MEASUREMENT OF EXTERNALITIES FOR RENEWABLE ENERGY INVESTMENT

ANBU MALAR SUNDARAM

THESIS TO OBTAIN THE MASTER OF SCIENCE DEGREE IN

ENERGY ENGINEERING AND MANAGEMENT

SUPERVISOR: PROF. JOÃO AGOSTINHO DE OLIVEIRA SOARES

EXAMINATION COMMITTEE

CHAIRPERSON: PROF. DUARTE DE MESQUITA E SOUSA

SUPERVISOR: PROF. JOÃO AGOSTINHO DE OLIVEIRA SOARES

MEMBER OF THE COMMITEE: PROF. CARLOS MANUEL FERREIRA MONTEIRO

DECEMBER 2016

ACKNOWLEDGEMENT

I owe a great debt of gratitude to my thesis mentor Professor Dr. João Agostinho de Oliveira Soares for his consistent guidance throughout the whole period. Thanks to his kindness and complete support, I was able to accomplish the thesis successfully. I am very much grateful to this opportunity.

I am also thankful to KIC InnoEnergy Programme for helping me pursue my master's studies with scholarship. Thanks to the community, I had an opportunity to study in a multi-cultural environment.

Finally, I would like to thank all my friends and family, especially my parents Sundaram & Maheswari, and my brother Kavin, for their unwavering conviction in me.

ABSTRACT

Climate change and cleaner environment have been some of the growing concerns in the 21st century. Electricity production has been a major contributor to the emission of greenhouse gases and several other harmful pollutants into land, air and water. Hence, an understanding of the externalities created by the different fuels over their life cycle can aid in better engagement of an honest policy discussion about a ‘level playing field’ of different electricity generation technologies. The idea of internalization of the externalities favours the deployment of renewable energy technologies over the fossil fuels. In an attempt to internalize the externalities, countries have employed several policy incentives promoting renewable energy systems. However, the large and recent penetration of these renewable systems have raised the concern of policy makers on the cost of the policy incentives over the benefits. In order to gain a perspective on the policy costs, an economic analysis is performed comparing the benefits of avoided external costs and the fossil fuel savings through the penetration of renewables in the electricity mix with the cost incurred in the policy incentives promoting renewables. Knowing well that the results vary for each and every country and each technology significantly, on a broader picture, the results show that the benefits are higher than the policy costs for hydro power and wind energy while solar and biomass energy have exhibited higher costs over the benefits in many countries.

Keywords: Externalities, Renewable energy, European Policy Incentives, Fossil Fuel Savings.

RESUMO

As alterações climáticas e um ambiente mais limpo têm sido algumas das preocupações crescentes no século XXI. A produção de electricidade tem sido um dos principais contribuintes para a emissão de gases de efeito estufa e vários outros poluentes nocivos para a terra, o ar e a água. Assim, uma compreensão das externalidades criadas pelos diferentes combustíveis ao longo do seu ciclo de vida pode ajudar a um de debate político mais informado sobre as condições de concorrencia equitativas de diferentes tecnologias de geração de energia elétrica. A ideia da internalização das externalidades favorece a implantação de tecnologias de energias renováveis em desfavor dos combustíveis fósseis. Numa tentativa de internalizar as externalidades, os países têm utilizado vários incentivos políticos que promovem sistemas de energias renováveis. No entanto, a vasta e recente introdução destes sistemas renováveis tem levantado a preocupação dos decisores políticos sobre o custo dos incentivos em relação aos seus benefícios. A fim de obter uma perspectiva sobre os custos dos incentivos, é realizada uma análise económica comparando os benefícios dos custos externos evitados e a economia de combustíveis fósseis, através da intodução das energias renováveis no mix de eletricidade, com o custo incorrido nos incentivos políticos na promoção das energias renováveis. Sabendo bem que os resultados variam de forma significativa de acordo com cada país e cada tecnologia, num quadro mais amplo, os resultados mostram que os benefícios são superiores aos custos com incentivos políticos para as energias hídrica e eólica, enquanto a energia solar e a biomassa têm apresentado em muitos países custos mais elevados do que benefícios.

Palavras-chave: Externalidades, energia renovável, incentivos políticos, economia de combustíveis fosseis

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

GWh	Giga Watt Hour
TWh	Terra Watt Hour
EU	European Union
OECD	Organisation for Economic Co-operation and Development
IRENA	International Renewable Energy Agency
ExternE	External Costs of Energy
NEEDS	New Energy Externalities Development for Sustainability
CASES	Cost Assessment of Sustainable Energy Systems
GDP	Gross Domestic Product
GHG	Green House Gas
CH_4	Methane
N_2O	Nitrous Oxide
UK	United Kingdom
SOx	Sulphur Oxide
NOx	Nitrogen Oxide
IPA	Impact Pathway Approach
LCA	Life Cycle Analysis
DC	Direct Current
PV	Photovoltaic
BOS	Balance of System
c-Si	Crystalline Silicon
sc-Si	Single-Crystalline Silicon
mc-Si	Multi-Crystalline Silicon
CdTe	Cadmium-Telluride
CIGS	Copper-Indium-Gallium-Diselenide
CIS	Copper- Indium-Selenide

DSSC	Dye-sensitized solar cells
MG-Si	Metallurgical-grade silicon
MW	Mega Watt
kW	Kilo Watt
VOC	Volatile Organic Compounds
O_3	Ozone
CO_2	Carbon Dioxide
tCO_2-eq	Tonne of Carbon Dioxide Equivalent
$PM_{2.5}$	Particulate Matter of size 2.5 micron or less
PM_{10}	Particulate Matter of size 10 micron or less
LCOE	Levelized Cost Of Electricity
CCGT	Combined Cycle Gas Turbine
VSL	Total Value of Life
VSLY	Value of life per year lost
FIT	Feed-In Tariff
FIP	Feed-In Premium
TND	Tenders
QO	Quota Obligations
II	Investment Incentives
TE	Tax Exemptions
NM	Net Metering
FI	Financial Incentives
η	Efficiency

CHAPTER 1. INTRODUCTION

For the past decades, sustainable growth and energy policy have been a major concern for many developed and emerging countries. Reducing fossil fuel emissions, improving the clean combustion and promoting renewable energy technologies had been on focus amongst the policy makers.

With growing environmental concerns and increasing public awareness, the decision making process of identifying and promoting both environmentally and economically efficient technologies has become very crucial. Energy sector remains as the heart and skeleton of any technological and economic development of a country. The continuous history of oil shocks and their aftermath events have repeatedly proved us the degree of influence energy has on the humanity on the whole. Energy independence has become a vital goal for all the countries. There are several fuels and technologies for the production of electricity, ranging from the age old yet the prominent fossil fuel power plants to renewable power plants which use regenerative technologies.

It is a challenge put forth to the decision makers in choosing the appropriate energy mix for the countries because fossil-fired power plants are generally economically advantageous and ecologically disadvantageous on the other hand renewable energy technologies tend to be ecologically advantageous and economically disadvantageous. As any economic activity can have externalities involved. While the externalities of any energy technology can be positive or negative depending on their impact in the society, it is important to assess them and include them in the utility (internalize the externalities) to have better understanding and comparison of the technologies.

The difficulty is that economic and ecological criteria cannot be compared directly as the economic factors are measured in monetary units (internal costs such as production cost) whereas ecological advantages are usually not. Hence, renewable energy technologies which have good ecological benefits are at a disadvantage. To encourage and level the playing field the benefits of renewable technologies have to be internalized in their cost. Thus, several attempts are made to calculate ecological aspects in monetary terms (external costs) in order to provide a comparison of various technologies with a holistic assessment including both economic and ecological criteria. This gave rise to the monetary valuation of the externalities of the energy systems which are discussed further in this dissertation. Three studies assessing the external cost of energy are discussed and further the avoided external costs by the renewable penetration in the electricity generation mix of a nation is calculated to compare the policy cost with the benefits obtained from the avoided external costs and fossil fuel savings.

ELECTRICIY SECTOR

Any economic activity will have an impact on the environment. Energy sector, especially, has been on the lime light for the past few decades when it concerns to environment protection. Energy is intertwined with the economic growth of any sector and hence, simultaneously as a major cause for many environmental issues. This chapter discusses about the energy mix of various technologies and the link between energy generation and climate change.

Safe, uninterrupted, continuous electricity is crucial for many economic and technological advancements. The Annual production of electricity in 2014 all over the world was around 22400 TWh. yet, the world is not completely electrified. Despite the serious efforts, today an estimated 1.2 billion people – 17% of the global population – remain without electricity, and 2.7 billion people – 38% of the global population – put their health at risk through reliance on the traditional use of solid biomass for cooking. (International Energy Agency, 2015). The demand and consumption of electricity only keeps increasing with time. Whereas on the other hand, the climate concerns brings in stringent emission laws. The future holds good for clean, efficient electricity generation technologies.

