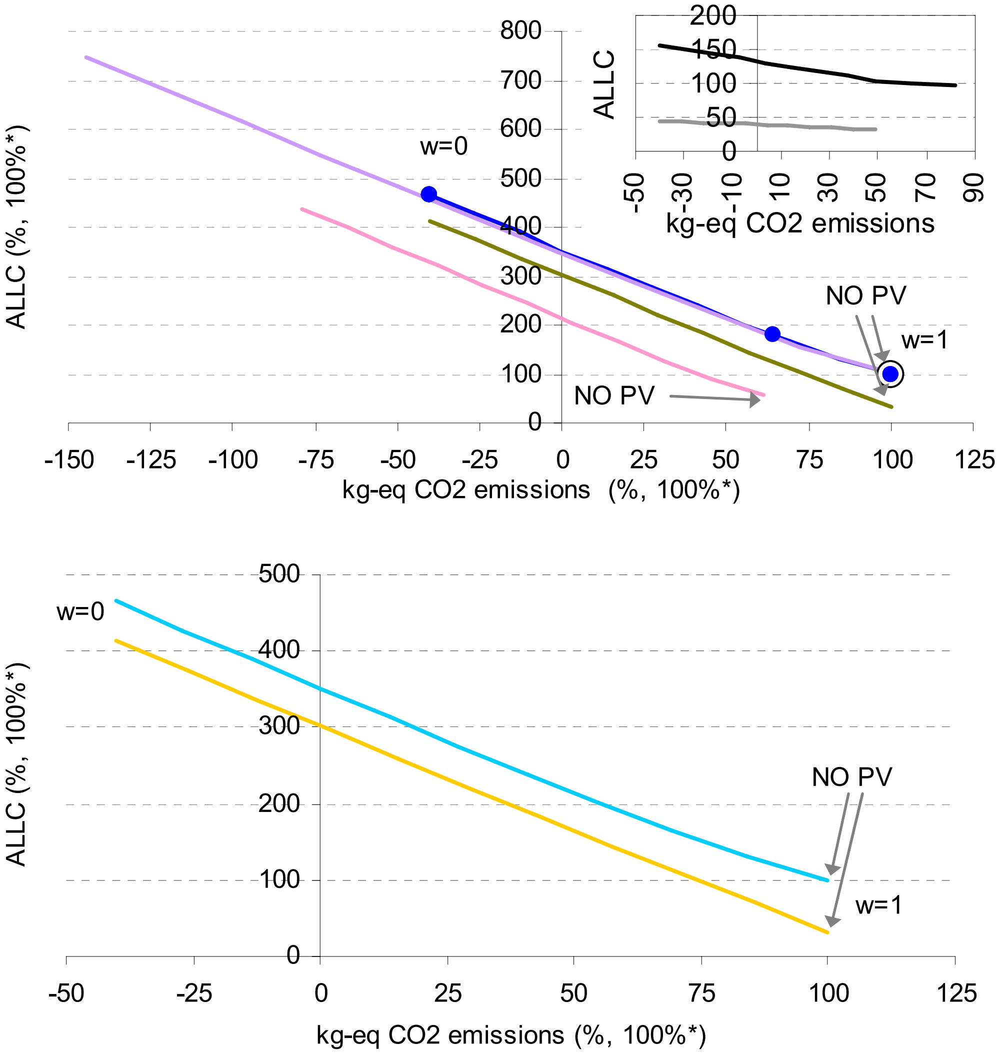
Figure 7.6: Optimal values of design variable - A_{PV} for multi-objective Z_1^{NPV} vs Z_2^{E}

Table 7.4: Summary of the Compromise Solution Sets for the scenarios in Table 7.2

CS metrics	Obj1 (NPV) £	Obj2 (E_I) kWh	A_{PV} m^2	Abatement Cost £/kWh	Trade-off at £/kWh
Scenario 1:	⬛	⬛	⬛	⬛	⬛
L_1	-635.06	22173.80	11.54	0.30	-0.50
L_∞	-643.64	22159.00	11.65	0.30	
Scenario 2:	🟨	🟨	🟨	🟨	🟨
L_1	-155.15	21904.40	14.99	0.06	-0.39
L_∞	-155.51	21903.60	15.00	0.07	
Scenario 3:	◼	◼	◼	◼	◼
L_1	-2041.06	22292.80	11.98	1.02	-1.28
L_∞	-2036.73	22296.20	11.95	1.02	
Scenario 4:	🟩	🟩	🟩	🟩	🟩
L_1	-1459.32	21299.60	12.84	0.49	-0.59
L_∞	-1459.86	21298.70	12.85	0.49	
Scenario 5:	🟩	🟩	🟩	🟩	🟩
L_1	-3447.23	18531.90	25.00	0.60	-0.73
L_∞	-1504.43	21206.90	13.14	0.49	
Scenario 6:	🟦	🟦	🟦	🟦	🟦
L_1	-2242.44	21080.90	13.93	0.70	-0.77 / -0.85
L_∞	-4084.51	21609.40	11.39	1.52	
Scenario 7:	🟦	🟦	🟦	🟦	🟦
L_1	-4594.33	18531.50	25.00	0.80	-8.78
L_∞	-4084.51	18866.10	24.25	0.75	
Scenario 8:	🟪	🟪	🟪	🟪	🟪
L_1	-1852.68	23308.90	8.74	1.88	-4.78
L_∞	-1910.99	23299.30	8.93	1.92	

7.5.2 Macro-level analysis – economic objective vs CO_2-eq emission

The micro-level analysis is repeated this time considering the CO_2-eq Emission with the economic objective. The trade-off relationships between the two conflicting objectives, the economic objective (Z_1^{ALLC}) and the equivalent emitted / benefited CO_2 from equipment installed, grid imports and grid exports ($Z_2^{CO2\text{-}emitted}$), are shown in Figure 7.7 under various scenarios as in Table 7.1. The ALLC is decreased almost linearly as the



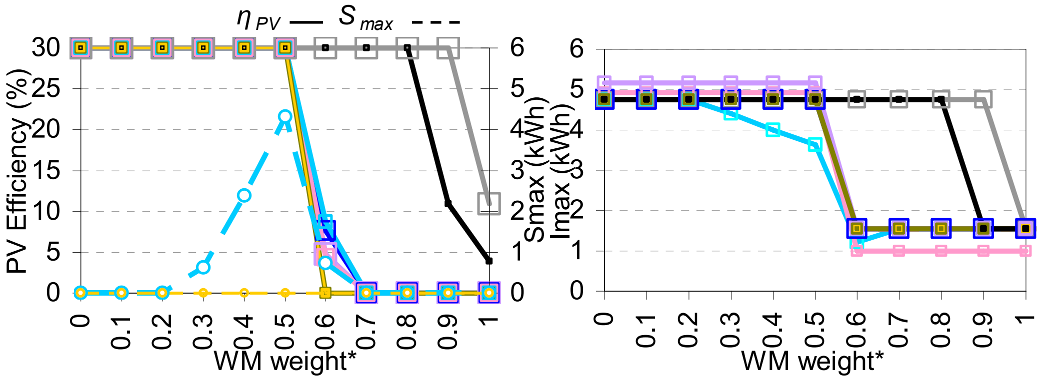
**100% is the baseline for a 4 Bed G & E without PV system under fixed electricity tariffs. Plots are plotted with the NNC method. Dotted points represent the WM results.*

Figure 7.7: Trade-off relationships scenarios between Z_1^{ALLC} and $Z_2^{CO2\text{-}emitted}$

PV contribution is lessened. The 100% represents the reference 4 bed gas and electricity category profile for the original grid electricity costs and grid CO_2 emissions. Similar to previous analysis, the trade-off shifts accordingly to the original electricity cost of household without PV system, for a higher LEC than grid. With energy storage, the trade-off extends to higher cost to mitigate the energy consumed from the grid. Again, the MO formulation considers any PV module efficiency between 0% to 30%, the latter is a likely reachable efficiency for commercial modules by mature PV technologies and emerging PV technologies. The formulation also assumes a threshold in energy storage of up to 100kWh.

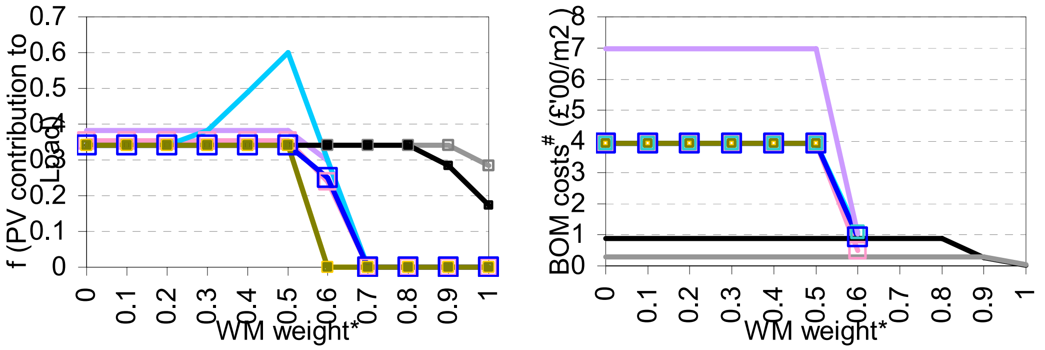
Figure 7.8 (a) and (b) show the optimal values of efficiency (η_{PV}) and energy storage ($S_{SOC}^{\max}$) and Grid Rating ($E_{grid}^{\max}$) respectively, in relation to the weight, *w,* which measures the importance to the economic objective (ALCC).

In Figure 7.8 (a), by setting $w = 0.7$ to 1.0, the optimal value of efficiency becomes zero in most cases except where the PV LEC is higher than the grid electricity tariff. On the other hand, η_{PV} increases abruptly as the importance to the economic objective is lessened. Energy storage is only suggested between $w = 0.2$ to 0.7, to mitigate CO_2 emission with lower ALLC. However, since energy storage has a high CO_2 impact during manufacturing, this is again reduced to 0 when the importance is given for the environmental benefit.



(a) PV Efficiency & Storage Capacity
η_{PV}<=30%, S_{max}<=100kWh

(b) Suggested Grid Rating @ £25/kWh



(c) Calculated PV Contribution

(d) Suggested BOM Costs
$^{\#}$5 year lifetime

* Significance of the economic benefit

Figure 7.8: Optimal design variables for multi-objective Z_1^{ALLC} vs $Z_2^{CO2\text{-}emitted}$

As shown in Figure 7.8 (b), at grid fixed rating cost at £25/kWh/yr, the optimal value for grid connection ($E_{grid}^{\max}$) increases suddenly at w = 0.5 since access PV energy production exported to the grid have a contribution of lower the net CO_2 flows.

Figure 7.8 (c) and (d) are derived calculations for the PV contribution to the local load (f_{PV}) and BOM costs (C_{BOM}) for a 5 year lifetime module, in relation to the weight, *w,* which measures the importance to the economic objective (ALCC).

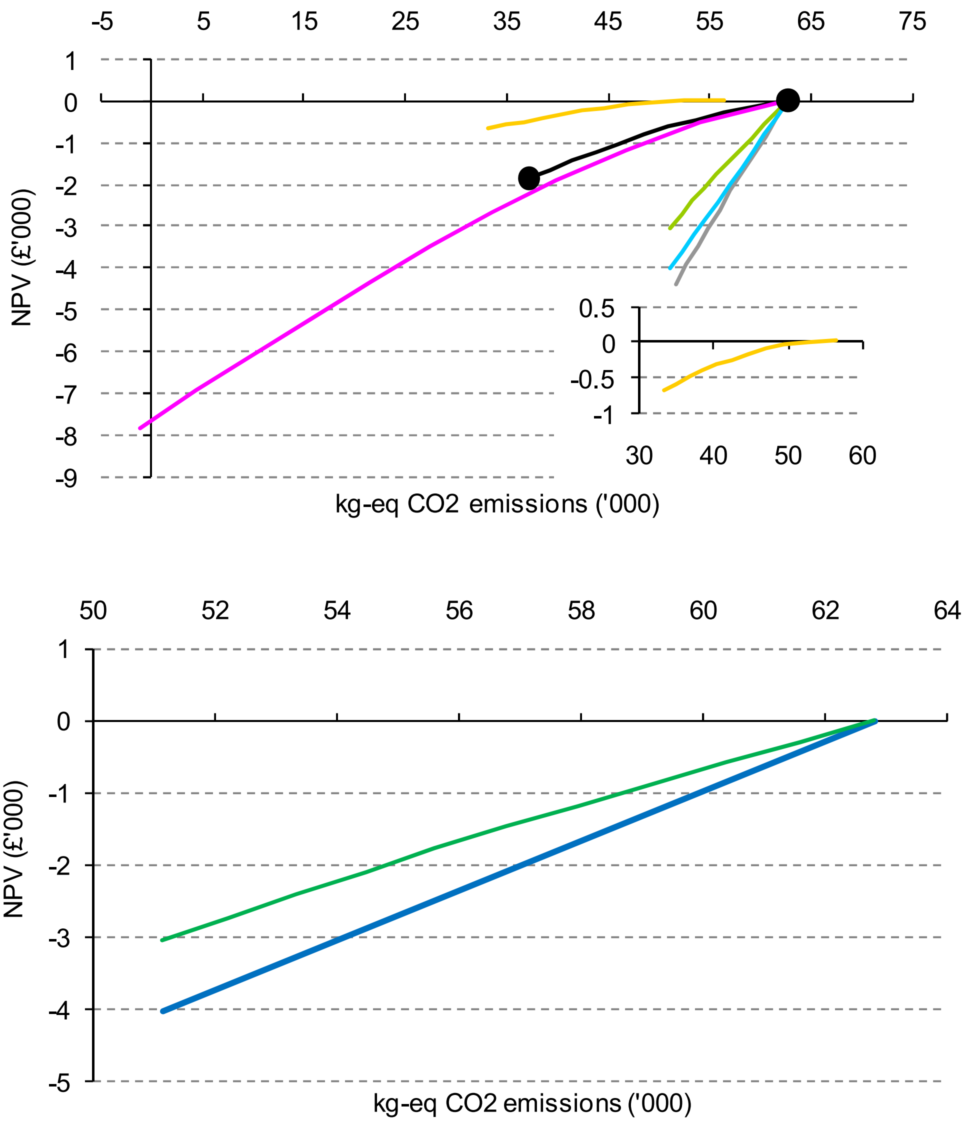
As shown in Figure 7.8 (c), for PV LEC lower than grid, the PV contribution cost does not improve significantly. On the other hand, for systems with energy storage, the PV contribution to local load is much higher at w = 0.5. The sudden increases in efficiency are also noticed in the PV contribution. There is a limit to the contribution to the local load. This depends on the correlation between the load and solar resource. In Figure 7.8 (d), the BOM costs, which may include a margin for module replacement costs, has a wider range for systems under higher solar radiation for a LEC at 41.3p/kWh. Similar to the micro-level MO analysis, integrating PV system at a lower LEC than grid tariff, suggests BOM cost lower than £100/m^2.Table 7.5 summarises the compromise solution sets of the above macro-analysis between the two conflicting objectives the economic objective (Z_1^{ALLC}) and the equivalent emitted CO_2 ($Z_2^{CO2\text{-}emitted}$). The compromise solution sets' optimal values for efficiency lie in between 10% to 20%. These efficiencies can also be found in commercial PV modules. The Trade-off cost of saving a kg-eq CO_2 from energy imports is much higher for systems with LEC greater than grid tariff at 41.3p/kWh.