1.1 ELECTRICITY GENERATION IN EU

Total net electricity generation in the EU-28 was 3.10 million Giga Watt hour (GWh) in 2013 (Eurostat, 2015). Various fuels were involved in the electricity generation. The Share of various are given in the figure 1. While the fossil fuels dominate the electricity generation in EU, there has been a formidable growth in the renewable energy production share. “The relative importance of renewable energy sources in relation to EU-28 net electricity generation grew between 2003 and 2013 from 12.6 % to 23.2 %, while there was a relatively small decrease in the relative importance of combustible fuels from 56.4 % to 49.8 % and a larger reduction in the amount of electricity generated from nuclear power plants from 30.9 % to 26.8 %. Among the renewable energy sources, the proportion of net electricity generated from solar and wind increased greatly: from 0.01 % in 2003 to 2.7 % in 2013 for solar power and from 1.4 % in 2003 to 7.5 % in 2013 for wind turbines.” (Eurostat, 2015). The above statistics prove that the renewable penetration has been promising in EU.

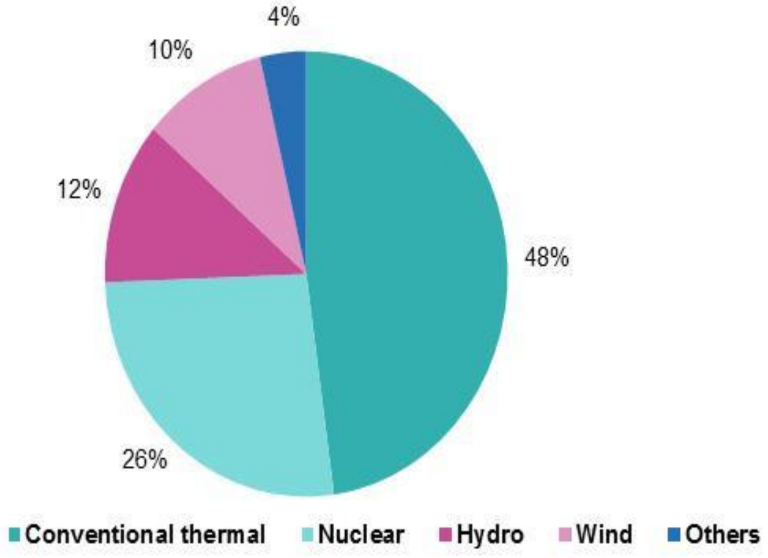
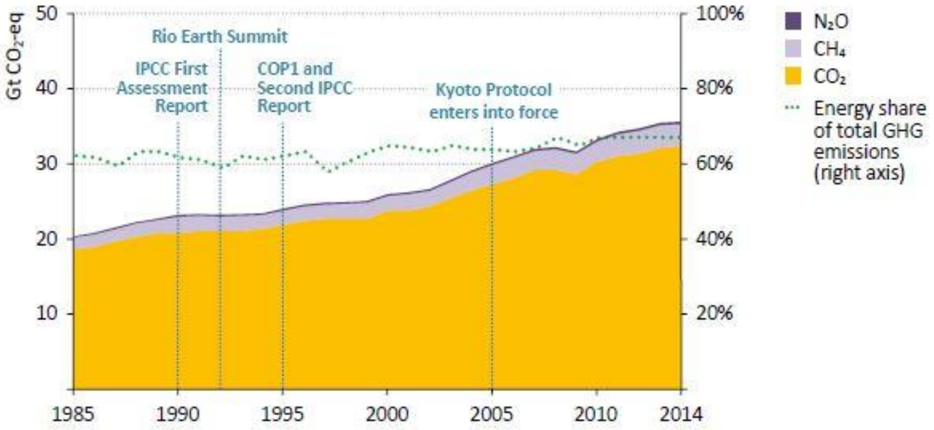


Figure 1: EU-28 electricity production by source in 2015 (Eurostat, 2016)

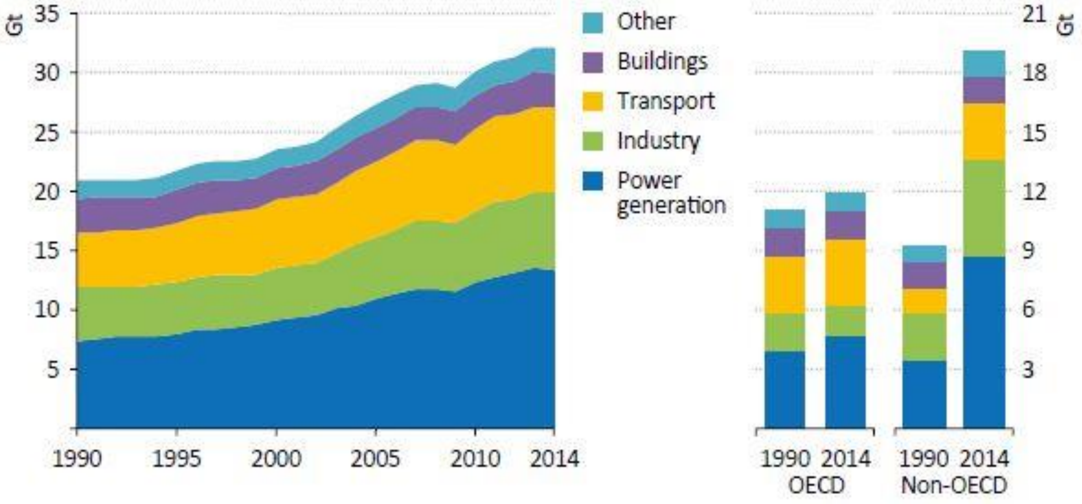
Besides the renewable penetration, fossil fuels continue to meet more than 80% of total primary energy demand and over 90% of energy-related emissions are CO2 from fossil-fuel combustion as shown in the graph in figure 2. Since 2000, the share of coal has increased from 38% to 44% of energy-related CO2 emissions, the share of natural gas stayed flat at 20% and that of oil declined from 42% to 35% in 2014. While smaller in magnitude, yet with high global warming potentials, methane (CH_4) and nitrous oxide (N_2O) are also emitted by the energy sector. Methane accounts for around 10% of energy sector emissions and originates mainly from oil and gas extraction, transformation and distribution. Much of the small remainder is nitrous oxide emissions from energy transformation, industry, transport and buildings. (International Energy Agency, 2015)



Notes: CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide. CH_4 has a global warming potential of 28 to 30 times that of CO_2, while the global warming potential of N_2O is 265 higher than that of CO_2.

Figure 2: Global GHG emissions over the years (International Energy Agency, 2015)

The Greenhouse Gas emissions from the energy sector contributes to roughly two thirds of the total emission as represented in the figure 3. Especially over the past century, annual emission levels increased at an ever higher rate: the energy sector emitted as much CO_2 over the last 27 years as in all the previous year put together. The global distribution of CO_2 emissions has also shifted: at the beginning of the 20th century, emissions originated almost exclusively in the United States and Europe, while today together they account for less than 30%. Much because of the reason that most of the Europe and United states have developed while the third world developing countries still have a high growing demand. (International Energy Agency, 2015).



Notes: "Other" includes agriculture, non-energy use (except petrochemical feedstock), oil and gas extraction and energy transformation. International bunkers are included in the transport sector at the global level but excluded from the regional data.

Figure 3: Share of energy related CO2 emissions (International Energy Agency, 2015)

Even though CO_2 emissions increased nearly three-fold in China and two-and-a-half times in India between 1990 and 2014 as in figure 4, per-capita emissions in both countries are still below the average level in OECD countries. China's per-capita emissions in 2014 reached 6.2 tonnes, a third lower than the OECD average. India's per-capita emissions were 1.6 tonnes in 2014, or about 10% of the level in the United States and 25% of the level in China. (International Energy Agency, 2015).

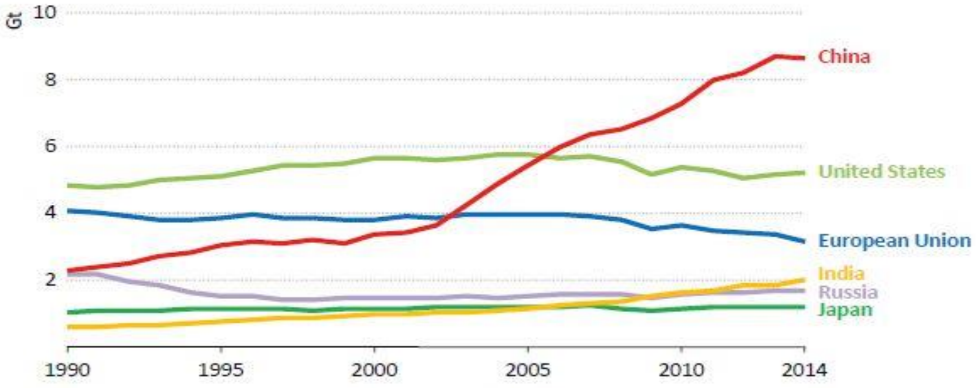


Figure 4: Energy related CO2 emission in selected region (International Energy Agency, 2015)

Energy sector being the major contributor of the GHG emissions, it is crucial to understand the implications of the emissions and take steps to mitigate it. Fossil fuel combustion contributes to around 90% of the GHG emissions. Increasing the efficiency of the fossil fuel power plants already existing and penetration of more clean renewable energy are the two ways to reduce the GHG emissions and hence the global warming.

From the graph in the figure 4, it can be noticed that the energy-related CO_2 emissions in the European Union dropped by more than 200 Mt (over 6%). This is because of the decline in the demand for the fossil fuels. Power generation from non-hydro renewables grew by 12% as they continued to benefit from active decarbonisation policies (International Energy Agency, 2015). Figure 5 shows the electricity production statistics for the European countries. Countries such as Sweden, Norway and Austria benefit from the hydro power while France, Slovakia and Hungary have fair share of nuclear in their energy mix. While European Union has been actively promoting the involvement of renewable energy production, it is important to understand the blanket effect of global warming and the joint commitment of all the nations to mitigate CO_2 and other GHG emissions is important to reduce the impacts of global warming. In the absence of fully committed and urgent action by all the nations united together, Climate change will become an irrecoverable and irreversible impact on the world.

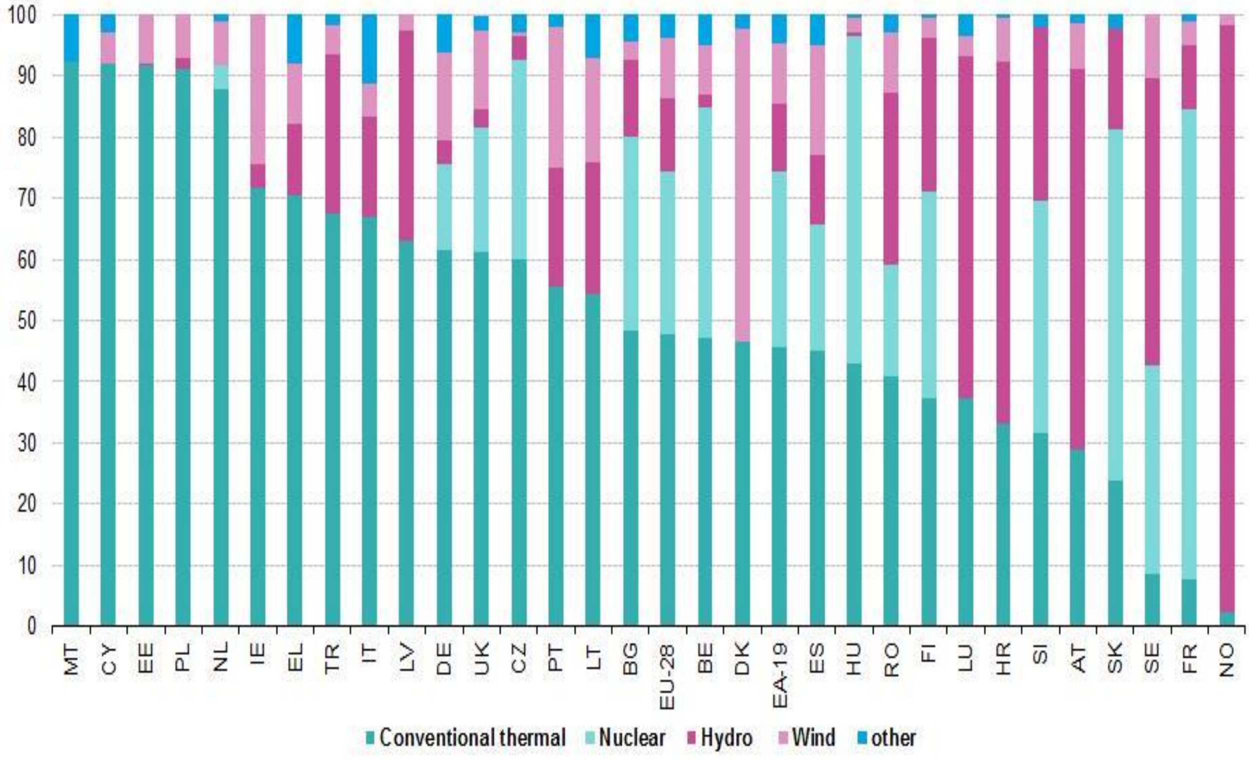


Figure 5: Breakdown of electricity source for each country 2015 (Eurostat, 2016)

The long lifetime of greenhouse gases means that it is the cumulative build-up in the atmosphere that matters most. In its latest report, the Intergovernmental Panel on Climate Change (IPCC) estimated that to preserve a 50% chance of limiting global warming to 2 °C, the world can support a maximum carbon dioxide emissions “budget” of 3000 Giga tonnes. (IPCC, 2014). The key pillar for many countries to achieve this target is the decarbonizing the energy sector. As by now, it has been repeatedly mentioned that two third of the GHG emissions are from energy sector. Decarbonizing is possible only with the successful penetration of renewable energy systems into the energy mix of every country. Ramping up renewables is essential to meet climate goals without decelerating economic growth and reducing welfare. IRENA's analysis in REmap 2030 reveals that doubling the share of renewable sources in total final energy consumption from 18% in 2010 to 36% by 2030, combined with significant improvements in end-use energy efficiency, is required to limit global temperature increases to under 2 degree Celsius (IRENA, 2015).

This thesis, in a way, serves as a platform to review and understand the externalities involved in the fuel cycle of the renewable energy generation technologies.

1.2 ORGANIZATION OF THE THESIS

This thesis has the following purposes.

First, an overview of the renewable energy scenario in Europe is given.

Chapter 2 presents the fundamentals of the externality and the purpose to measure them. This is followed by the discussion of the three primary renewable energy technologies: biomass, wind and solar and their fuel cycle.

Chapter 3 chalks out the basics of the three renewable energy technologies solar, wind and biomass. The life cycle of each fuel chain is discussed.

Chapter 4 presents the review of three externality studies: ExternE, NEEDS and CASES. The external costs of the renewable systems from the studies are discussed.

Chapter 5 presents the benefits and cost involved in the policy incentives implemented by EU nations to promote renewable energy systems. While this is not a complete cost benefit analysis including the system costs, the policy support costs and the benefits of avoided externalities by the renewables and the fossil fuel savings by the renewables are studied for each EU nation separately.

1.3 CURRENT SCENARIO OF RENEWABLE ENERGY

Any energy fuel is considered renewable if they are continually replenished by nature's activities and are a consistent pool of resources. Some of the renewable energy fuels are solar energy, wind, biomass, nuclear, tidal energy, geothermal energy.

For example, solar energy potential is highest in the South western United States, Northern Africa and the Middle East, and parts of Australia and South America. Some of the best regions for wind energy include Northern Europe, the southern tip of South America, and the Great Lakes region of the United States. Geothermal energy is prevalent in countries such as Iceland and the Philippines. Every world region has some renewable energy resources, though availability and cost of using these vary. (Coutts, 2014)

A recent study stated that renewable energy sources, based on wind, water, and sunlight could provide all new energy globally by 2030, and replace all current non-renewable energy sources by 2050 (Jacobson et al, 2011). Figure 6 from (Jacobson et al, 2011) describing the availability of renewable energy shows estimates of the potential energy from various renewable energy sources, converted into trillions of watts. Projected global energy demand in 2030 is 17 trillion Watts. Thus we see in figure 6 that the availability of energy from wind and solar in likely-developable locations is more than sufficient to meet all the world’s energy needs (Coutts, 2014)

Energy Source	Total Global Availability (trillion watts)	Availability in Likely-Developable Locations (trillion watts)
Wind	1700	40 – 85
Wave	> 2.7	0.5
Geothermal	45	0.07 – 0.14
Hydroelectric	1.9	1.6
Tidal	3.7	0.02
Solar photovoltaic	6500	340
Concentrated solar power	4600	240

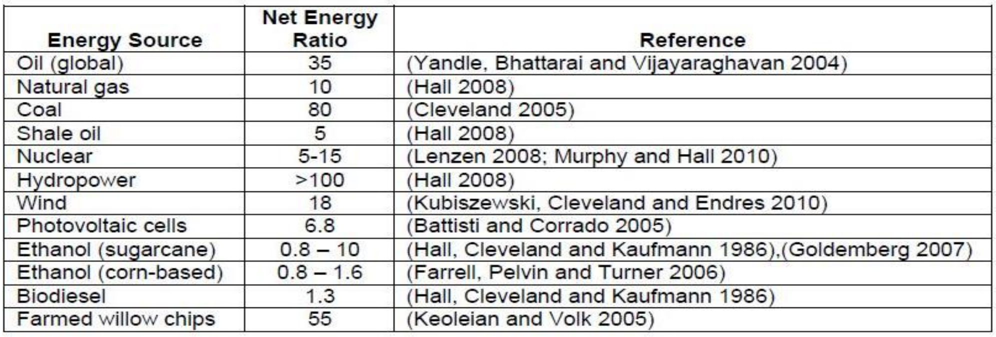
Figure 6: Availability of global renewable energy (Delucchi et al, 2011)

While researches promise such abundant available energy and technology, the major road block in the development and penetration of renewable energy in the energy sector is the issue of cost. By cost, the fixed cost in building and deployment of the renewable systems and the daily operation, maintenance and fuel costs contribute to the marginal cost of the system. While the fuel cost for many renewable systems are close to nil or very minimal (in case of biomass). The fixed cost for renewable systems is generally very high.

Some of the challenges faced by renewable systems are:

High capital intensity required for renewables. Especially the fixed cost. While fossil fuels have high fuel cost (especially when imported), the cost is paid over a period of time and hence is more feasible in many situations.