The above macro-analysis was based on the additional annual cost required by minimising 1kg-eq CO_2 from the domestic environment, the trade-off. In this analysis, the domestic environment economic benefit / loss is expressed with NPV of the system. Hence the trade-off relationships between the two conflicting objectives the economic objective (Z_1^{NPV}) and the environmental objective ($Z_2^{CO2\text{-}Benefit}$) are shown in Figure 7.9 under various scenarios in Table 7.2. The NPV is decreased as the CO_2 mitigation is increased. NPV greater than zero represents profitable investment. Having a higher LEC than grid, investment is not profitable at any point and hence the trade-off begins from 0. With energy storage, the trade-off extends to lower NPV to mitigate CO_2 impact. Again, the MO formulation considers a maximum available area of 25m^2, the latter a typical household roof area. Similarly, the formulation also assumes a threshold in energy storage of up to 100kWh.

Table 7.5: Summary of the Compromise Solution Sets for the scenarios in Table 7.1

CS metrics	Obj1 (*ALCC*) £	Obj2 (*CO_2*) kg-eq CO_2	η_{PV} %	*f*	S_{max} kWh	I_{max} kWh	C_{BOM} £/m²	Trade-off at £/kWh
Scenario 1:								
L_1	681.71	753.88	14.27	0.30	n/a	2.09	36.65	-0.15
L_∞	688.14	711.37	14.67	0.31		2.15	37.97	
Scenario 2:								
L_1	1479.92	875.96	13.11	0.30	1.90	1.90	166.77	-0.74
L_∞	1491.09	860.87	13.25	0.30	1.92	1.92	168.71	
Scenario 3:								
L_1	1928.36	213.33	11.10	0.36	n/a	1.72	251.62	-0.73
L_∞	1934.67	204.80	11.14	0.36		1.73	252.71	
Scenario 4:								
L_1	1065.04	303.26	10.21	0.31	n/a	1.55	127.72	-0.75
L_∞	1137.29	207.04	11.13	0.32		1.70	140.04	
Scenario 5:								
L_1	1460.70	895.35	12.98	0.35	0.92	1.61	165.00	-0.73
L_∞	1433.33	932.27	12.62	0.34	0.76	1.57	160.14	
Scenario 6:								
L_1	1007.12	1103.96	10.94	0.28	n/a	1.55	137.58	-0.74 / -0.72
L_∞	1171.38	882.49	13.05	0.30		1.89	165.94	
Scenario 7:								
L_1	223.49	323.16	18.36	0.32	n/a	2.76	14.06	-0.04
L_∞	227.92	207.54	19.46	0.32		2.95	15.49	
Scenario 8:								
L_1	1171.38	882.49	13.05	0.30	0.00	1.89	165.94	-0.75 / -0.72
L_∞	1007.12	1103.96	10.94	0.28	0.00	1.55	137.58	

Figure 7.10 shows the optimal values of the PV module sizing (A_{PV}), in relation to the weight, *w,* which measures the importance to the economic objective (NPV). It is shown that the sudden increase in the area / sizing is just within marginal importance to the environmental objective. On the other hand, energy storage was only considered at mid-range ($w = 0.5$).Table 7.6 summarises the compromise solution sets of the above analysis between the two conflicting objectives the economic objective (Z_1^{NPV}) and the environmental objective ($Z_2^{CO2\text{-}Benefit}$). The compromise solution sets' optimal values for area lie in between 0 to 16m². Under the investigated emerging PV developments, the abatement



Plots are plotted with the NNC method. Dotted points represent the WM results.

Figure 7.9: Trade-off relationships scenarios between Z_1^{NPV} and $Z_2^{CO2\text{-}Benefit}$

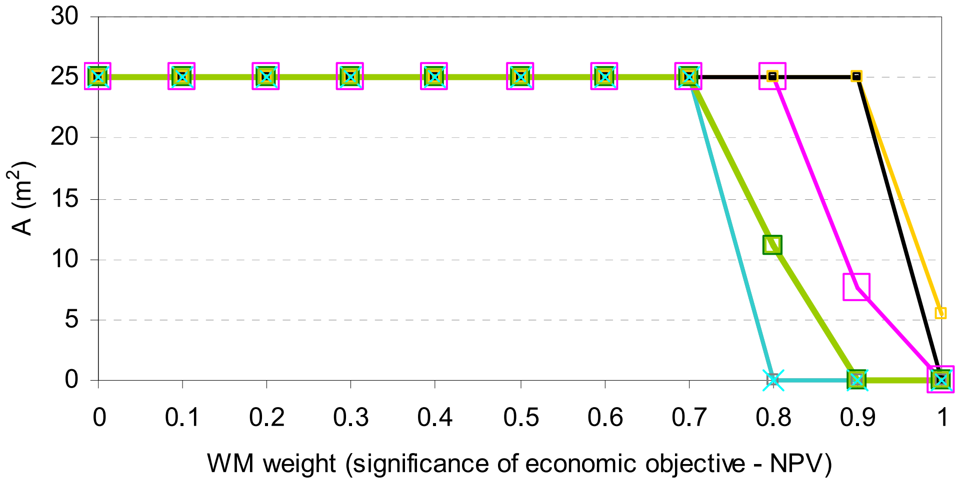


Figure 7.10: Optimal design variable - A_{PV} for multi-objective Z_1^{NPV} vs $Z_2^{CO2\text{-}Benefit}$

Table 7.6: Summary of the compromise solution sets for the scenarios in Table 7.2

CS metrics	Obj1 (NPV) £	Obj2 (CO_2) kg-eq	A_{PV} m^2	Abatement Cost £/kg-eq CO_2	Trade-off at £/kg-eq CO_2
Scenario 1:					
L_1	-731.03	49685.50	12.80	0.06	0.00
L_∞	-738.87	49583.50	12.90		
Scenario 2:					
L_1	-193.81	43880.20	16.01	0.01	-0.03
L_∞	-192.40	43922.50	15.97		
Scenario 3:					
L_1	-2163.36	57125.40	12.68	0.38	-0.39
L_∞	-2262.91	56871.30	13.25		
Scenario 4:					
L_1	-1469.64	56767.60	12.93	0.24	-0.24
L_∞	-1590.39	56301.40	13.93		
Scenario 5:					
L_1	0.00	62800.30	0.00	0.35	-0.24
L_∞	-1283.31	59081.10	7.97		
Scenario 6:					
L_1	-1283.31	59081.10	7.97	0.35	-0.35
L_∞	0.00	62800.30	0.00		
Scenario 7:					
L_1	0.00	62800.30	0.00	0.09	-0.35
L_∞	-733.94	54802.00	3.75		
Scenario 8:					
L_1	0.00	62800.30	0.00	0.06	-0.06
L_∞	-597.75	52989.80	3.83		

cost to mitigate CO_2 emissions from the grid is lower for emerging technologies than for mature technology at the compromise solution set.

7.6 Conclusion

This chapter has considered the hypothetical introduction of grid-connected PV systems using emerging PV technologies in a domestic environment, using MO approach. The approach was applied on the end-user interest (micro level) and public interests (macro levels).

The mathematical model described in this chapter was developed to determine and demonstrate the cost of integrating emerging PV technologies within a domestic environment under different scenarios. In return, the model suggests a compromise set between two conflicting objectives which include the optimal integration point of any scenario under consideration.

For a fixed available area and PV LEC, the optimal efficiency, energy storage capacity and grid rating are decided, which in turn will result in an optimal PV load contribution and BOM cost for a particular fixed lifetime. On the other hand, for optimal system sizing, the PV module area is suggested together with the energy storage capacity and grid rating under any BOM module developments on efficiencies, lifetime and costs.

According to the investigated studies the results can be summarised as follows:

- The trade-off relationships, between the end-user interests (micro level) or public interests (macro level), and economic objective, were clarified from a set of non-inferior optimal solutions obtained by this MO approach.
- The influence of higher and lower radiation due to BIPV applications and different locations were also clarified within a MO approach
- There are particular acceptable technical specifications to be met for integrating emerging PV technologies. Hence markets can be searched and prioritised by geographical location, market segments and / or household use, dependent on the solar cell characteristics.
- Future support policies may be required to consider this presented conceptual framework in order not to opt for a costly abatement cost. There is a potential that, under no subsidies, low efficient PV solar cells trade-off objectives are favourable compared to high efficient solar cells.
- Storage systems still require further development for low costs and CO_2 impact.

Although the case studies are related to scenarios, locations and electricity tariffs, this PV system integration framework draws attention to the optimal and compromise characteristics of PV modules in a PV system and also the optimal and compromise sizing of a PV system.

8

Decision Support System for Ranking PV Technologies

This chapter emphasises the need for a decision support system when designing a PV system. Hereinafter, a review on the use of ELECTRE III and similar ranking methods in RE applications is given. The ELECTRE III algorithm is then described. Next, the design and implementation of the decision support tool and its evaluation are discussed. Finally, a summary of the main points on PV technology ranks for micro-generation is given.

8.1 Introduction

The decision on a PV technology is based on the compilation and integration of a series of factors. The overall assessment combines the most relevant technical, economic and environmental parameters that determine the selection of a PV technology, particularly when the number of PV technologies and systems are diversified. This requests the overall consideration of the location, the available PV area, the performance of the technology within a system, the efficiency offered by the PV technology, the economics of the system and CO_2 impact; an approach leading to a number of alternative solutions. The application of multi-criteria analysis (MCA) can combine the various viewpoints into a standardised evaluation procedure.

8.2 Review on the application of ELECTRE III

Using MCA methods, like ELECTRE III and their variants, has increased many folds in the past few years, by helping decision makers (DMs) choose one alternative from a discrete set [37, 187-191]. This chapter produces a customised ranking of PV Technologies within a domestic environment system using ELECTRE III reflecting political, customer and system installers' perspectives giving importance to certain criteria. Current PV programs modelling PV systems produce feasibility studies including potential energy production indications. However, comparison is very difficult, and choice is only based on the available equipment by the contractor or database available.

MCA models and approaches are available in the literature, such as the multi-attribute utility theory, analytic hierarchy process, weighted sum and others [187]. From the outranking methods, the ELECTRE III method, defined in section 8.3, was chosen as it makes use of the discordance concept and do not hold "structural properties" in outranking relations, which may turn out to be a difficult task [192]. Specifically from the ELECTRE family, ELECTRE III method is appropriate if the relative importance of criteria can be quantified, while other approaches are specifically designed for selection problems (ELECTRE I) and problems assignment (ELECTRE TRE). On the other hand, the other outranking ELECTRE II method is an old version of ELECTRE III and ELECTRE IV is used when quantification is not possible. As a highly developed MCA model, the ELECTRE III model allows for the uncertainty and ambiguity that is found in predictions and estimations. However, there are other decision modelling approaches, having other various advantages. Though, there is no difference in robustness, for example, between SMART and ELECTRE methods even though there are clear differences in the approaches [193]. However, when deciding on one method between SMART, PROMETHEE and ELECTRE, ELECTRE III method is preferred due to its superior features, discussed above, of partially having non-compensatory treatment of the problem and proportional thresholds for imprecise data [194].

The ELECTRE family has been extensively used in environmental assessment and appraisal, and engineered infrastructure investment [194-203]. The method has also been widely applied in a number of models and tools based on outranking approaches for multiple criteria decision making (MCDM) and multiattribute rating techniques. These applications were applied to municipal solid waste management [198, 204-212], personalised ranking of British Universities [213], investment stock selection [214], sustainable demolition waste management strategy [215], energy systems selection [216], thin-film PV technology processes [217], urban storm water drainage [218] and housing evaluation [219]. However, ranking PV systems have not been yet performed. Most of these approaches provided excellent insight in related to complex problems, which involved conflicting objectives among different stakeholders. In conclusion, the choice of ELECTRE III was also influenced by the above, successful applications.

8.3 The ELECTRE III method

The ELECTRE III method is part of the ELECTRE, ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality), outranking decision making family within multi-criteria decision analysis methods that originated in Europe in the mid-1960s. Bernard Roy and his colleagues at SEMA consultancy company developed this method to solve concrete, multiple criteria, real-world problem on firms' new activities using a weighted sum technique. Though at first the ELECTRE method was to find the best action(s) from a given set of actions, the method was further developed for ranking and sorting [220].

Similar to other outranking methods, the ELECTRE III method, is based on 'partial comparability'. Therefore, it makes use of four binary relations: I, indifference; P, heavy preference; Q, light preference and R, non-comparability. In addition, thresholds of preference (p), indifference (q) and veto (v) are used. The use of pseudo-criteria was introduced so that the method allows for imprecise, indeterminate and uncertain criteria intrinsic to complex human being decision processes. The decision is chosen by ranking and sorting among pre-determined decision alternatives described by their attributes in discrete decision space.

The construction and the exploitation of the outranking relations are the two distinct phases of the ELECTRE III method illustrated in Figure 8.1. Construction of the outranking relation is performed by comparing alternatives in pairs to discover which alternative is quantitatively better. This is called pairwise comparison. Each pairwise comparison has an outranking relation. Exploitation of the outranking relation is performed by constructing two pre-rankings with two opposite procedures, ascending and descending order. The combination of these two pre-ranking gives the final ranking.

8.3.1 Construction of the outranking relations

The indifference (q) and preference (p) and veto (v) thresholds permit a pseudo-criterion to build the concordance index and the discordance index.

8.3.1.1 Concordance index

The concordance index in (8.1) indicates the truthfulness of the assertion "alternative A outranks alternative B". If $C = 1$, the assertion is true, and, if $C = 0$, the assertion is false. The graphical representation is illustrated in Figure 8.2.

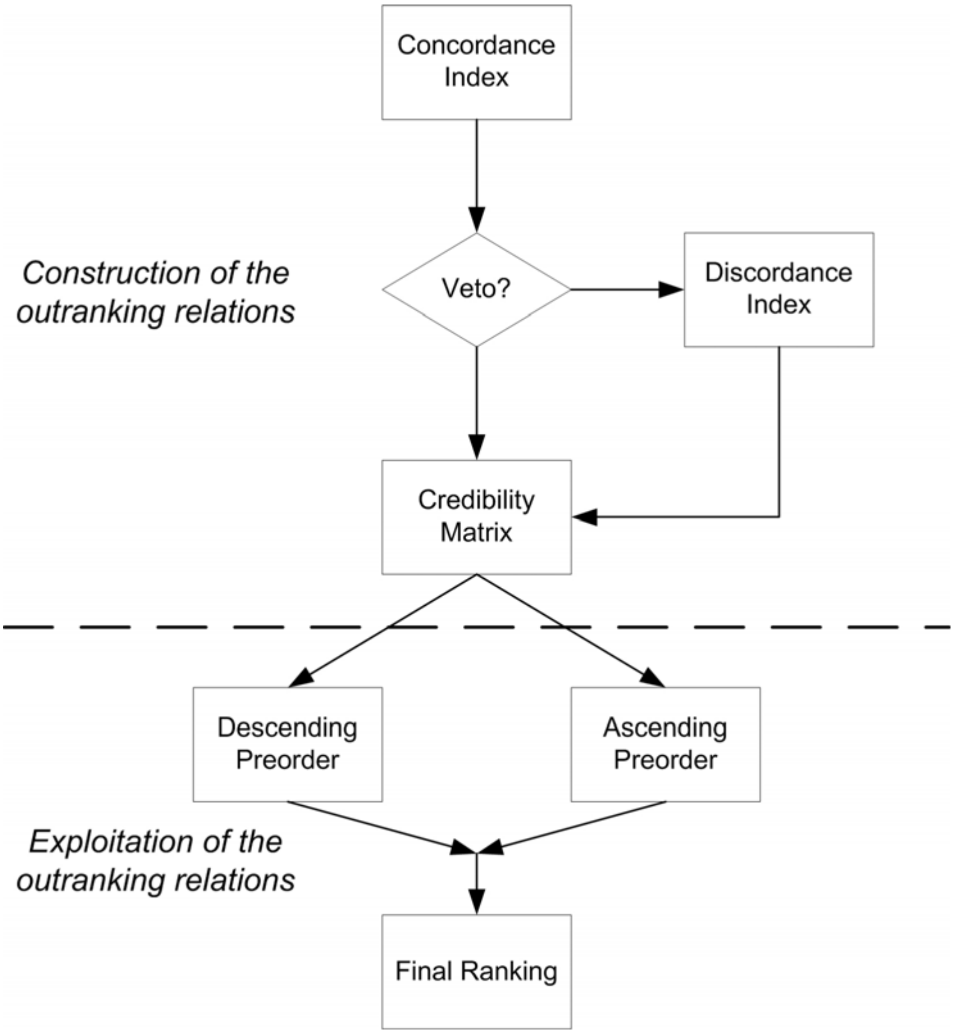


Figure 8.1: ELECTRE III process flow

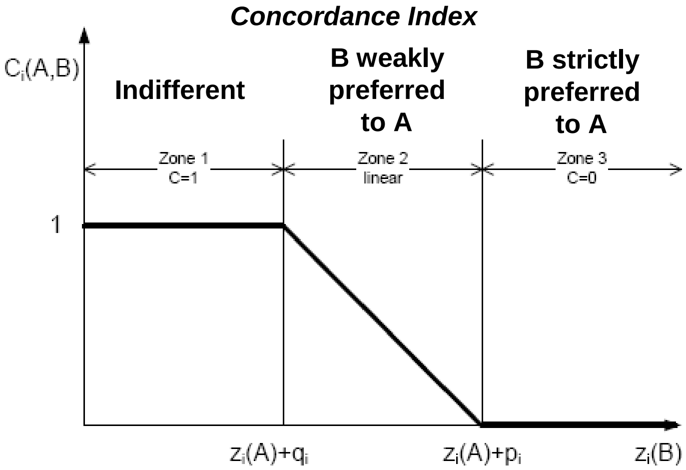


Figure 8.2: Graphical representation of the Concordance Index

$$c_i(A,B)=\begin{cases} 1 & \text{if } z_i(B)-z_i(A)\le q_i \\ \dfrac{p_i(z_i(A))+z_i(A)-z_i(B)}{p_i(z_i(A))-q_i(z_i(A))} & \text{if } q_i \le z_i(B)-z_i(A)\le q_i \\ 0 & \text{if } z_i(B)-z_i(A)\ge p_i \end{cases} \tag{8.1}$$

$$C(A,B)=\frac{1}{W}\sum_{i=1}^{n} w_i c_i(A,B)$$

$$\text{where } W=\sum_{i=1}^{n} w_i$$

where:

w_i is the criterion (i) weight,

n is the criteria number,

$z_i(X)$ is the performance of the alternative X with respect to the criterion,

q_i is the indifference threshold for the criterion i, and

p_i is the preference threshold of the alternative on the criterion i

Hence, from Figure 8.2, the three relations between two alternatives A and B are:

i. Indifference (A ***I*** B): $z_i(B)-z_i(A)\le q_i$, is an agreement on the statement “A outranks B”

ii. Weakly Preferred (A ***Q*** B): $q_i<z_i(B)-z_i(A)<p_i$, is a part agreement on the statement “A outranks B”

iii. Stricly Preferred (A ***P*** B): $z_i(B)-z_i(A)\ge p_i$, is a disagreement on the statement “A outranks B”

8.3.1.2 Discordance index

The optional discordance index is used to be cautious measure to refuse the assertion “A outranks B”, if the discrepancy of performances between the alternative A and B is higher than the veto threshold v_i, on a criterion i. The discordance index for each criterion i is given in (8.2). The graphical representation is shown in Figure 8.3.

$$D_i(A,B)=\begin{cases} 0 & \text{if } z_i(B)-z_i(A)\le p_i \\ \dfrac{z_i(A)-[z_i(A)+p_i]}{v_i-p_i} & \text{if } p_i\le z_i(B)-z_i(A)\le v_i \\ 1 & \text{if } z_i(B)-z_i(A)\ge v_i \end{cases} \tag{8.2}$$

where:

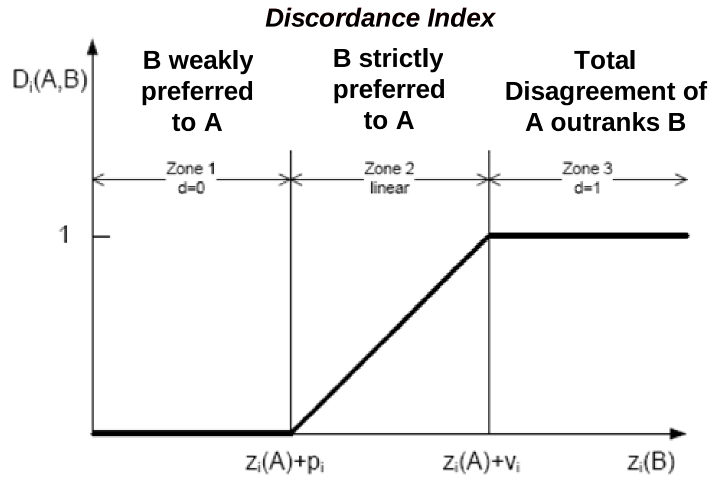


Figure 8.3: Graphical representation of the Discordance Index

$z_i(X)$ is the performance of the alternative X with respect to the criterion i,
p_i is the preference threshold of the alternative on the criterion i, and
v_i is the veto threshold for the criterion i.

From Figure 8.3, if there is veto threshold, the three relations between two alternatives A and B are:

i. Indifference (A ***I*** B): $z_i(B)-z_i(A)\leq p_i$, is an agreement on the statement "A outranks B"
ii. Weakly Preferred (A ***Q*** B): $p_i<z_i(B)-z_i(A)<v_i$, is a weak disagreement on the statement "A outranks B"
iii. Strictly Preferred (A ***P*** B): $z_i(B)-z_i(A) \geq v_i$, is a disagreement on the statement "A outranks B"

8.3.1.3 Credibility matrix

The Credibility Matrix, using the concordance and discordance indices, is constructed in (8.3). The Credibility Matrix indicates if the outranking hypothesis is true or false. The degree of credibility is equal to the concordance index, in the case of concordance index being higher or equal to the discordance index of all criteria. Otherwise, the degree of credibility is equivalent to the concordance index directly related to the magnitude of those discordances.

$$S(A,B)=\begin{cases} C(A,B) & \text{if } D_i\left(A,B\right)\le C(A,B)\forall i \\ C(A,B)\bullet\prod_{i\in J(A,B)}\dfrac{\left(1-D_i\left(A,B\right)\right)}{\left(1-C\left(A,B\right)\right)} & \text{otherwise} \end{cases} \tag{8.3}$$

where $J\left(A,B\right)$ is the set of criteria for which $D_i\left(A,B\right)>C\left(A,B\right)$

8.3.2 Exploitation of the outranking relations

8.3.2.1 Distillation procedures

The distillation procedure ranks the alternatives in two pre-orders. The first pre-order is found with a descending distillation, by selecting the best-rated alternatives initially and finishing with the worst ones. The best alternatives are extracted from the whole set of alternatives by applying very strict rules of (8.4). Within this sub-set, the best alternatives are then selected by applying less stringent rules of (8.6). The procedure continues with incrementally minor restrictive rule and incrementally minor sub-sets of alternatives. The procedure finishes when only one alternative is leftover or a set of alternatives cannot be disconnected. The second ascending distillation uses the same process. This distillation is performed on the original set of alternatives, by removing alternative(s) from the best ones resulted from first distillation. Therefore, a fresh sub-set is found at each distillation. This sub-set will contain the best alternative(s) of the outstanding set. At every distillation, the found alternative(s) are ranked on a lower position. Hence, the worst rated alternatives are selected first. For the distillation, the hypothetical condition is that an alternative A is preferred to B if the degree of credibility of "A outranks B" is above a threshold λ_2, and considerably above the degree of credibility "B outranks A" in (8.4).

$$S\left(A,B\right)>\lambda_2 \text{ AND } S\left(A,B\right)-S\left(B,A\right)>s\left(\lambda_0\right) \tag{8.4}$$

where λ_2 is the principal credibility index, just underneath the cut-off level λ_1 as follows:

$$\lambda_2=\max_{\{S(A,B)\le\lambda_1\}} S\left(A,B\right) \qquad \forall\left\{A,B\right\}\in G \tag{8.5}$$

where G is the group of alternatives. λ_1 is the subsequent cut-off level:

$$\lambda_1=\lambda_0-s\left(\lambda_0\right) \tag{8.6}$$

where λ_0 is the uppermost degree of credibility in the subsequent credibility matrix:

$$\lambda_0=\max_{A,B\in G} S\left(A,B\right) \tag{8.7}$$

and $s(\lambda_0)$ is the following discrimination threshold:

$$s(\lambda_0) = \alpha + \beta\lambda_0 \tag{8.8}$$

where α=0.3 and β=-0.15 are the two values recommended [220]

With successive distillations, the cut-off level λ_1 is reduced every time, making the condition weaker. Therefore, it is much easier for A to be preferred than B. The discrimination threshold $s(\lambda)$ contains some parameters values α and β, recommended at $\alpha=0.3$ and $\beta=0.15$ [220]. Other values may be used but may change the ranking, to some extent.

8.3.2.2 Extraction

The extraction from the distillation procedure is performed on scores. Whenever A outranks B, A has a score of +1 (strength) and B is given -1 (weakness). The final qualification score for each alternative is the sum of the strengths and weaknesses. For the descending distillation, the highest qualification scored alternative is ranked and removed from the credibility matrix. This process is repeated until all alternatives remaining are ranked. If two or more alternatives result with the identical qualification score, the process is done again within this subset. If an alternative has a higher qualification score, the alternative is ranked. On the other hand if the utmost degree of credibility λ_0 is equal to 0, then alternatives are declared indifferent. Similarly, ascending distillation procedure extraction is an iterative process with the difference that alternatives are chosen with the lowest qualification score.

8.3.2.3 Final ranking

The final ranking is the collective results of the two pre-orders into a ranking matrix with the following four possible cases:

i. A **P+** B: A is better than B (i.e. A is ranked over B in both distillations, or A is higher than B in one distillation, and has the identical ranking in the other distillation),

ii. A **R** B: A is incomparable to B (i.e. A is ranked over than B in one distillation but B is ranked over A in the other distillation),

iii. A **I** B: A is indifferent to B (i.e. A has the same ranking than B in both distillations), and

iv. A **P-** B: A is worse than B (i.e. A is ranked below B in both distillations or A is ranked below B in one distillation and has the identical rank in the other distillation).

The final ranking is achieved by adding the number of **P+**. In case of same scores, the similarity between the two alternatives with the identical score decides between an indifferent or incomparable relation.

8.4 The evaluation criteria

The alternative scenarios for PV micro-generation were compared with economic, technical and environmental categories, to perform an overall assessment. For these different categories, the most relevant parameters were chosen as shown in Table 8.1.

The importance of criteria differs from different stakeholder. The importance is reflected in weightings for the respective criteria. Three different perspectives are considered in this study. These perspectives have different allocated weights on criteria. These are political, customer and contractor. The case study is based on the 4 Bed gas and electricity category, grid-connected PV system at optimal slope in UK Manchester under no financial support schemes. Hence the presented results and calculations are based on the specific assumptions. Thus, the results and discussions in this chapter must be seen in this context. Though, the framework developed can be applied with other assumptions. The studied alternative scenarios compare PV technologies on a 25m^2 available area for micro-generation. These are presented in Table 8.2.