Net energy is the ratio of the energy available for final consumption divided by the energy required to produce it. It is also called as “energy return on (energy) invested”. A large net energy ratio means we get lots of useful energy for a small energy investment, as with the case of most of the fossil plants. Figure 7 shows the net energy ratios for various energy sources. The net energy for renewable energy fuels are considerably low compared to fossil fuels. (Coutts, 2014)



Energy Source	Net Energy Ratio	Reference
Oil (global)	35	(Yandle, Bhattarai and Vijayaraghavan 2004)
Natural gas	10	(Hall 2008)
Coal	80	(Cleveland 2005)
Shale oil	5	(Hall 2008)
Nuclear	5-15	(Lenzen 2008; Murphy and Hall 2010)
Hydropower	>100	(Hall 2008)
Wind	18	(Kubiszewski, Cleveland and Endres 2010)
Photovoltaic cells	6.8	(Battisti and Corrado 2005)
Ethanol (sugarcane)	0.8 – 10	(Hall, Cleveland and Kaufmann 1986),(Goldemberg 2007)
Ethanol (corn-based)	0.8 – 1.6	(Farrell, Pelvin and Turner 2006)
Biodiesel	1.3	(Hall, Cleveland and Kaufmann 1986)
Farmed willow chips	55	(Keoleian and Volk 2005)

Figure 7: Net energy from various sources (Murphy et al, 2010)

Although renewable energy can be replenished over a period of time, they are not widely and consistently available over time and seasons. For an example, solar is available only during the day with varying intensity over seasons and time. Similarly wind is not available in all the seasons of the year. While they are predictable to certain extent, they are **highly intermittent**. Such intermittency is a huge issue with all the renewable energy sources.

Connecting renewable systems to grid has been one of the issues. Owing to the high intermittent nature of the renewable sources, a nation's grid cannot yet completely rely on the renewable power as the grid stability could be affected. With the current technological advancements in the grid management, however, to certain limit, they can be added to the grid. This is when the fossil plants are fired as backup to offset the intermittency.

While we have discussed various challenges faced by the renewable energy technologies, it has to be noted that it is a young field of research with a huge potential and hence, consistent support from the nation in the ways of policies and support to the industries, the promoted research and development can help in overcoming the barriers faced by the renewable systems and tap the most of the benefits from it.

"Renewable energy creates multiple public benefits such as environmental improvement (reduction of power plant greenhouse emissions, thermal and noise pollution), increased fuel diversity, reduction of energy price volatility effects on the economy, national economic security, increase of economic productivity and GDP through more efficient production processes. It has been estimated that a 10% increase in renewable energy share avoids GDP losses in the range of $29–$53 billion in the US and the EU ($49–$90 billion for OECD). These avoided losses offset half the renewable energy OECD investment needs projected by a G-8 Task Force. For the US, each additional Kw of renewable energy avoids on average $250–$450 in GDP losses" (Angeliki Menegaki, 2007). If all these benefits are considered for the renewable energy sources and the policies are framed in such a way to promote technologies taken into account of all the costs and benefits, renewable energy can have a level playing field with the fossil fuels until the technology matures to overcome to barriers.

Targets are set by many nations to promote the share of electricity obtained from renewables. Over 60 countries have set renewable energy targets. The European Union has set a goal of 20% of total energy from renewables by 2020, with different goals for each member country. The 2020 targets include goals of 18% for Germany, 23% for France, 31% for Portugal, and 49% for Sweden. (Coutts, 2014).

CHAPTER 2. FUNDAMENTALS OF EXTERNALITIES

DEFINITION

The concept of environmental economics is taken from the neo-classical paradigm in microeconomics where the main assumption of the paradigm revolves around the concept that there is perfect competition on all markets. There is a pareto-optimal market equilibrium in the market so that supply and demand are equal.

Usually, these pareto-optimal results are not achieved in real market conditions where there are many market imperfections. One such market imperfection is the externalities involved (Few other examples include imperfect information, public goods, etc).

An externality exists if two conditions exist. First, an impact (which can be negative or positive) is generated by an economic activity and it is imposed on third parties. Secondly, that impact must not be priced in the market place, for an example, if the effect is negative, no compensation is paid by the generator of the externality to the victim. If the effect is positive, the generator of the externality does not receive any gains from the benefiter.

The externalities can exist an as external cost or an external benefit based on whether the welfare is lost or gained by the third party. In the perfect market conditions, the cost of producing a good is compensated by the money paid for the good by the consumer. Similarly, a compensation for the change in welfare of the third party (which can be an external cost or external benefit) can help in removing the market imperfection created by the externalities. This process of compensating the externality is called as the internalisation of the externality. In such a situation in which all externalities are internalised, the compensation corresponds to the same utility as the change of welfare so that there is no unaccounted externality anymore.

2.1 PURPOSE OF CALCULATING THE EXTERNALITIES

While there are many uncertainties and difficulties in the estimation of the externalities of the economic activity, there are a number of reasons to explain the importance to evaluate the externalities. Some of them are explained below,

1. To **make sustainable long term investment decisions**, e.g. about which power plant technology to use or to decide the location of the plant, it is obvious that it would be of interest for society to take environmental and health impacts into account and include the external effects into the decision process. (ExternE, 2005)
2. Externality estimations are useful **to assess any technology** and identify the weaknesses and strengths of a technology and assess the overall performance and usefulness of a technology. Such an assessment can help in identifying the areas that require further improvement and whether subsidising it or supporting further research might be justified. (ExternE, 2005)

3. Apart from investment, consumption of goods can cause external costs, **whereby the choice made between alternative technologies or consumer goods** can influence the size of externalities considerably. Again, marginal external costs are needed, for example the costs that are caused by driving a car on a certain road or the costs of using a stove for heating. The best way of internalising these costs is via imposing taxes that are equal to the external costs, so that prices reflect the true costs and tell the ecological truth. (ExternE, 2005)

4. It is **useful cost-benefit analyses for policies and measures** that reduce environmental and health impacts. Policies and measures for reducing environmental pollution generally imply additional costs for industry and consumers such as environmental taxes. Thus it is important for the acceptance of the measure to show that the benefits, for example reduced health risks, outweigh or justify the costs. The benefit can be expressed as avoided external costs. (ExternE, 2005). The UK has at least two taxes based on externality estimates which, in turn, contain elements of external estimates taken from energy benefit studies (the aggregates tax and the landfill tax). (NEA, 2001)

5. The fifth area of application is the assessment of health and environmental impacts occurring in a region due to activities of different economic branches, in short green accounting. For example one could monetise the health effects occurring due to emission of different pollutants, and can then rank different source categories, economic sectors or pollutants (NEA, 2001)

6. **It can be used for awareness raising**, i.e. simply drawing attention to the fact that all energy sources have externalities which give rise to economically inefficient allocations of resources.(NEA, 2001).

2.2 EXTERNALITIES IN RENEWABLE ENERGY

The externalities are measured along the fuel chain of the energy technology rather than just during the operation phase of the life cycle. The externalities of the renewable energy systems accounted in this thesis are as follows,

1. Environmental impact
2. Global warming impact
3. Accidents

Environmental Impact

The emission of pollutants such as SOx, NOx and particulate matters cause various health impacts, loss of habitat by the means of the environmental media into which the pollution is released such as air, soil,water. Apart from that, there are noise pollution, radiation released during the entire fuel chain. These impacts are measured.

Global Warming Impact

The greenhouse gases emitted cause the global warming each GHG based on their global warming potential. These impacts are measured in this sector. It has to be noted that while the studies on the damage cost of climate change is increasingly significant, there is still a huge degree of uncertainties on the possible consequences.

Accidents

The fuel chain includes various activities starting from mining the minerals, (fuels in case of fossil plants) required to build the components, manufacturing processes, transportation, commissioning, operation and maintenance. There are risky tasks involved along the fuel chain path. The public risks and unwanted accidents cause an inconvenience. These impacts because of the accidents are measured for each fuel chain.

2.3 UNCERTAINITIES

When it comes to the measurement of externalities, the nature of uncertainties are not greatly due to the scientific nature of the data or the model uncertainty. It is rather the ethical dilemma such as the value of the lost life years in different regions of the world, uncertainty about the future. One approach to reduce the range of results arising from different assumptions on discount rates, valuation of mortality, etc. is to reach agreement on (ranges of) key values. (ExternE, 2005)

Damage cost estimates are usually accompanied by large degree of uncertainties.

It is very difficult to determine the current level of emissions. In order to achieve exact numbers, every emission source should be under permanent measurement. This is economically not feasible. Therefore, estimations of the emissions about similar sources are based on a representative source.

While considering the dispersion of the emission o analyse the impact of the pollutants, meteorological conditions are estimated to understand the direction, distance of dispersion. The weather forecast with which the meteorological conditions are modelled are always accompanied with huge degree of uncertainty because of the complex behaviour of regional and local weather.

Besides all the uncertainties, efforts have been made by many organizations to calculate the external costs of the energy systems, be it for market or non-market values. This is because an uncertainty by a factor of three is better than infinite uncertainty. Second, in many cases the benefits are either so much larger or so much smaller than the costs that the implication for a decision is clear even with the uncertainty. (ExternE, 2005) . With two and half decades of research, the knowledge on externalities of energy have been quite developed. It is only with time and continuous improvement of the studies, we can reduce the degree of uncertainties.