The quantitative criteria, that are PV contribution, Net kg-eq CO_2 and Net Present Value (NPV), are calculated for a system lifetime of 30 years, as defined in previous chapters. The energy management system using an optimised time series simulation considers distinct PV technology parameters including PV module efficiency, PV module efficiency degradation limit, system performance ratio and CO_2 content during manufacturing.

Table 8.1: The different chosen criteria for evaluation and their meaning

Technical	C1	PV Contribution (f_{PV})	PV to local load contribution (ratio)
	C2	Module Design	Indication of flexibility
Environmental	C3	Net kg-eq CO_2	Net CO_2-eq (surplus / deficit)
	C4	Aesthetic	Indication of the level of Aestheticity possible
Economic	C5	Net Present Value	Net Present Value of the PV system
	C6	Maturity	Indication of the maturity of the module technology

Table 8.2: Possible PV technology alternatives for PV micro-generation

			Technology Assumed and Estimated Parameters						
			Technical				**Environmental**		**Economic**
		Technology	*PR*	η_{PV}	δ_{PV}	L_{PV}	*MJ/m*^{2}	*kg-eq CO*$_2$	*£/m*^{2}
Alternative 1	A1	mono-Si	0.85	22%	80%	30	6034	241	660
Alternative 2	A2	multi-Si	0.82	17%	80%	30	3870	155	510
Alternative 3	A3	a-Si	0.94	9%	80%	30	1110	44	248
Alternative 4	A4	CIS	1	11%	80%	30	2965	118	366
Alternative 5	A5	CdTe	0.66*	11%	80%	30	1828	73	366
Alternative 6	A6	emerging PV (a)	1	5%	50%	5	-	30	50
Alternative 7	A7	emerging PV (b)	1		50%		-	30	
Alternative 8	A8	emerging PV (c)	1		50%		-	30	
Alternative 9	A9	emerging PV (d)	1		50%		-	30	

*This was one of the first PR calculated on a demostration modules. PR for CdTe may have improved significantly

(b), (c) and (d) refer to reference, optimistic and pessimistic technology anticipated development respectively in efficiency, lifetime and price of emerging PV technologies

The qualitative measures are other elements taken into account. These are ranked from 1 to 3, the higher the number, the better the alternative. Module Design reflects the flexibility of the PV module within a system design for BIPV and ease of installation. Aesthetic measure reflects the possible visual impact of the modules. In general BIPV systems, possibly frameless modules, have lower visual impact than bolt-on solutions. Maturity of the PV technology indicates the needs for more research and development investments. Hence mature technologies tend to be less expensive than emerging technologies due to learning by doing attitudes.

Table 8.3 presents the performances of the nine alternative solutions, which originate from the estimates and assumptions in Table 8.2, from the different analytical approaches in previous chapters namely NPV, f_{PV}, and the CO_2 emissions. The data for qualitative criteria are relative values, which are compared with each other. These values reflect the technology status under three technologies namely crystalline modules, thin-film and emerging technology. It is evident that no scenario stands out completely from others in all criteria, which entails a multi-criteria analysis.

8.5 Weights and threshold values

The thresholds and the importance coefficients are listed in Table 8.4. The calculated

Table 8.3: Performance of alternative scenarios

	$C1^+$	$C2^+$	$C3^-$	$C4^+$	$C5^+$	$C6^+$
A1	0.34	1	(19439)	1	(14242)	3
A2	0.32	1	4531	1	(9957)	3
A3	0.29	2	26186	2	(3763)	2
A4	0.31	2	16713	2	(6527)	2
A5	0.28	2	32260	2	(6856)	2
A6	0.22	3	48725	3	(2123)	1
A7	0.26	3	32570	3	(967)	1
A8	0.28	3	28076	3	248	1
A9	0.20	3	49281	3	(3503)	1

+ high values are best alternatives

- low values are best alternatives

indicators are based on estimations and assumptions. The selected threshold are 15% for the indifference threshold, 30% for preference threshold and 3 times of performance threshold, that is 90% veto threshold as suggested [195, 221]. On the other hand, the qualitative indicators' thresholds were given as 1 for the indifference threshold and 1.5 for preference threshold.

The Simos method with updates [201, 222-225] was used to calculate the weights. The weights are first given to the quantitative criteria followed by the qualitative ones. The political perspective which is the basis for any renewable support schemes in which case would anticipate a balance between all categories. Hence equal weights to the categories are assigned. Table 8.5 shows the calculation for the political perspective with all categories having equal ranks on the quantitative and qualitative indicators respectively. The other weights for other perspectives, customer and contractor, are given in Table 8.4.

Table 8.4: Weights and threshold values

Criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Indifference (*q*)	15%	1	15%	1	15%	1
Preference (*p*)	30%	1.5	30%	1.5	30%	1.5
Veto (*v*)	90%	n/a	90%	n/a	90%	n/a
Political Importance (*weight*)	0.259	0.074	0.259	0.074	0.259	0.074
Customer Importance (*weight*)	0.238	0.095	0.19	0.048	0.29	0.143
Contractor Importance (*weight*)	0.271	0.104	0.208	0.042	0.271	0.104

Table 8.5: Calculating criteria weight using the Simos Method.

Ranking r[a]	Criteria	No. of Criteria in Rank	Weight, W	Average Weight	Relative Weight	Total
1	C2 C4 C6	3	1, 2, 3	(1+2+3)/3=2	7.41	22.22
2	-	-	(4)	-	-	-
3	-	-	(5)	-	-	-
4	C1 C3 C5	3	6, 7, 8	(6+7+8)/3=7	25.93	77.78
5	-	-	(9)	-	-	-
6	-	-	(10)	-	-	-
		6	27[b]			100.00

a - from worst to best

b - sum of weight excluding parenthesis

Political Perspective

The weights of the different criteria of these categories are discussed. The political perspective, which is the baseline of this study, considers equal importance to technical, environmental and economic parameters, as described in the previous section. Since the social behaviour was not studied, the rankings of the criteria for the customer and the contractor were based on a similar study for battery technologies for electric vehicles [226]. Customers and contractors tend to look more into the technical and economic criteria rather than the environmental one.

The customer perspective is driven by economic benefit. Customers do not often take into account the PV contribution, whether there is a net export or import. Hence this parameter is of less important than the political perspective. On the other hand, the flexibility of a technology can make a difference for available area and hence such parameter may have a slightly higher importance to customers. The closer the NPV is to 0 or above, the greater potential benefit. In addition, the maturity of the technology will probably attract attention due to its reliability.

The manufacturer is driven mainly in balance by the technical and economic indicators. Hence the weights for these criteria are equal or slightly higher than the political perspective.

8.6 Sensitivity analysis

Different perspectives are assessed and compared in this study. These perspectives are the sensitivity analysis of the MCA results. This sensitivity, using different weights, analyses the results from the three perspectives. Each perspective has different criteria preferences signified by their weights.

Further sensitivity analysis on the thresholds of the model is performed in order to identify the effect on the original results. The sensitivity was done on the p, q and v by varying the initial values at ±10% and ±20%.

8.7 Results and discussions

The calculations for the multi-criteria model ELECTRE III were implemented by the ELECTRE III program which was made available for academic purposes [227]. The final ranking of all the alternatives under three perspectives is shown in Figure 8.4.
Table 8.6 is the result scores for the degree of credibility matrix for the political perspective, calculated from the concordance and discordance matrixes. Meanwhile, Table 8.7 is the corresponding ranking matrix, described in section 8.3.1.1.

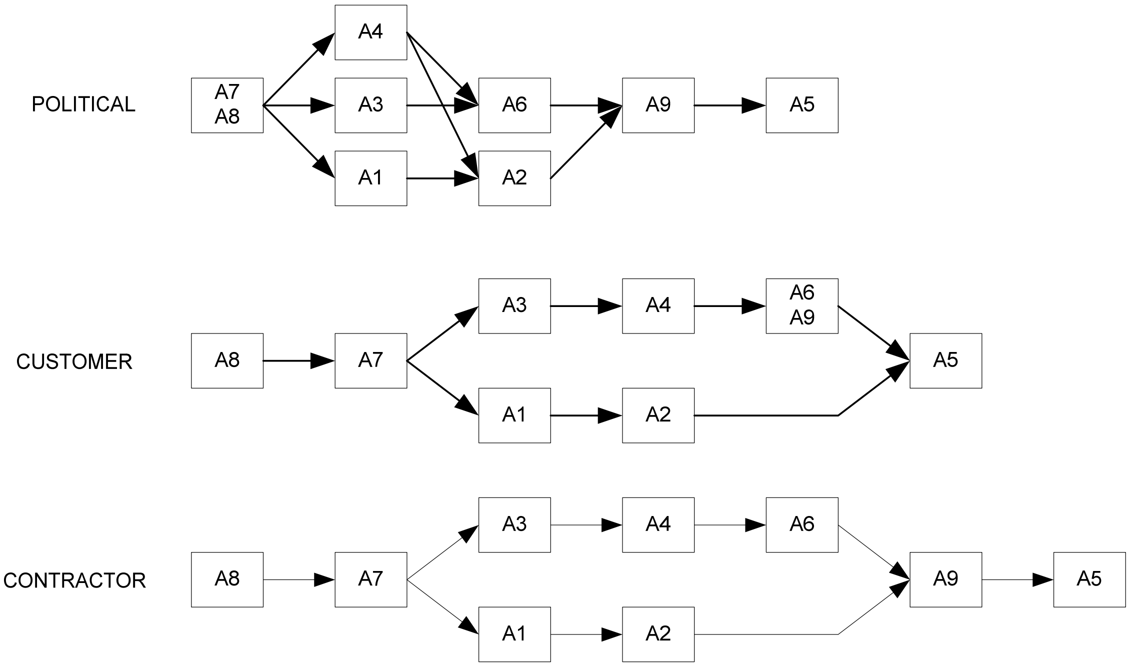


Figure 8.4: Final Ranking under three perspectives

Table 8.6: Credibility Matrix for the political perspective

	A1	A2	A3	A4	A5	A6	A7	A8	A9
A1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A2	0.00	1.00	0.00	0.47	0.74	0.00	0.00	0.00	0.00
A3	0.00	0.74	1.00	0.90	1.00	0.99	0.80	0.74	1.00
A4	0.00	0.74	0.74	1.00	1.00	0.74	0.74	0.10	0.74
A5	0.00	0.74	0.74	0.74	1.00	0.74	0.49	0.00	0.74
A6	0.00	0.29	0.48	0.48	0.63	1.00	0.79	0.45	1.00
A7	0.00	0.53	1.00	0.67	1.00	1.00	1.00	1.00	1.00
A8	0.00	0.67	1.00	0.85	1.00	1.00	1.00	1.00	1.00
A9	0.00	0.24	0.48	0.48	0.57	1.00	0.43	0.22	1.00

Table 8.7: Ranking Matrix for the political perspective

	A1	A2	A3	A4	A5	A6	A7	A8	A9
A1	I	P	R	R	P	R	P-	P-	P
A2	P-	I	R	P-	P	R	P-	P-	P
A3	R	R	I	R	P	P	P-	P-	P
A4	R	P	R	I	P	P	P-	P-	P
A5	P-	P-	P-	P-	I	P-	P-	P-	P-
A6	R	R	P-	P-	P	I	P-	P-	P
A7	P	P	P	P	P	P	I	I	P
A8	P	P	P	P	P	P	I	I	P
A9	P-	P-	P-	P-	P	P-	P-	P-	I

The top-ranked alternatives are A7 and A8. These alternatives are for certain assumed emerging PV technology developments over system lifetime. These assumed developments are based on a reference (stated targets) or optimistic technology development, discussed in section 4.4. These alternatives gained their high rank mainly due the quantitative economic benefit, high NPV, because of low capital investment costs. It should be mentioned that these technologies are still in the experimental stages. Hence, one cannot distinguish which emerging technology will ultimately make a successful development process in accordance to the assumptions and estimates taken. The next alternatives are crystalline silicon and thin film technologies (CIGS and amorphous Si) which are incomparable as seen in Figure 8.4. The alternatives that follow are for emerging technologies with fixed replacements and no technology developments and pessimistic developments (A6 and A9 respectively). Meanwhile, it is important to note that alternative A5 (CdTe) scored last mainly due to is low PR. Over the last years, PR for this technology might have significantly improved. In fact assuming a more plausible PR of 0.80 for all technologies will range A5 (CdTe) with other A4 (CIGS) as shown in Figure 8.5. Applying sensitivity to the threshold values of the model for the results in Figure 8.4 shows stability especially in the top ranks of the final ranking as seen in Table 8.8.

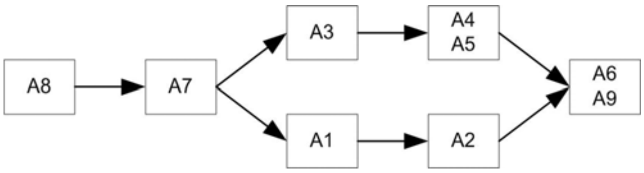


Figure 8.5: Final ranking under all three perspectives with 0.80 PR

Table 8.8: Sensitivity analysis

Sensitivity	*Final Ranking*	*Sensitivity*	*Final Ranking*
Political: A8 A7 - A1 A3 A4 - A2 A6 - A9 - A5			
-10% (q)	stable	*-20% (q)*	stable
+10% (q)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	*+20% (q)*	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5
-10% (p)	A8 A7 - A1 A3 A4 - A2 A6 A5 - A9	*-20% (p)*	A8 A7 - A1 A3 A4 - A2 A6 A5 - A9
+10% (p)	A8 - A7 - A1 A3 - A2 A4 - A6 A9 - A5	*+20% (p)*	A8 - A3 A7 - A4 A1 - A6 A2 - A9 - A5
-10% (v)	A7 A8 - A1 A3 A4 - A2 A5 - A6 A9	*-20% (v)*	A7 A8 - A1 A3 A4 - A2 A5 - A6 A9
+10% (v)	A7 A8 - A1 A3 A4 - A2 A6 A9 - A5	*+20% (v)*	A7 A8 - A3 A4 - A2 - A5 A1 - A6 A9
Customer: A8 - A7 - A1 A3 - A2 A4 - A6 A9 - A5			
-10% (q)	stable	*-20% (q)*	A8 A7- A1 A3 - A2 A4 - A6 A9 - A5
+10% (q)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	*+20% (q)*	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5
-10% (p)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	*-20% (p)*	A7 A8 - A1 A3 A4 - A2 A6 - A9 - A5
+10% (p)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	*+20% (p)*	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5
-10% (v)	A8 - A7 - A1 A3 - A2 A4 - A6 A9 A5	*-20% (v)*	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 A5
+10% (v)	stable	*+20% (v)*	A8 A7 - A3 A4 - A2 - A1 - A6 A9 - A5
Contractor: A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5			
-10% (q)	stable	*-20% (q)*	A8 A7 - A1 A3 - A2 A4 - A6 - A9 - A5
+10% (q)	stable	*+20% (q)*	stable
-10% (p)	A8 A7 - A1 A3 - A2 A4 - A6 - A9 - A5	*-20% (p)*	A8 A7 - A1 A3 A4 - A2 A6 A5 - A9
+10% (p)	stable	*+20% (p)*	stable
-10% (v)	A8 - A7 - A1 A3 - A2 A4 - A5 A6 A9	*-20% (v)*	A8 - A7 - A1 A3 - A2 A4 - A5 A6 A9
+10% (v)	A8 - A7 - A1 A3 - A2 A4 - A6 A9 - A5	*+20% (v)*	A8 A7 - A3 A4 - A2 - A1 A5 - A6 A9

8.8 Conclusions

The general conclusions of this MCA study were taken in the context of a number of assumptions and estimates. These assumptions and estimates are the result of the compilation and integration of other sections in this research work and available literature. The comparison of different technologies is always a difficult task as it involves a wide range of parameters. With PV technologies increasing in number over three generations, the assessment of such technologies on an application is not an exception. The technologies taken into consideration are PV technologies related to a domestic environment. Emerging PV technologies may vary in concepts and approaches. However, general assumptions were taken on these technologies which require meeting certain common requirements before market integration, as seen in previous chapters. These emerging PV technologies seem to be the drive towards the 3rd generation of PV technology.

As we have seen throughout this research, the economic net-benefit for today's commercial PV technology is still hindered by the expensive PV module costs. The research has also investigated a number of scenarios having lower costs and more frequent replacements. The MCA evaluated nine alternative scenarios including developments estimates and assumptions for emerging PV technologies within a domestic environment, by using the ELECTRE III method for three categories: technical, environmental and economic. However, a reduction in cost is needed, and technology developments are required for a preferential ranking. In order to achieve this, market growth is necessary if there is no revolution that changes suddenly PV technology. Hence, financial support is also a key stimulus for emerging PV technologies in a domestic environment. Today thin-film (TF) PV technology and crystalline (c-Si) PV technology are a competitive edge in the market, and this study shows certain insuperabilities. In this context, crystalline technologies are more expensive. However, this PV technology offers a much better CO_2 benefit than emerging technologies due to high efficiency levels.

On a technical point of view, all technologies can have a PV contribution to load in the region of 20% to 34% with respect to the system PR, PV module efficiency and PV module efficiency degradation. However, due to future uncertainty in PV support schemes the issue of PV contribution versus exports is a matter of further discussions.

The environmental impact of PV modules is far less than using other conventional sources of energy. In addition, even though c-Si modules have the highest energy impact amongst technologies, there is a favourable net benefit of CO_2 emission. The reason is mainly due to high module efficiencies. In fact the PV generation is higher than the local demand. This gained in ranking amongst other technologies. Hence, in this context c-Si resulted in a significant environmental ‘positive’ rating.

On the other hand, the overall net economic benefit for c-Si technology is the lowest since there is not much benefit from exports. Meanwhile for emerging technologies the number of replacements distant by time will lower the initial investments costs, something which so far is not common in the PV industry for a PV module.

So far, any PV technology can be integrated within a domestic environment as a sustainable source of energy. Hence this MCA study is a preferential indicator for any PV technology integration within a competitive market under three categories namely technical, environmental and economic.

9

Conclusion

This chapter highlights the main conclusions as well as contributions of the work undertaken in this research and suggests future research work.

9.1 Overview

The introduction of emerging PV technologies for micro-generation has its own challenges with regards to lifetime, efficiencies and price / costs for successful market penetration. In the short and medium term, emerging PV technologies are likely to exhibit low lifetime expectancy and low efficiency, nevertheless low-cost PV modules with more possibilities for BIPV applications. The aim of this research work was to provide complimentary viewpoints from the technical, economic, as well as environmental viability of emerging PV technologies for micro-generation, with a focus on the hybrid organic-based QD solar cells, developed within the project consortium. The uniqueness of this work is that, throughout this research, the issues for commercialisation of emerging PV technologies for micro-generation, regarding to low efficiency, short lifetime and high efficiency degradation, as well as low-cost / price were extensively analysed in every aspect.

Several companies are promising the availability of new cutting edge PV technologies such as SolarPrint, G24innovations, Hydrogen Solar, Dyesol, Aisen Seiki and Sony Corporation, for dye sensitised solar cells, and Konarka, for organic solar cells. Due to the potential of cheaper costs during mass production compared to mature PV technologies, by around one order of magnitude, these technologies are evolving as having the potential for the third generation of PV technologies. This will stimulate much more the PV market growth that has so far been dominated by costly PV modules. On the other hand, hybrid organic-based QD solar cells combine the advantages of both organic and nanoparticle inorganic semiconductors. Hence there is a significant potential for these hybrid organic-based QD solar cells to increase in PV conversion efficiency amongst other characteristics.

Similar to mature TF PV technologies, production of ultra thin flexible PV devices offers the flexibility for a higher potential for BIPV applications. These devices allow easier integration into appliances and building materials, while also being able to tune the solar cell colour through chemical structure [12, 13].

Overall a PV policy framework requires careful understanding of the specific site location that allow threshold for profitable operation of PV plants [228]. However, return on investment is not the only consideration affecting PV support schemes. Sustainability is a key measure which is enabling emerging PV technologies to compete with mature technologies for the micro-generation market. In this respect, the economic value of the project and cost / price of PV modules, the PV module efficiency, the local load fulfilment and the system design rating, as well as the environmental factors, such as EPB-T, NET and CFP, are important features for a holistic commercialisation approach.

Although design, sizing and planning tools for PV micro-generation systems are available, there are presently no adequate approaches to integrate emerging PV technologies in comparison with current PV technologies. In fact, as discussed during the literature review, there is a wide range of methods and approaches to address the integration of PV technologies into energy systems. However, despite the diversity of these methods, none has addressed emerging PV technologies on sustainability competitiveness that includes economic, technical and environmental aspects. Hence this research is novel because it deals with the practical implication of low-cost emerging solar cells coming to the very fast growing PV market, and addresses exhaustively the scenarios for frequent replacements of PV modules within a multi-disciplinary context. This is done by extending and developing methods and approaches already known in this field. The research is conducted at a systems level rather than at component level. This is due to some elements, such as characteristics, system performance, module sizes and inverter integration, which are still unknown at this time.

In general, the conclusions have to be taken in context of the assumptions and estimates taken at the time of the research. However, it is clear that the challenges that emerging PV technologies face to integrate into the micro-generation market can be transferred to opportunities. The following general conclusion can be drawn from this research:

i. Less durable emerging PV technologies may require higher system ratings for same energy production as mature PV technologies, with respect to efficiency degradation. In addition, having low defined efficiency limits with respect to lifetime (that is lower than 80%) may require a diligent system design to maintain system performance and reliability during the module lifetime.

ii. The Price Reduction Factor (PRF) is a good matric to measure competitiveness with mature technologies. PRF less than one order of magnitude is achievable if lifetime is higher than one year, while having a module life expectancy over 10 year will not significantly change this factor. On a cautious note, as system lifetime is extended the PRF is increased.

iii. Hybrid organic-based QD PV modules may be slightly more expensive than OPV. However these advance TF technologies are expected to have better performance than OPV ones. The estimated range with assumed mass-production process in place is between £0.22/Wp and £2.11/Wp. The higher end describes module on glass substrate. The higher end of the range is found not competitive with mature PV modules when considering the durability of emerging PV organic-based thin film modules. Hence flexible module with no glass substrate is recommended.

iv. With a module cost based at £50/m^2 the module performance, efficiency and lifetime require improvement for competitive integration. The BOS costs which nowadays are in comparison with module costs may become even more expensive within a PV system employing emerging PV technologies. Hence BOS costs reductions are also recommended. These above factors are also important so as not to lose the competitiveness with other mature PV technologies already in the market and the grid parity target.

v. The life cycle impact analysis and their evaluation for two structures assumed for hybrid organic-based QD PV module were found to be competitive with other PV technologies. A compromise between PV module lifetime and efficiency can lead to sustainable products. In this case, hybrid organic-based QD PV modules with lifetime and efficiency higher than 5 years and 5% respectively are favourable.

vi. Market penetration can be prioritised by geographical location, market segment and / or household energy consumption with acceptable PV module characteristics: efficiency and price target for a given lifetime, within a domestic environment. Future support policies may be required to consider the presented conceptual framework, that suggests trade-off relationships between the end-user interests (micro level) or public interests (macro level), and economic objective, in order not to opt for a costly abatement cost. There is a potential that, under no subsidies, low efficient PV solar cells trade-off objectives are favourable compared to high efficient solar cells. In addition storage systems still require further development for low cost and CO_2 impact.

vii. Optimistic and targeted progress in emerging organic-based PV, even with higher degradation but same system performance as mature PV technologies, may lead the ranking in PV technology when considering an investment. This showed that development is continuously required for emerging PV technologies to be preferred over mature PV technologies.

9.2 Achievements and contributions of this research

The above issues have been the focus of an extensive literature review of the research on PV technologies for micro-generation. Particular focus has been given to emerging PV technologies and the hybrid organic-based PV QD solar cell developed within the project.

The literature review, which is easily accessible to all stakeholders, including domestic user, manufacturer and policy makers, has highlighted the challenges to the growing interest in emerging PV technologies. Taking into consideration the objectives set out in Chapter 1, the main achievements and contributions of this research are summarised in the following sections.

9.2.1 Investigation and identification of cost boundaries

Economic competitiveness is normally compared on the basis of the following two factors:

i. life cycle energy outputs of the system, and
ii. life cycle investment costs.

These two factors influence the cost / price boundary for any emerging PV technology for micro-generation. The energy production is a function of high efficiency degradation while the project costs depend on future costs arising from regular replacements of PV modules. The developed lifetime-adjusted approach is based on life cycle costing (LCC) techniques. Therefore, it begins with the comparison of energy outputs with current PV technologies within a marketplace, taking into account PV module efficiency, PV module efficiency degradation and lifetime. The investment costs for both emerging and mature PV technologies are then balanced. The main achievement and contribution of this research in the area of the economic competitiveness can be summarised as follows:

A lifetime-adjusted calculation methodology for determining cost boundaries of emerging PV technologies was developed. The methodology takes the following aspects into account:

- Efficiency degradation
- Emerging PV module lifetime
- Emerging PV module efficiency
- System lifetime, and
- Financial parameters

The overall lifetime-adjusted approach was formulated as a two-stage approach for equivalent energy production and then equivalent investment cost when compared to a mature PV technology. This methodology was developed in chapter 3.

As a result of the methodology, the system ratio (*SR*), which is a design factor for equivalent energy production, and price reduction factor (*PRF*) can be estimated. Preliminary indications show a *PRF* of one order of magnitude, which is the expected cost reduction potential in emerging PV technologies, is feasible from a lifetime greater than 2 years even though 3 to 5 years lifetime was suggested in literature as a feasible commercialisation point.

Understanding future PV cost scenarios is critical for the formulation of public policies. It is worth noting that public policies affect the investment outcomes, such as pay-back times, and also the renewable energy (RE) market with regard to variations in supply and demand chains. Hence the upper price boundaries for emerging PV technologies compared with the mature PV technologies are crucial to enter the market competitively [36].

9.2.2 Development of organic-based PV module cost model

The few available cost models on emerging PV technologies, based on DSSC or OPV, do not consider large-scale manufacturing, and therefore, are based on lab-scale production. In addition, cost models for emerging hybrid organic-based QD solar cells do not exist. The first cost model for a hybrid organic-based QD solar cell has been developed in this work. A key feature of this cost model includes the consideration of a large-scale manufacturing, and different efficiency and lifetime considerations. The interest in emerging organic-based QD solar cells is important as these technologies offer the potential for higher efficiencies in the long term.

The developed model was used to carry out further investigations on the impact of a number of factors including efficiency, module lifetime, irradiance, BOS cost and PV energy price. These investigations led to the establishment of boundaries on market geographical location, efficiencies and BOS cost reductions for RE generation from PV to attain grid parity. The anticipated development of emerging organic-based PV technology was also given with respect to price, lifetime and efficiency.

9.2.3 Development of hybrid organic-based PV life cycle analysis

Sustainable weightings on typical hybrid organic-based QD PV modules were developed based on an extended LCA methodology. The LCA methodology was extended to take into account low lifetime, low efficiency PV modules to assess the NER and CFP matrices for the sustainability boundaries, that is lifetime and efficiency. This extended LCA is based on a published contribution by the author [4] and is presented in chapter 5.

Emerging PV technologies LCA, based on DSSC or OPV, do not usually consider system integration. In addition, LCA for hybrid organic-based QD cells does not exist.

This research has also added Life Cycle Inventory for ‘green’ synthesis of PbS QD. Eco-invent database and openLCA software were used to model the whole system integration for a coherent comparison with other PV systems using mature PV technologies.

9.2.4 Development of conceptual multi-objective optimisation framework

A system base level optimisation for the optimal integration of PV technology was developed. Parameters such as optimal efficiency / area, energy storage and grid interconnection were evaluated.

Therefore, the optimisation problem was formulated as an hourly time series mixed integer programming (MIP) for two on-grid PV system configurations namely with and without energy storage. The overall problem minimises the annualised life cycle cost (ALCC) or maximises the NPV of the system on the economic objective. However, other objectives are also considered. These objectives are (i) minimising grid energy imports on a micro-level objective, or (ii) minimising CO_2 emissions on a macro-level objective. These added objectives, which in total consider the economic, technical and environmental factors, formed the basis for development of the conceptual framework for multi-objective optimisation for PV market penetration subject to energy management constraints in a domestic environment, grid interconnection and energy storage response constraints.