CHAPTER 3. RENEWABLE ENERGY TECHNOLOGIES

3.1 LIFE CYCLE ASSESSMENT

When comparing environmental issues of different options fulfilling a similar function, it is important to consider the complete life cycle and not just the operation phase of the system. Various impacts and benefits may occur at different phases of the life cycle of the energy system. The most important phases may not be the same when two options are compared (Athanasios Rentizelas et al, 2014). Hence, for the calculation of the externalities of the renewable energy systems, studies assessing the entire fuel cycle are considered. Impacts induced along the full life cycle is considered, including the extraction of the fuel, its transportation, the construction of the power generation facility, the combustion or generation of electricity at the plant and the final disposal of the waste (Anil Markandya, 2012).

The life cycle of the electricity generation system can be sub classified into two types based on the use of fuel. In cases like fossil fuel or biomass, the life cycle of the fuel plays a crucial role whereas, in case of other renewable fuels such as wind and solar, the construction phase of the plant has the major impacts. The general overview of the life cycle scope of an electricity generation system is pictured in the figure 8.

While the life cycle scope of each renewable technology is discussed further below, an overview of the different phases assessed in the electricity system are,

1. Fuel preparation (exploration and prospecting of fuel resources, fuel resource extraction and processing, and fuel transports)
2. Infrastructure (construction of power plant including exploration, prospecting and extraction of ores, minerals, etc., material manufacture, production of components and transports)
3. Operation (normal malfunctions, incineration of operational waste, disposal processes, handling of fuel residues)
4. End-of-life processes (incineration of waste and disposal processes).

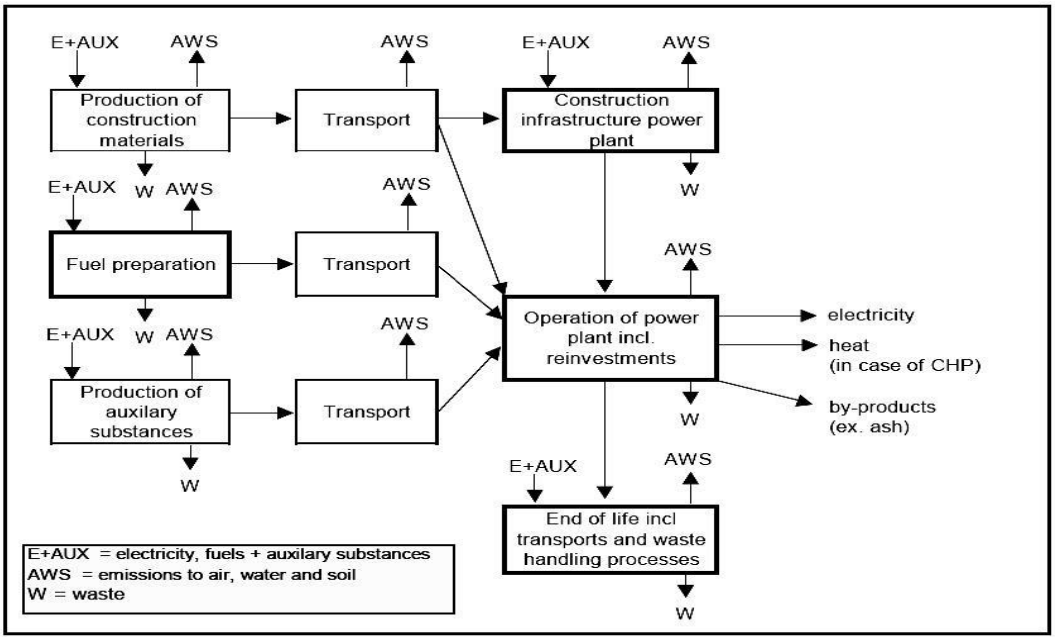
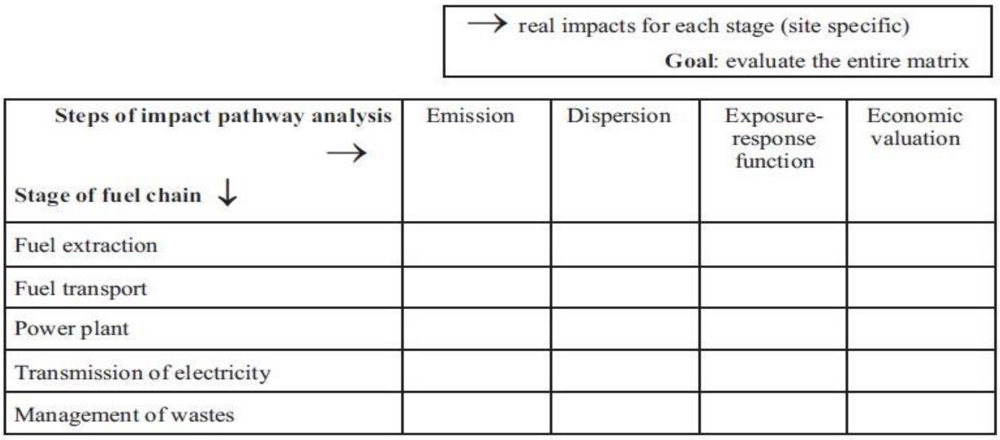


Figure 8: The life cycle scope of electricity generation systems (Setterwall et al, 2003)

In the impact pathway approach adapted in the measurement of the externalities in the studies, the life cycle of the energy system in considered. The externality studies discussed further uses LCA in combination with IPA (impact pathway analysis) to get a complete assessment of external costs due to electricity production, by involving impacts that occur upstream and downstream of the power plant itself. That practice requires a modification if the external costs upstream or downstream have already been completely internalised and the studies have cautiously assessed considering the situation.

The need to include upstream or downstream impacts in the external cost calculations arises from the lack of complete internalisation by the current environmental policies. If an external cost that arises upstream or downstream has already been internalised by an optimal pollution tax or by trade-able permits that are auctioned by the government, it should no longer be included to avoid double counting to the external cost calculation.

The Life cycle assessment employed in the Impact Pathway Approach hence involves assessing the emissions, dispersion and their dose-response function to analyse the impact along each step of the fuel cycle.



→ real impacts for each stage (site specific)
Goal: evaluate the entire matrix

Steps of impact pathway analysis → **Stage of fuel chain** ↓	Emission	Dispersion	Exposure-response function	Economic valuation
Fuel extraction				
Fuel transport				
Power plant				
Transmission of electricity				
Management of wastes				

Figure 9: LCA employed in the Impact Pathway Approach (ExternE, 2005)

3.2 SOLAR PHOTOVOLTAIC

3.2.1 INTRODUCTION

Solar energy refers to sources of energy that be attributed to light of the sun or heat generated by the sunlight. Photovoltaic (PV) cells are semiconductor devices which directly convert solar energy into direct current (DC) electricity. Photovoltaic acquires the name from the process of converting light (photons) to electricity (voltage), which is called the PV effect. While the net solar energy reaching earth every day is enormous, available energy at any specific point is modest. The amount of energy derived from the solar panels depends on the ambient solar level, the collector efficiency, angle of tilt of the solar panels and various other factors.

Today, PV is one of the fastest growing renewable energy technologies and it is expected that it will play a major role in the future global electricity generation mix. A connection of several PV modules is a string and all strings are a PV generator. Due to this modularity the installation possibilities concerning the installed power, the arrangement, or the location have a wide range. Hence, they are one of the most “democratic” renewable technologies, in that their adjustable modular size means that they are within the reach of individuals, co-operatives and small-businesses who wants to have their own electricity generation.

Solar PV technology have significant benefits, including:

- Solar PV technologies are highly modular and can be used virtually anywhere, unlike many other electricity generation technologies.
- Unlike conventional fossil fuels, solar PV has no fuel costs and relatively low operation and maintenance (O&M) costs. PV can therefore offer a price hedge against volatile fossil fuel prices.
- Although variable, solar PV has a high coincidence with peak electricity demand driven by cooling in summer and year round in hot countries.

A PV system consists of PV cells that are grouped together to form a PV module, and the auxiliary components (i.e. balance of system - BOS), including the inverter, battery, control system and other auxiliaries.

PV cell technologies are usually classified into three generations, depending on the basic material used and the level of commercial maturity:

- First-generation PV systems are fully commercial and use the wafer-based crystalline silicon (c-Si) technology, either single crystalline (sc-Si) or multi-crystalline (mc-Si).
- Second-generation PV systems are in the early market deployment stage and are based on thin film PV technologies and generally include three main families:
  - 1) amorphous (a-Si) and micromorph silicon (a-Si/μc-Si)
  - 2) Cadmium-Telluride (CdTe)
  - 3) Copper- Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).
- Third-generation PV systems include novel technologies, such as concentrating PV (CPV) and organic PV cells that are still under demonstration or have not yet been widely commercialised.

concepts under development (IRENA, 2012b)

First Generation Technologies

Silicon is one of the most abundant elements in the earth‘s crust. Crystalline silicon is the material most commonly used in the PV industry, and wafer-based c-Si PV cells and modules dominate the current market. This mature technology utilises the accumulated knowledge base developed within the electronic industry. Crystalline silicon cells are classified into three main types depending on how the Si wafers are made. Crystalline silicon technologies accounted for about 87% of the global Photovoltaic market in 2010. The efficiency of crystalline silicon modules ranges from 14% to 19%. While first generation technology are mature, cost reductions are possible through improvements in material and manufacturing processes. (IRENA, 2012b)

Second Generation Technologies

After more than 20 years of first generation technologies, thin-film solar cells are beginning to be deployed in significant quantities. Thin-film solar cells are comprised of successive thin layers of solar cells deposited onto a large, inexpensive substrate such as glass, polymer, or metal. They require a lot less semiconductor material, such as up to 99% less material than crystalline solar cells, to manufacture in order to absorb the same amount of sunlight. Because of this, their production and material costs are very low. Yet, currently their efficiencies are much lower than crystalline solar cells. The efficiencies are in the range of 10 to 16%.