Practical application of multi-objective optimisation for a conceptual framework to integrate emerging PV technologies for micro-generation was illustrated on a number of studies. The studies were tailored for a domestic environment. For the case without subsidies, low efficiency, low cost PV solar cells, are favoured compared to high efficient high cost solar cells. In addition, energy storage systems still require further development in order to minimize costs and CO_2 impact. The suitability of this conceptual framework is highlighted in Chapters 6 and 7. This PV system integration framework draws attention to the optimal and compromise characteristics of PV modules in a PV system and also the optimal and compromise sizing of a PV system.

9.2.5 Demonstration of multi-criteria analysis for PV micro-generation

A multi-criteria analysis (MCA), using the ELECTRE III method, was employed to compile and integrate assumptions and estimates presented in this research work. This is the first time PV technologies for micro-generation have been ranked. The ELECTRE III method, explained and illustrated in chapter 8, was used to analyse a fixed available area site with both qualitative and quantitative criteria based on technical, economic and environmental factors. This chapter has demonstrated the ELECTRE III method as a useful decision support tool for PV technologies. The general conclusions of this MCA study by the ELECTRE III have to be taken in the context of a number of assumptions and estimates that are the result of the compilation and integration of other sections in this research work and available literature.

9.3 Suggestions for future work

The important factors for emerging PV technologies regarding economic competitiveness, technical boundaries and environmental sustainability are investigated in comparison with mature PV technologies for micro-generation. Taking this assumption of adopting emerging PV technologies for micro-generation, with a focus on the hybrid organic-based QD PV investigated in this project, methodologies and approaches were developed, applied and /or extended. In the following subsections, the basic vision of future research work is given based on the research presented and discussed in this thesis.

9.3.1 Design models for diversified PV technologies

Current on-grid PV system design models are not considering emerging PV technologies and energy storage, as these have not yet made it into the micro-generation market. In addition, the performance of these emerging PV technologies within a PV system is still unknown even though it is thought that organic-based PV module may absorb from a wider angle, lower radiation, and performance is not badly affected by high temperatures. This instigates that such technology may perform better than mature PV technologies.

Hence the motivations for future research underlying concepts of modelling are:

- the evaluation of field tests using emerging PV technologies. This will identify system level performances related to emerging PV technologies radiation absorption, which helps to create accurate technology specific mathematical PV models.
- the evaluation of other energy storage options such as hydrogen storage and fuel cells. The use of hydrogen energy storage systems and fuel cells is another form of energy storage that should be studied as an option to include in the small power system, which may lead to lower costs and environmental impacts than batteries. In any case, energy management in a domestic environment is required in the future.
- the design of web-based user friendly decision support tool for PV technology for micro-generation, based on the individual ranking of criteria. This will result in a customer informed design approach.

9.3.2 Policy adaptation for the inclusion of emerging PV technologies

Current policies for the implementation of financial RE support schemes are usually based on the market electricity price of the respective RE source. However, even though current policies may encourage high CO_2 mitigation, they may not necessarily encourage economic competitiveness between technologies. Hence the motivation of this future research, which can be built on the conceptual multi-objective framework presented in this research work, may reach compromise solutions between domestic users and public objectives, introducing emerging technologies within the PV market.

Besides, the present and future financial RE support schemes to PV applications must be considered as an investment with strong public support and long-term human benefits policy.

9.3.3 Emerging PV technologies large-scale manufacturing investigations

There is only a handful of large-scale manufacturing of emerging PV technologies mainly DSSC and OPV. Cost assessments and life cycle analyses were based on lab-process or small-scale productions. This research has focused on the potential cost assessment and life cycle analysis on hybrid organic-based PV modules, which were extrapolated from lab-scale solar cell designs. Studies on the potential fabrication process for mass production of hybrid organic-based QD solar cells are yet unknown to the industry. Hence there is a need for pilot projects related to large-scale manufacturing of a number of emerging PV technologies, including hybrid organic-based PVs, that may encourage higher efficiencies and stability from current OPV technology. These pilot projects will reveal the cost reduction potential, and low environmental impact to integrate successfully within the PV market for micro-generation.

APPENDIX A

Input Data

Climate Data

The isotropic solar radiation model in (A.1), translate horizontal radiation data of typical meteorological years, obtained from SoDa [229], to any orientation. The total solar radiation on a surface at an angle is given by summing the beam, diffused and albedo radiation referred to the inclined angle (*β*).

$$\left.\begin{array}{l} I_T(\beta) = B(\beta) + D(\beta) + R(\beta) \\ where \\ B(\beta) = I_B \cos\theta \\ D(\beta) = I_{DH}\left(1+\cos\beta\right)/2 \\ R(\beta) = I\rho_g(1-\cos\beta)/2 \\ I_H = I_{DH} + I_{BH} \\ I_{BH} = I_B\cos(90-\gamma) \\ I_H = I_B(\sin\gamma + C) \\ C = 0.095 + \left(0.04\left\{\frac{\sin(360\times(d-100))}{365}\right\}\right) \end{array}\right\} \quad (A.1)$$

where:

C, the sky diffuse factor, is an approximation based on the fraction of the sky to which the measuring device is assumed to point [230].

I_H, is the global radiation on the horizontal as per data

I_B, is the direct beam radiation normal to rays

γ, is the altitude angle

I_{BH}, is the beam radiation on the horizon

I_{DH}, is the diffused radiation on the horizon

β, is the tilt angle, the optimal slope is the latitude of the location [231].

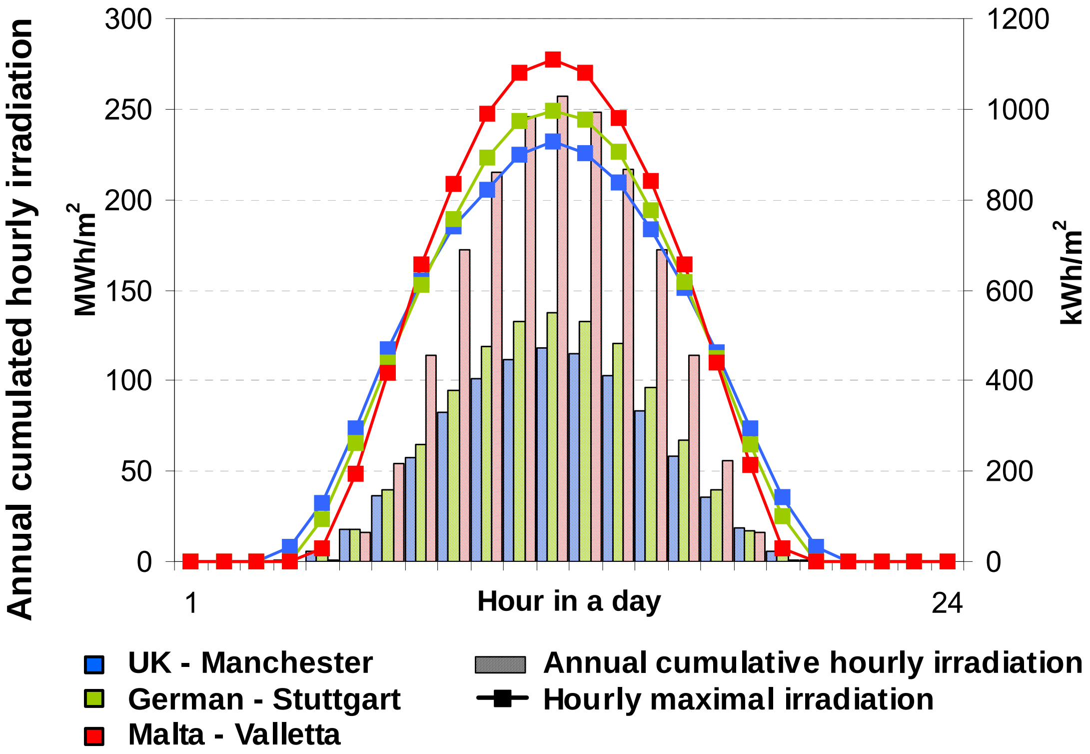
ρ_g, is the surface reflectance

θ, is the ray incident angle assumed at 0.2 (concrete – grass index)

Three locations were chosen for the studies with contrasting solar energy availability. The UK-base case is in Manchester, the German-base case is in Stuttgart and the Malta-base is representing the southern region of EU, and the Mediterranean region. The annual cumulated hourly radiation and hourly maximal irradiation on a flat surface are shown in Figure A.1.

Domestic Environment Load within a Household

At different locations, the domestic environment load profile may have different load profiles due to different electricity needs and tariff structures. However, the available UK based load profiles obtained from UKERC [173] are used. The load profiles were filtered; sorted and averaged in hourly time steps under 4 different household categories as in Table A.1. To illustrate each load profile category, the annual summation for hourly load and the hourly maximal loads, and their load duration curves are shown in Figure A.2 and Figure A.3.



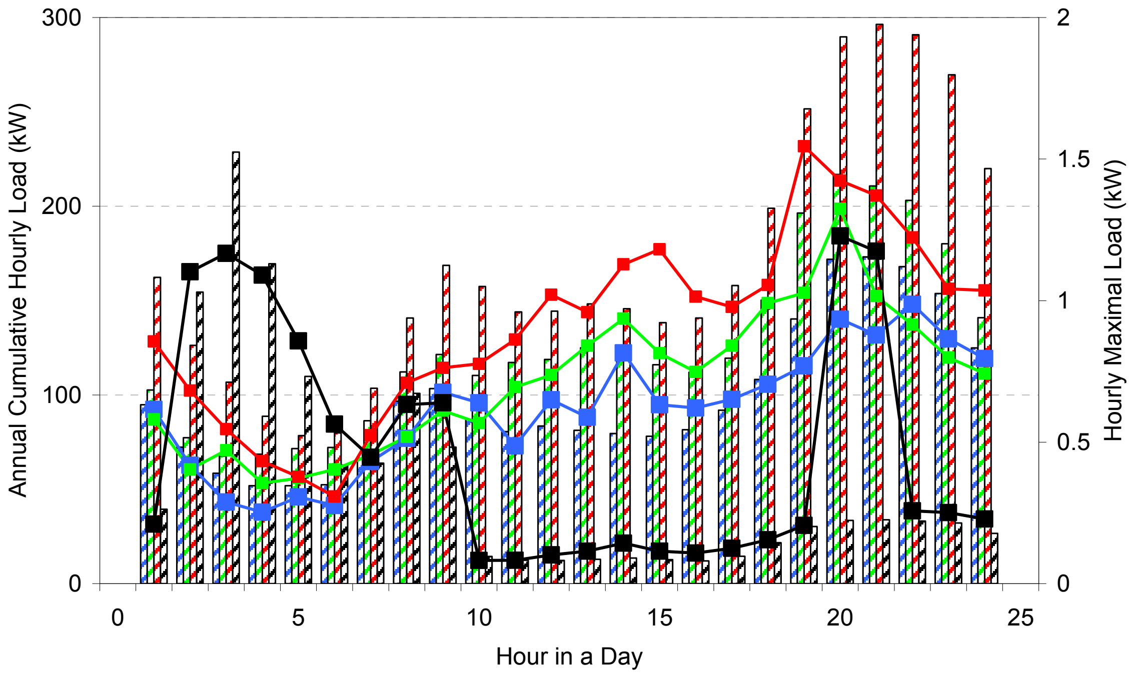
Annual cumulated hourly radiation and hourly maximal irradiation on flat surface

Figure A.1: Solar irradiance data plot.

Table A.1: Load data categories

Abbrevation	Description	Colour	Correlation (%) with 4 Bed G & E	
			Cum*	**Max***
2 Bed G & E	2 bedroom household having gas and electrcity energy sources	**BLUE**	88.39	99.17
3 Bed G & E	3 bedroom household having gas and electrcity energy sources	**GREEN**	92.79	97.02
4 Bed G & E	4 bedroom household having gas and electrcity energy sources	**RED**	--	--
3 Bed E only	3 bedroom household having electrcity energy sources only (x10)	**BLACK**	-26.47	-43.58

** Cum stands for Annual Cumulative Hourly Load and Max stands for Hourly Maximal Load according to figure XX*



The Annual Cumulative Hourly Load in kW (represented with Bar Graph) and the Hourly Maximal Load in kW (represented with Line Graph). Colours are indicated in Table A.1 above.

Figure A.2: Load data plot

Figure A.3 shows that, domestic loads tend to have very low demand levels (less than 500W) for the most of the year. In the case of 3 Bed E only, which makes use of a day-night tariff, the main consumption would be storage heaters during the night. Hence, the consumption during the day is very minimal. Meanwhile, the loads having both electricity and gas energy sources are highly correlated and have similar profiles independent of the number of bedrooms.

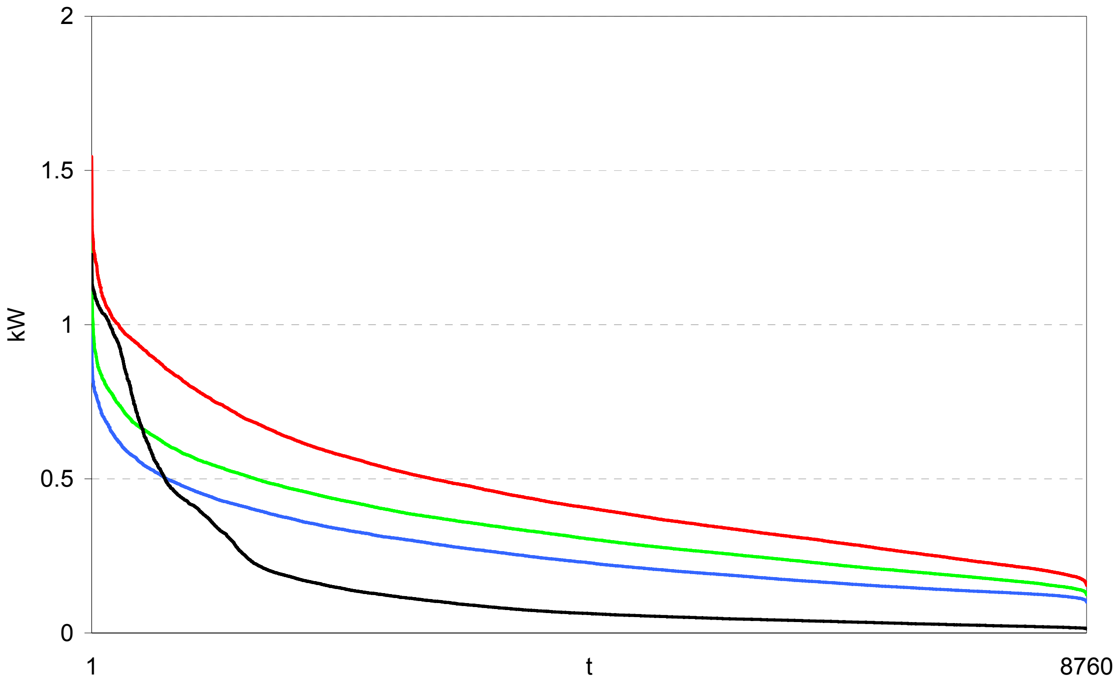
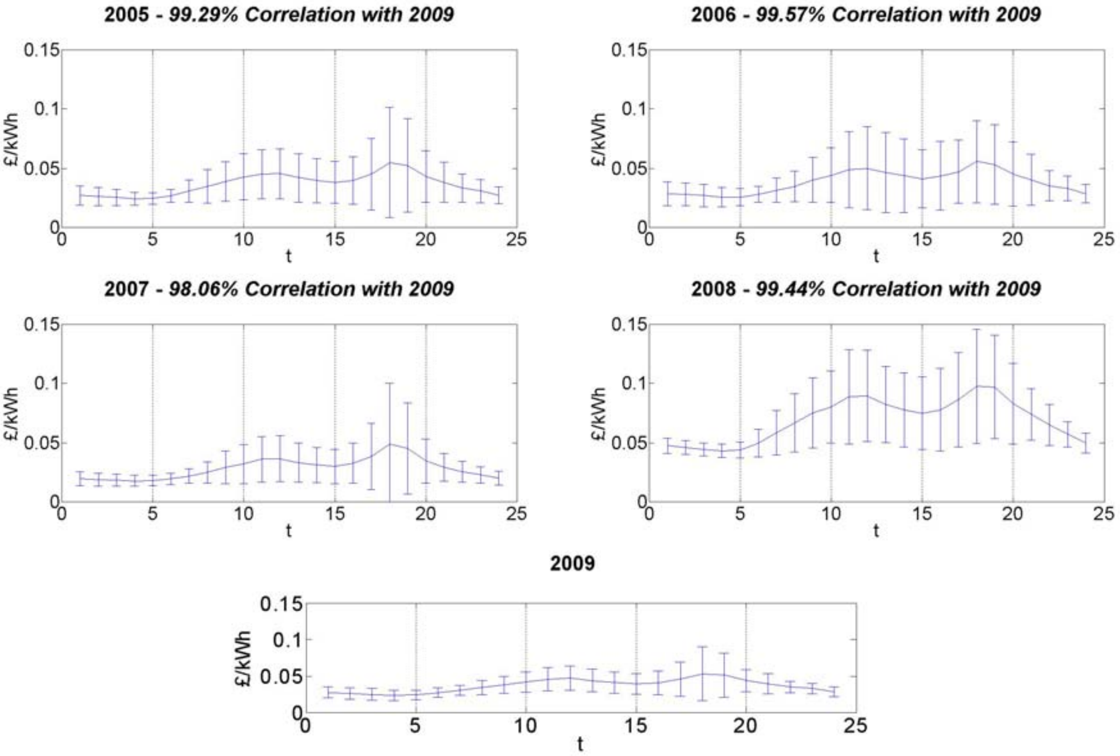


Figure A.3: The load duration curves of the load categories in Table A.1.

Electricity Tariffs

The Market Index (MI) Price, reflecting the price of wholesale electricity in Great Britain in the short-term market; is referred to the dynamic grid tariff rate. The MI-Price is divided in 30 minute segments. Hence the data was averaged, for every two segments, to represent an hourly price [232]. Figure A.4 shows the daily means and standard deviations of yearly export tariffs based on the available data in 2005, 2006, 2007, 2008 and 2009. Year 2008 had the most deviations in electricity prices with high and low prices during a whole day, recording higher prices than other years even during the day. In fact, the electricity prices may be said to follow a pattern and their yearly average day profile are highly correlated as indicated. The PV generation, which occurs during the day, is also positive correlated with higher electricity tariffs during the day than night tariffs.



2005 - *99.29% Correlation with 2009*

2006 - *99.57% Correlation with 2009*

2007 - *98.06% Correlation with 2009*

2008 - *99.44% Correlation with 2009*

2009

Figure A.4: Market Index Price hourly means and standard deviation of a day

APPENDIX B

PV Performance

It is a well known fact that PV systems performance differ when it comes to the solar cell technology due to the combined climatic conditions such as effects of temperature, cloud cover and elevation of the sun. So far, there is still no coherent methodology on how monitored data is presented and interpreted. In fact, there has been an increase in the number of studies on PV system performance under changing climatic conditions. However, these studies are either technology specific or site specific, making it difficult to compare technologies or climatic conditions [233-236].

PV systems performance definition

The International Energy Agency (IEA) Photovoltaic Power has established performance indices that describe energy performance under the IEC standard 61724 [237]. Three of the system performance parameters are:

Final Yield (Y_f) - defines the energy production is a measure of the total annual electricity output (kWh) per kWp rated power installed calculated as in (B.1).

$$Y_f = \frac{E_{OUT}}{P_{\max}} \tag{B.1}$$

where:

E_{OUT} is the energy output of the system

P_{max} is the nominal power rating of the PV module

Reference yield (Y_r) – defines solar irradiation resource of the PV array by the number of peak sun-hours if the reference irradiance (H_{ref}) is STC at 1000W/m^2.

$$Y_r = \frac{H}{H_{ref}} \tag{B.2}$$

where: H is the total plane of array irradiance in kWh/m^2.

Performance Ratio (*PR*) - defines the system losses such as shadowing, inverter inefficiencies and soiling effect. PR is the main index for characterising the system performance under certain conditions. PR is calculated in (B.3)

$$PR = \frac{Y_f}{Y_r} \tag{B.3}$$

Hence the PR is directly proportional to the system yield which is a fundamental parameter for PV generation, as it is pivotal for cash flow calculations and related energy output indices. Hence it is ideal to use annual yield figures differentiated according to module technologies installed within any PV analysis. However, these figures are based on field monitored performance data, and due to the time required for data gathering and lack of PV alternatives in the old days, there are only few studies. In fact, the only UK based study, providing directly comparable data on PV module technologies performance under UK and Mediterranean climate conditions, is the PV-Compare project. Eleven different systems comprising different PV technology from commercial available products were tested under two climate conditions. This project offers an informative tool for retailers, systems designers, architects, energy advisors and product developers. The expected annual energy yield for each technology was determined as shown in Table B.1. Though the results from the project may differ from current performances due to technology progress, the outdoor performance of PV systems under different technology and climatic conditions is yet to be understood. However, for the purpose of this thesis, the PV-Compare project results were aggregated to differentiate between different PV technologies as in Table B.1. So far, comparable performance studies on PV systems using emerging PV technology has still not been developed, since these technologies are mainly lab-based ones. However, companies may state that their organic PV panel may absorb from a wider angle, instigating that such technology performs better than commercial available PV. Hence for this reason, the PR of emerging PV technologies is taken as the highest recorded that is similar to the CIS technology type results in PV-Compare analysis. However in some cases within this thesis a commonly used *PR* is taken as 0.85 for comparison purposes.

Table B.1: PV performance results in PV-Compare project

Product Technology	**Product**	**Mediterranean (Mallorca - Spain) Annual Radiation 1700kWh/m^2**		**UK (Begbroke - Oxford) Annual Radiation 1022kWh/m^2**	
		kWh/kWp	**PR**	**kWh/kWp**	**PR**
Amorphous (3-j)	Unisolar US64	1380.40	0.81	858.6	0.84
Amorphous (2-j)	ASE 30 DG-UT	1655.30	0.97	991.8	0.97
Amorphous (2-j)	Solarex Millennia	1515.50	0.89	926.6	0.91
Amorphous (1-j)	Intersolar Phoenix	887.40	0.52	557.3	0.55
Monocrystalline	BP 585	1389.20	0.82	871.8	0.85
Multicrystalline	Evergreen	1283.30	0.75	824.8	0.81
Multicrystalline	Astropower	1352.90	0.80	821.8	0.80
Multicrystalline	Solarex MSX	1368.00	0.80	842	0.82
Multicrystalline	ASE 300DGUT	1340.40	0.79	875.1	0.86
CIS	Siemens ST40	1553.30	0.91	1025.3	1.00
CdTe	BP Apollo	958.50	0.56	673.7	0.66
	Assumed PR				
Amorphous			0.93		0.94
Monocrystalline			0.82		0.85
Multicrystalline			0.79		0.82
CIS			0.91		1.00
CdTe			0.56		0.66

APPENDIX C

The Basics of PV Devices

The core of a PV system is the solar cell that performs energy conversion from light to electricity. An overview is portrayed on the drivers of a solar cell to function. Firstly the semiconductor properties and basic material structure principles will help understand the basis of the usage of semiconductors as solar cells. Then electricity production, associated losses and constraints from solar cells is explained.

Introduction

Isolated atom electrons have defined energy levels. Atom electrons in solids have discrete energy levels grouped into energy bands. Hence, atoms in a solid crystal tend to bond with each other. There are three types of bonding: Ionic (Insulators), Metallic (Metals) and Covalent Bonds.

The Covalent Bond, shown in Figure C.1, is the evidence for semiconductors. Covalent bond is a special bond where the atom shares its free electrons with other neighbouring atoms to close the shell. When the shell is closed there are no free electrons hence, behaving similar to insulators in the ionic bonding. However, an element of conduction can be induced in the lattice by doping, which is further explained below.

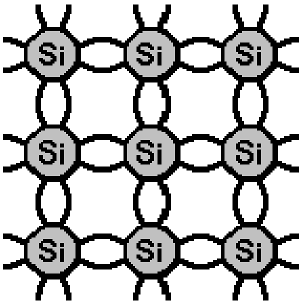


Figure C.1: Covalent bond for pure silicon crystal (intrinsic)

The energy band diagram for a semiconductor lies between an insulator and a metal. At $0^{o}K$ semiconductors are mainly insulators. The difference is the size of the energy gap between the valence band, which is full of electrons, to the conduction band. Hence electron excitation occurs from the valence band to the conduction band by hitting the electron with a form of energy, light in the case of PV. Hence an important parameter in semiconductors is the energy gap or bandgap where it specifies the energy required, for an electron, to depart and go to the conduction band. Different semiconductors have bandgap parameters and can range from wide band gaps like the Gallium Nitride (3.4eV) to narrow bandgap Indium Antimonide (<0.5eV).

Figure C.2 represents a static band structure for a semiconductor. There is an energy-momentum relationship E-k that reflects the dynamics of electrons. Figure C.3 illustrated E-k diagrams for two types of semiconductors namely direct and indirect. The electrons on top have the highest energy than electrons below. The direct type semiconductor has the minimum of the conduction band, and maximum of the valence band, occurring at the same value of momentum. For indirect type, there is a different value of momentum. Therefore in the latter as the electron gaps the band it also has to change its momentum.

Light absorption is a crucial property in semiconductor devices to have a good photovoltaic effect. However, this also depends on the quantum nature of light. Light wavelengths contain packets of discrete energy called photons. In theory, every photon having energy above the bandgap energy may excite an electron form the valence band

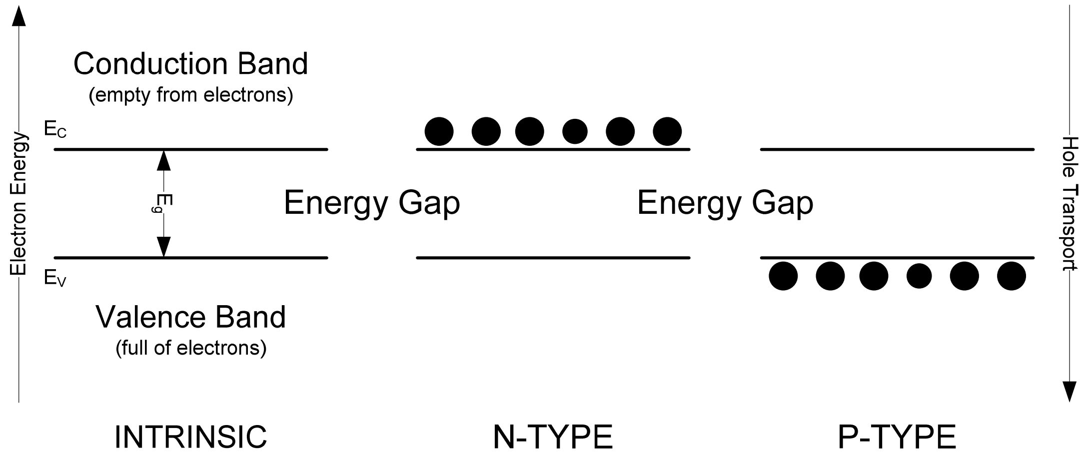


Figure C.2: static band structure of a semiconductor

	$E_{\Gamma 1}$	$E_{\Gamma 2}$	E_X	E_L	E_{SO}	n_c
Si	3.4	4.2	1.12	1.9	0.035	6
GaAs	1.42		1.90	1.71	0.34	1
InP	1.34		2.19	1.93	0.11	1

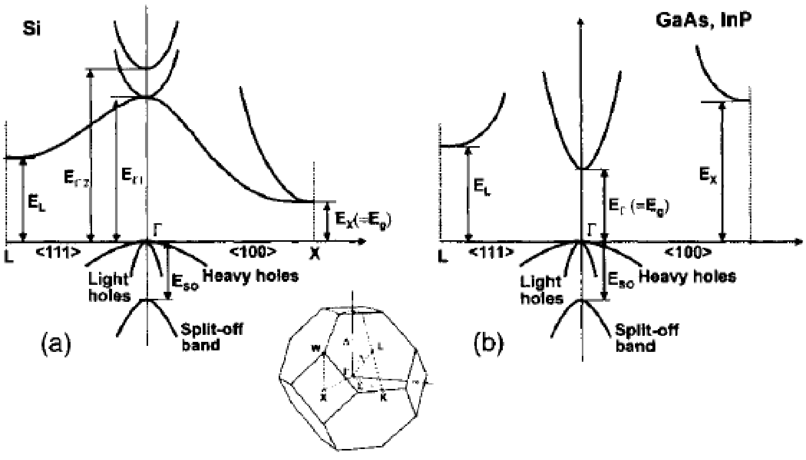


Figure C.3: The E-k diagrams for Si (a) *indirect* and GaAs and InP (b) *direct* [238]

to the conduction band. Hence, every semiconductor has a range of wavelengths within the solar spectrum that can be absorbed. This is called the spectral response of a semiconductor also referred to as the quantum efficiency. It is a measure of the photocurrents collected at each wavelength relative to the number of photons incident on the surface at that wavelength.