Three basic types of thin film solar cells are,

1. Amorphous silicon (a-Si and a-Si/µc-Si);
2. Cadmium Telluride (Cd-Te); and
3. Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS). (IRENA, 2012b)

Amorphous silicon cells together with the CdTe cells are the most widely known cells. A number of companies are developing light and flexible a-Si modules suitable for flat and curved surfaces such as roofs and facades. While CdTe have lower production costs and higher efficiencies, their toxicity limits their application. While current module efficiencies are in the range of 7% to 16%, efficiencies of up to 20.3% have been achieved in the laboratory, close to that of c-Si cells (Green M.A et al, 2011)

Third Generation Technologies

Third-generation PV technologies are at the pre-commercial stage and vary from technologies under demonstration like the multi-junction concentrating PV to novel concepts in need of more research and development such as quantum-structured PV cells. There are four types of third-generation PV technologies:

1. Concentrating PV (CPV)
2. Dye-sensitized solar cells (DSSC)
3. Organic solar cells
4. Novel and emerging solar cell concepts. (IRENA, 2012b)

3.2.2 MARKET TREND

PV is one of the fastest growing renewable energy technologies today and is projected to play a major role in global electricity production in the future. Driven by attractive policy incentives, the global installed PV capacity has multiplied by a factor of 37 in ten years from 1.8 GW in 2000 to 67.4 GW at the end of 2011, a growth rate of 44% per year. (EPIA, 2012).

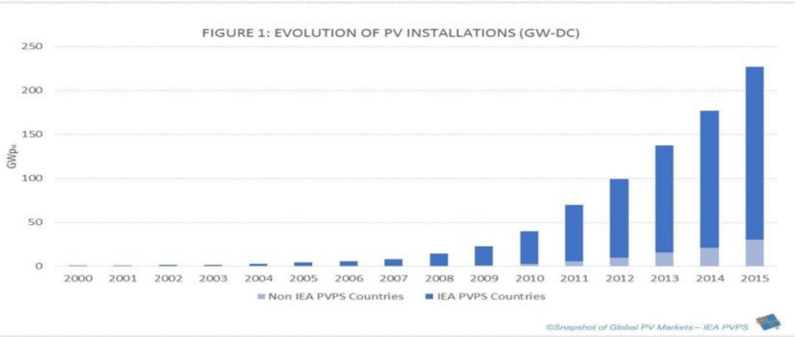


Figure 10: Global market development for PV over the years (IEA PVPS, 2016)

In 2015, the PV market broke several records in the global expansion with a market growth of 25% to previous year and reached a capacity of 227 GW electricity production. The graph in the figure 11 shows the global market development of PV sector over the years. The largest European market in 2015 was UK with 3.51 GW, followed by Germany (1.46 GW) and a stable French market of 0.87 GW. PV represents around 1.3% of the global electricity demand, it represents at least 3.5% of the electricity demand in Europe and 7% of the peak electricity demand. (IEA PVPS, 2016). The graph of figure 11 shows the annual production of electricity from PV among different regions.

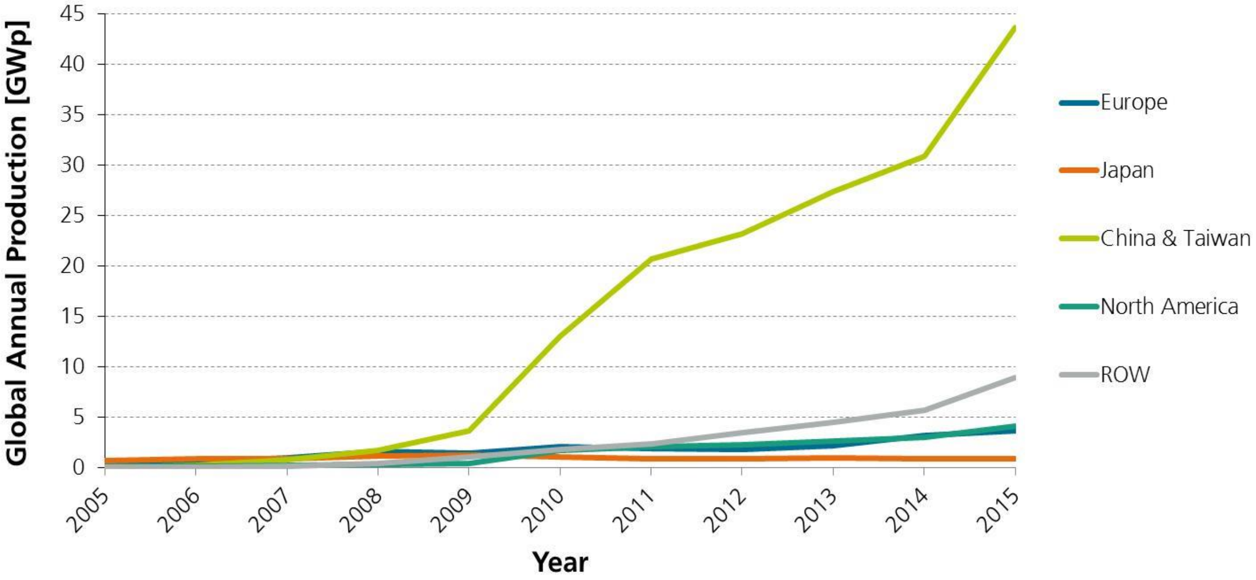


Figure 11: Global annual production of electricity from PV (Kovach-Hebling, 2016)

This rapid growth is boosted by declining PV module prices, government incentives and other forms of policy support. Many of these policies are created to stimulate PV market growth and mature the technology thus spur the price reductions necessary to make PV-generated electricity cost competitive without incentives. For an example, the U.S. Department of Energy’s Sun Shot Initiative aims to achieve PV system price reductions that reduce the cost of PV-generated electricity by about 75% between 2010 and 2020. (D. Feldman et al, 2014).

Among the PV modules, Si-wafer based PV technology accounted for about 93 % of the total production in 2015. The share of multi-crystalline technology is now about 69 % of total production. In 2015, the market share of all thin film technologies amounted to about 7 % of the total annual production. (Kovach-Hebling, 2016). The figure 12 represents the percentage of global production of PV module by each technology.

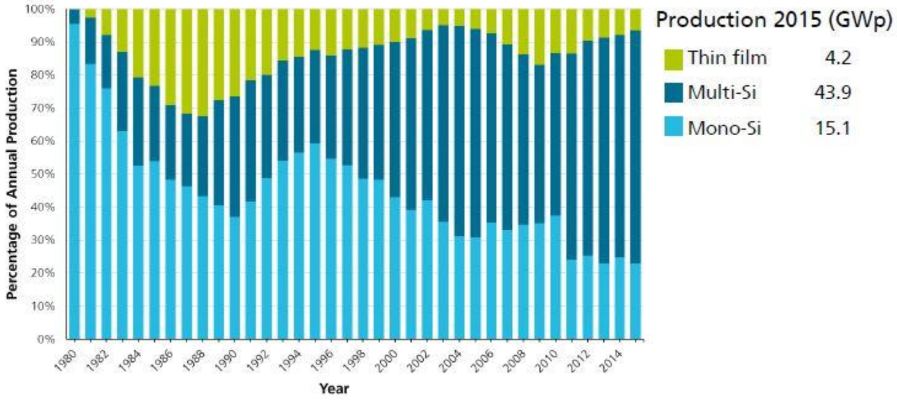


Figure 12: PV Percentage of Annual Production by Technology (PSG AG, 2014)

As the cost of PV systems are steadily decreasing, the energy payback time has considerable reduced over the years. It should be noted that the payback time is highly dependent on the geographical location as demonstrated by the figure 13. PV systems in Northern Europe need around 2.5 years to balance the input energy, while PV systems in the South equal their energy input after 1.5 years and less, depending on the type of technology installed.

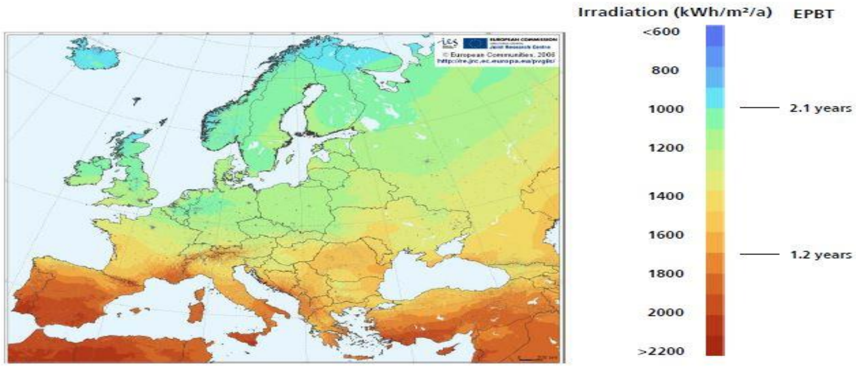


Figure 13: Energy Pay-Back Time of Multi crystalline Silicon PV Rooftop Systems - Geographical Comparison (PSG AG, 2014)

3.2.3 LIFE CYCLE OF SOLAR PV

The main life cycle phases of a PV system are (as shown in the figure 14),

(1) Production of raw materials,

(2) Raw material processing and purification,

(3) The manufacture of modules and balance of system (BOS) components,

(4) The installation and use of the systems and

(5) Decommissioning and disposal or recycling

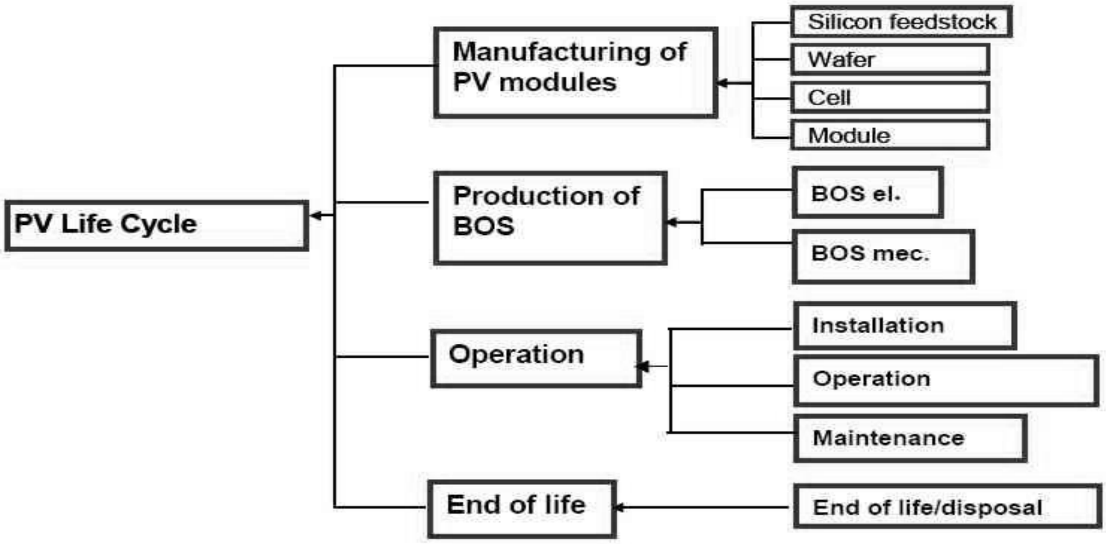


Figure 14: Life cycle phase of PV system (Frankl et al, 1998)

The first step for the production of crystalline silicon modules is the production of the silicon feedstock. Metallurgical-grade silicon (MG-Si) is prepared from quartz sand within an arc furnace at temperatures higher than 1500 °C. This MG-Si has to be purified further into electronic-grade silicon (EG-Si). After several stages of purification and extraction, Poly-crystalline silicon produced by the silicon industry is directly sold as feedstock to the PV industry.

After continuous scraps washing, ingot growth, squaring, ingot cutting and purification, sc-Si wafers are produced. The PV cells are then manufactured with the wafers. The main points of concern for PV cell manufacturing are electricity consumption and emission of chemicals into the water. Also, in the wafer production as well as in the cell manufacturing silicon waste is produced. After the PV cells are manufactured, the modules are assembled. The life time of the current PV modules are around 25 years. Apart from the manufacturing of the panel, the impact share of BOS over the whole life cycle of PV systems is mainly caused by indirect impacts related to the production processes of materials used for the mounting structures of the PV modules (steel, concrete, aluminium etc.).

The installation and maintenance of the PV system should also be considered which includes the transportation, replacement of invertors and other parts. The end of life of the system involves dismantling, recycling of metal and further disposal.

The emissions along all these processes are considered in the externality assessment over the fuel cycle.

3.3. BIOMASS

3.3.1 INRODUCTION

Biomass is any fuel derived from plant matter in the recent past, and includes wood, crops, crop residues, and animal waste. Fossil fuel was also once biomass, but in the ancient past. Biomass is humanity’s original energy source, in use since the discovery of fire. It still accounts for 10% of world primary energy supply and is the world's largest single renewable energy source, since much of the world's population uses wood, charcoal, straw, or animal dung as cooking fuel (IEA, 2012).

There are plenty of advantages in using biomass energy over fossil fuels such as,

Biomass is a renewable energy source which is considered as carbon neutral (when produced in a sustainable way).

It is easily produced in almost any environment, regenerated quickly and has a history of use for direct heating applications.

Biomass is the only fuel available for renewable, combustion based electricity generation. For these reasons, it has gained significant attention as a substitute for fossil fuels. (Evans et al., 2010).

The biomass from the forest residues can improve forest sustainability by reducing the load of flammable material thus decreasing the risk of wildfires and pest outbreaks (Susaeta et al, 2011)

Biomass can be processed and stored to utilize them according to the requirement. Unlike, other intermittent renewable sources, biomass can be combusted accordingly to meet the required demand.

There are four primary technologies to utilize biomass for electricity. They are,

1. Pyrolysis
2. Gasification
3. Direct Combustion
4. Co-firing

Pyrolysis is an anaerobic thermal decomposition of the biomass fuel into gas and vapour. Later, the gas is combusted in the gas turbine or used for various chemical processes.

In gasification, the biomass fuel is partially oxidized in the elevated temperatures to form producer gas of high calorific value. The additive can be oxygen, steam or air depending on the requirement. The producer gas is combusted in the gas turbine, preferable combined cycle power plant.

Whereas in direct combustion, complete oxidation of the biomass fuel in the presence of air is done. The heat during the combustion is used to produce steam which runs the turbine in the Rankine cycle.

While direct combustion is the cheapest of all the three technologies, it is inefficient compared to gasification and pyrolysis. The latter technologies however, require high investment in the process control.

Co-firing is also a direct combustion technology where the biomass is combusted along with the coal in the boilers to produce steam for the steam turbine

COMBUSTION

There are two main components of a combustion based biomass plant:

1) The biomass-fired boiler that produces steam

2) The steam turbine which is then used to generate electricity.

The two most common forms of boilers are stoker and fluidised bed. These can be fuelled entirely by biomass or can be co-fired with a combination of biomass and coal or other solid fuels (IRENA, 2012a)

Stoker boilers burn fuel on a grate, producing hot flue gases that are then used to produce steam. The ash from the combusted fuel is removed continuously by the fixed or moving grate. Fluidised bed boilers suspend fuels on upward blowing jets of air during the combustion process. The fuel size in the fluidized bed boilers are very small in the range of 6-12 mm. They are categorised as either atmospheric or pressurised units. Atmospheric fluidised bed boilers are further divided into bubbling-bed and circulating-bed units; the fundamental difference between bubbling-bed and circulating-bed boilers is the fluidisation velocity which is higher for circulating fluidized bed boilers. Circulating fluidised bed boilers separate and capture fuel solids entrained in the high velocity exhaust gas and return them to the bed for complete combustion. Atmospheric-bubbling fluidised bed boilers are commonly used for biomass as they effectively generate electricity from biomass with a higher moisture content than in a stoker boiler (UNIDO, 2009)

CO-FIRING COMBUSTION

Co-firing is combusting a small fraction of biomass fuel along with the coal in a utility boiler. In Europe, approximately 45 GW of thermal power generation capacity is co-fired with biomass with from as little as 3% to as much as 95% biomass fuel content. The advantage of biomass co-firing is that, on average, electric efficiency in co-firing plants is higher than in dedicated biomass combustion plants. (IRENA, 2012a) . Co-firing is considered as one of the cost effective method to reduce the net carbon dioxide emitted from the coal based power plants. The use of biomass in the ordinary coal boiler has some drawbacks such as slagging, clinkering and corrosion of the tubes due to the high moisture content and low energy density of the biomass fuels.