The absorption coefficient quantifies the capability of the semiconductor to absorb light energy. This energy travels inside the semiconductor and decays exponentially. Many semiconductors are good light absorbers, and all energies falling above the bandgap are absorbed within few micrometers thickness. These are mainly the direct type of semiconductors. In fact, higher material thickness is essential for indirect bandgap semiconductor for light absorption.

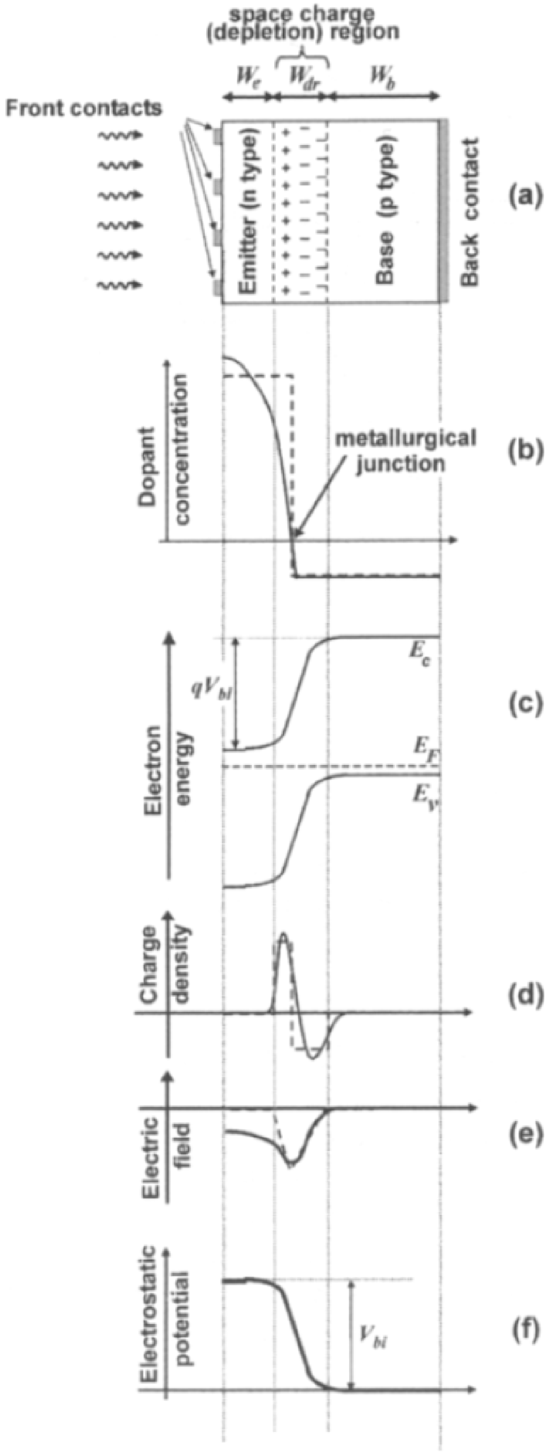
The imperfections in the lattice structure give rise to recombination centres within the structure. Recombination occurs when free electrons and holes extinct before they are collected by the external circuit. This recombination takes place either through within recombination centres or by bulk recombination. The result is a reduction in carriers' lifetime that is the mean time between production and extinction of a charge carrier.

Diffusion length is the average distance travelled by a charge carrier before recombination, a measurement for carriers' lifetime. Hence only carriers within this diffusion length from the junction are collected, the others recombine and therefore reduce efficiency of photocurrents production. In addition, part of the incident photon is lost also in the electron-hole pair generation. The energy in excess of the bandgap is dissipated as heat both within the valence and conduction band. This is one of the loss mechanisms in solar cells.

The charge particles in semiconductors are electrons, negative charge carriers, and holes, positive charge carriers. Excited electrons, due to light, heat or electric current, cross the small band gap between the valence band to the conduction band. A perfect semiconductor crystal with no impurities has no free charge carriers at 0^{o}K, intrinsic semiconductor. Impurities are added to the crystal by doping process from group 5 element, to have n-type semiconductor, excess of electrons called donors, while from group 3 element, to have p-type semiconductor, excess of holes called acceptors. Having an n-type and p-type semiconductor material will tend to create an electric field, developing a dipole called the p-n junction.

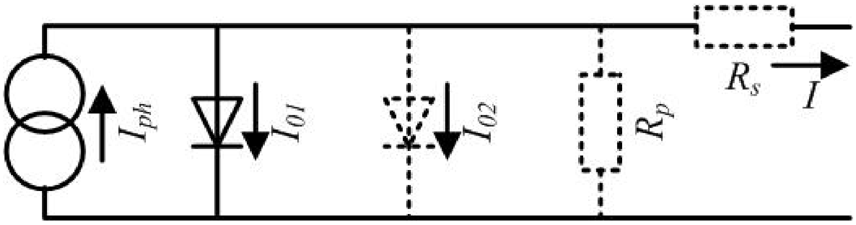
The p-n Junction

Figure C.4 illustrates a simple p-n junction, a classical model of a solar cell. Other types of junction exist. These junctions are p-i-n junction, to enhance photogeneration in short diffusion length materials, and p-n heterojunction, to improve carrier collection with different band gap materials. For an n-type semiconductor, the donor level will be very close to the conduction band. On the other hand, for a p-type semiconductor, the acceptor level will be very close to the valence band. Electrons from the donor level excite with little energy and jump to the conduction band. On the other hand, electrons from the valence band of the p-type semiconductor jump to the acceptor level leaving holes in the valence band. The force exerted by these charge carriers creates an electric field between the n-type and p-type semiconductors. Hence, a depletion region is established which gives rise to an internal potential difference. As light hits the semiconductor surface, both semiconductors will generate an electron hole pair. The minority carriers in semiconductor, holes in n-type and electrons in p-type, are diffused in the p-n junction and are swept away by the electric field resulting in a light-generated current. Hence the p-n junction separates opposite charge carriers and hence transforms the light-generated current into electric current. The front and rear of a solar cell contacts extract this electric current being generated. On top, the top front contact needs to allow light to pass.



The physical layout (not to scale): (b) the difference of dopant concentrations ND -- N A; (c) the band diagram; (d) charge density; (e) electric field; (f) electrostatic potential. The quantities shown by the dashed line correspond to an idealised abrupt junction with constant dopant concentrations in the base and in the emitter; the full line corresponds to a typical industrial solar cell with a diffused emitter.

Figure C.4: The p-n junction cell in equilibrium [238]



Non-ideal components are shown by the dotted line

Figure C.5: Equivalent circuit of an ideal solar cell (full lines) [238]

Electrical Principles

The solar cell can be represented in Figure C.5 as an equivalent circuit, consisting of the current source (I_{ph}) with an ideal diode. A practical solar cell equivalent circuit consist also of a series and shunt resistor described later.

Considering the ideal solar cell equivalent circuit in Figure C.5, the net current can then be given by (C.1).

$$I = I_{ph} - I_{o1}\left[e^{\frac{qV}{kT}} - 1\right] \tag{C.1}$$

where:

I_{ph} is the light-generated current

V is the voltage potential

I_{01} is the reverse saturation current (dark)

q is the electronic charge i.e. $1.6\text{x}10^{-19}$C

k is Boltzmann's Constant i.e. $1.38\text{x}10^{-23}$J/K

The I-V characteristic of a solar cell is compared to a diode, refer to Figure C.6. Two important parameters are the short-circuit current (I_{SC}), determined by the light spectrum and solar cell spectrum response mentioned earlier, and open-circuit voltage (V_{OC}) related to the band gap. The open-circuit voltage is derived in (C.2):

$$V_{OC} = n\frac{kT}{q}\ln\left(\frac{I_{SC}}{I_o} + 1\right) \tag{C.2}$$

where n is the junction "idealistic" factor which is a measure of the quality of the material.

(for n=1 V_{OC} is maximum).

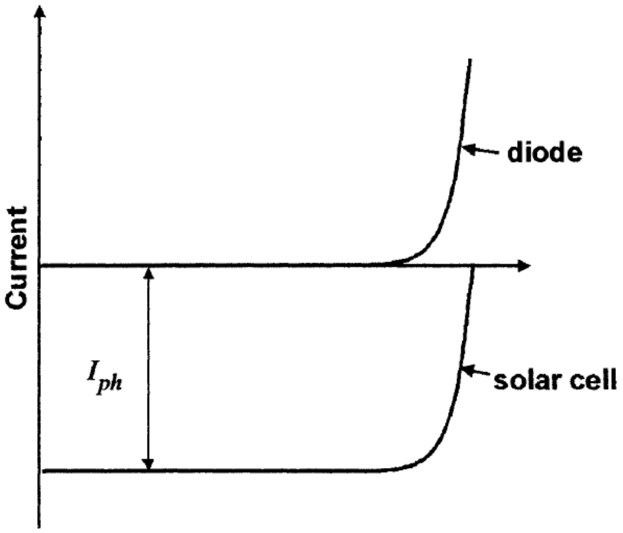


Figure C.6: I-V characteristic of a PV device [238]

The maximum power point is where the product I-V characteristics exhibit the maximum rectangular area under the I-V characteristics described the Fill Factor FF denoted by (C.3).

$$P_{\max} = FF \cdot V_{OC} I_{SC} \tag{C.3}$$

The Power Conversion Efficiency in (C.4) or solar cell efficiency (*PCE* or η) is a fundamental parameter for PV performance. It is the ratio of maximum power output under standard test condition and the incident power radiation. The standard test conditions are irradiance at 100mW/cm^2 at spectrum air mass (AM) 1.5 and temperature 25°C.

$$PCE = \frac{P_{\max}}{\varphi_e} \tag{C.4}$$

Efficiency Losses

Recombination losses are due to defects in the crystal structure, impurities or at energy levels inside the gap where electrons fall back to the valence band and recombine, surface recombination. Part of the recombination is activated by metal contacts that exhibit ohmic value. For high-efficient solar cells, this recombination is lessened by protected layers and heavily doped regions.

Current losses affect the collection efficiency. These losses are a measure of the capability that the number of carriers generated by light reaches the junction. In some solar cells, amorphous and polycrystalline, carrier transport is not simply made by diffusion. So electric fields are essential to pull the carriers. Other current losses are due to light reflection, shading and pure absorption properties. Hence solar cell developments led to reflection layers, surface texturing and light trapping designs.

The practical equivalent circuit of the solar cell contains series and shunt resistor as shown in Figure C.5 with dotted lines. The series resistor clearly effects the operation of the solar cell as it reduces the fill factor and PCE. It is a representation of the imperfections of the solar cell and other factors such as doping densities and lifetime of carriers. Hence a very low series resistance will result in a more square-like I-V characteristic. Though the shunt resistor is less problematic, a very high shunt resistor is desired as this has effects in decreasing the Voc.

Two operational consequences on solar cells performance are the ambient temperature and the irradiance. The temperature has a significant impact on the solar cell output voltage. As the temperature of the solar cell increases, voltage decreases. Normally a parameter of mV/^{o}C is specified. Another effect on the I-V characteristics is the irradiance. As the irradiance increases, the short circuit current increases, generating a higher output current. The voltage variation is insignificant as it depends logarithmic on the irradiance.

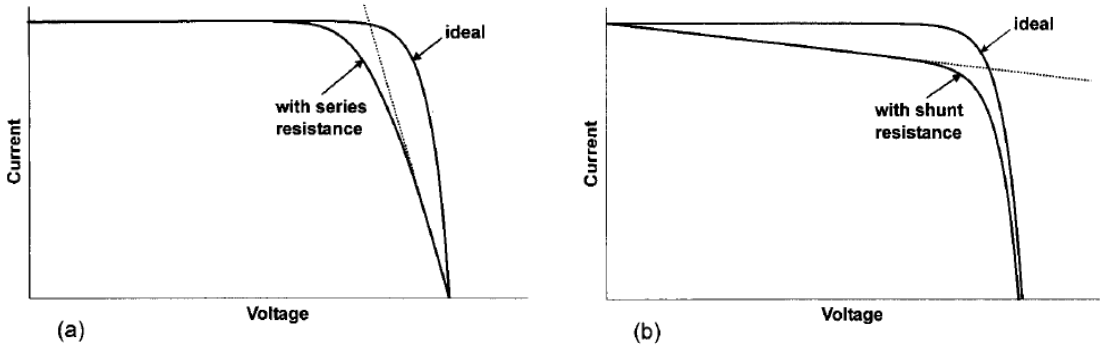


Figure C.7: Series (a) & parallel (b) resistance effects on the I-V characteristic [238]

APPENDIX D

Example: Sizing of Grid-Connected PV System

Sizing of an on-grid system involve electrical customers adding up the total electrical consumption for one year, which is available on utility bills. Then for an average daily consumption the annual electrical consumption is divided by 365 days per year. Finally, this daily electrical consumption (kWh) is divided by the average solar resource in the available area (irradiance).

For example, in the UK, the average irradiance factor is 2.5 hours per day. This is the amount of 1000W received by the solar array, not accounting for design inefficiencies.

A UK home electricity annual average consumption is 3,300kWh per year.

Hence a simple calculation follows in (D.1):

$$\left.\begin{aligned}
&3{,}300kWh \div 365days = 9.04kWh/day \\
&9.04kWh/day \div 2.5 = 3.62kW = 3620Wp \\
&3600Wp \div 0.9(\eta_{inverter}) = 4018Wp \approx 4000Wp \\
&4000Wp \text{ PV system cost } \approx £18{,}000
\end{aligned}\right\} \qquad \text{(D.1)}$$

The system calculation above will approximately match the local load. This is not necessary the best option. The UK has introduced FITs for PV at a maximum rate of $41.3\text{p/kWh}_{\text{PV}}$ and $3\text{p/kWh}_{\text{export}}$. In addition, UK households can save from electricity bills at around $13\text{p/kWh}_{\text{imports}}$ when solar resource correlates with the grid. Hence the calculation above is for illustrative purposes only, based on average irradiance data and 100% correlation between load and solar resource. Costs and rebates may also vary. There are interactive web-based or software program based calculators for on-grid applications. These calculators have system costs and applicable financial incentives.

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