There are three possible technology set-ups for co-firing as mentioned in the figure 15. They are,

1. Direct co-firing, whereby biomass and coal are fed into a boiler with shared or separate burners
2. Indirect co-firing, whereby solid biomass is converted into a fuel gas (by gasification) that is burned together with the coal
3. Parallel co-firing, whereby biomass is burned in a separate boiler and steam is supplied to the coal-fired power plant. (IRENA, 2012a)

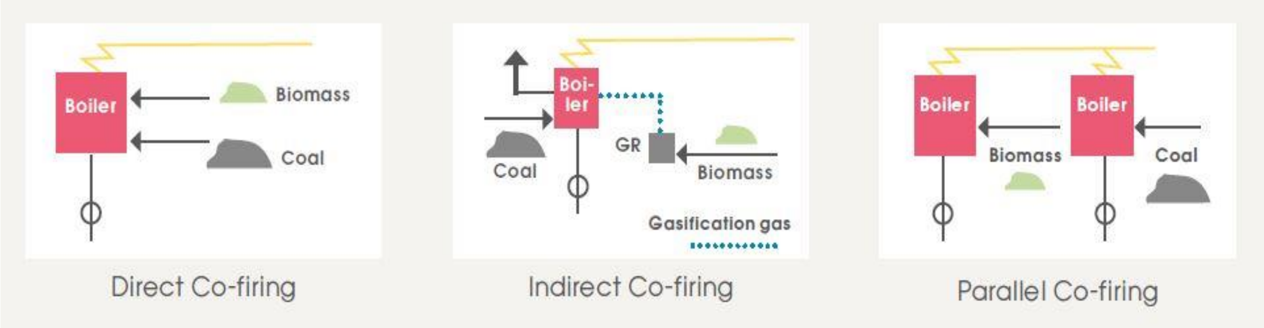


Figure 15: Biomass co-firing configurations (EBIONET, 2003)

ANAEROBIC DIGESTION

Anaerobic digestion is the process of conversion of biomass fuel into biogas by the microorganisms in the absence of oxygen. It is an effective way to treat biomass with high moisture content, organic wastes, municipal wastes and also energy crops. The products of anaerobic digestion are mainly biogas and the residue digestate. The biogas is usually a mixture of methane, carbon dioxide, ammonia and minor proportion of sulphur dioxide and hydrogen. The residue digestate can be used as fertilizer after proper treatment. The biogas can be used to produce heat and power and are good substitute for natural gas after proper gas pre-treatment. The biogas plant are effective ways to produce heat and electricity in the rural areas. It is one of the commonly used technology in the decentralised electrification.

In Europe in mid-2011, Germany, with 7090 digesters, was the leading country for both the number and installed capacity of anaerobic digesters. The total installed electrical capacity of these plants is 2394 MW. Virtually all of this capacity is located in the agricultural sector where maize silage, other crops and animal slurry are used (IRENA, 2012a)

GASIFICATION

Gasifier technologies offer the possibility of converting biomass into a producer gas, which can be burned in simple or combined-cycle gas turbines at higher efficiencies than the combustion of biomass (IRENA, 2012a). Upon partial oxidation, the biomass feedstock yields producer gas which is a composition of carbon monoxide, carbon dioxide, hydrogen gas and small proportion of methane.

Although gasification technologies are commercially available, more needs to be done in terms of R&D and demonstration to promote their widespread commercial use, as only around 373 MW of installed large-scale capacity was in use in 2010, with just two additional projects totalling 29 MW planned for the period to 2016 (US Department of Energy, 2010). This is also because the process control of gasification is tedious to achieve the desired results which increases the capital cost. The fuel range for gasification is very high and plenty of research is done on new feedstock.

The gasification process yields a producer gas that contains a range of contaminants, depending on the feedstock and the gasification process. These contaminants are not usually a major problem when the gas is combusted in a boiler or an internal combustion engine. However, when used in turbines to achieve higher electric efficiencies, some form of gas clean-up will be required to ensure the gas reduces contaminant concentrations to harmless levels (IRENA, 2012a). Emission control is much easier in the gasification process compared to combustion as the producer gas in gasification is at higher temperature and pressure than in combustion. These higher temperatures and pressures allow for easier removal of sulphur and nitrous oxides (SOx, and NOx), and other trace contaminants. It is also much efficient to remove carbon dioxide in gasification compared to direct combustion.

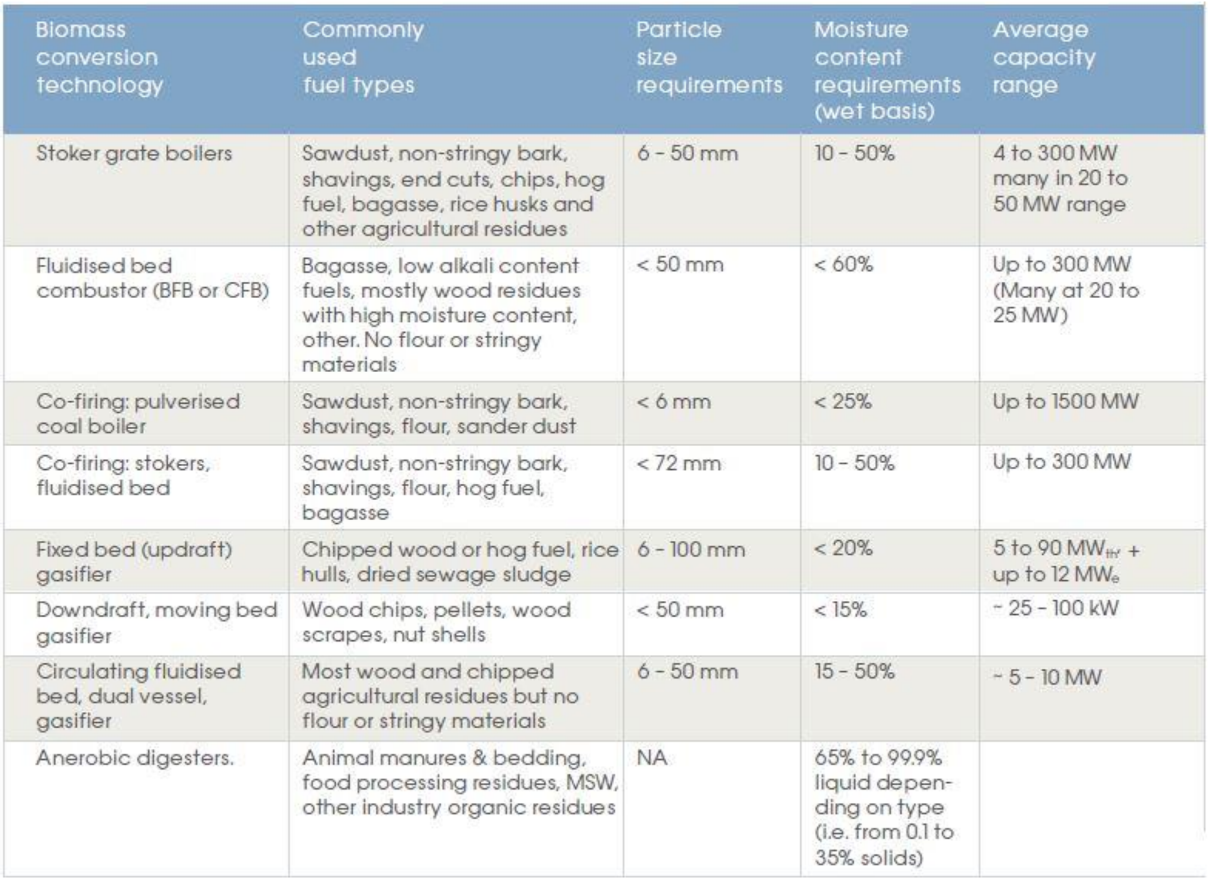
PYROLYSIS

In a way, pyrolysis is a subset of the gasification system. Pyrolysis uses the same process as gasification, but the process is limited to between 300°C and 600°C. Conventional pyrolysis involves heating the original material in a reactor vessel in the absence of air, typically at between 300°C and 500°C, until the volatile matter has been released from the biomass. At this point, a liquid bio-oil is produced, as well as gaseous products and a solid residue. The residue is char, commonly known as charcoal, a fuel which has about twice the energy density of the original biomass feedstock and which burns at a much higher temperature. Research and development on using the charcoal and the oil produced by this technology for electricity production is going on. (IRENA, 2012a)

FUEL TYPES

In general, the characteristics of an ideal energy culture may be enumerated as: high output (maximum production of dry matter per hectare), low energy requirement for production, low production cost, composition with the least possible contaminants, low nutrient requirements and high dry matter yields (Carneiro, Ferreira, 2012). The feedstock types of biomass is vast with myriad of properties and they can be classified into various types based on their source. A critical issue for the biomass feedstock is its energy, ash and moisture content, and homogeneity. These will have a high impact on the cost of biomass feedstock per unit of energy, transportation, pre-treatment and storage costs, as well as the appropriateness of different conversion technologies. The moisture content can vary vastly from 10% to 60%. The high moisture content can reduce the energy content of the fuel, induce corrosion in co-firing or direct combustion and increase the transportation and pre-treatment costs. Similarly, high ash content can lead to deposit formation called slagging inside the boiler or gasifier. The size and density of the feedstock can affect the rate of heating inside the combustion chamber. Hence, understanding of the feedstock properties plays very crucial role in deciding the mode of combustion technology and the feedstock handling methods. (IRENA, 2012a)

The figure 16 gives the list of feedstock used by different technologies and their primary properties. Woods, bagasse and saw dust are some of the widely used biomass feedstock.



Biomass conversion technology	Commonly used fuel types	Particle size requirements	Moisture content requirements (wet basis)	Average capacity range
Stoker grate boilers	Sawdust, non-stringy bark, shavings, end cuts, chips, hog fuel, bagasse, rice husks and other agricultural residues	6 - 50 mm	10 - 50%	4 to 300 MW many in 20 to 50 MW range
Fluidised bed combustor (BFB or CFB)	Bagasse, low alkali content fuels, mostly wood residues with high moisture content, other. No flour or stringy materials	< 50 mm	< 60%	Up to 300 MW (Many at 20 to 25 MW)
Co-firing: pulverised coal boiler	Sawdust, non-stringy bark, shavings, flour, sander dust	< 6 mm	< 25%	Up to 1500 MW
Co-firing: stokers, fluidised bed	Sawdust, non-stringy bark, shavings, flour, hog fuel, bagasse	< 72 mm	10 - 50%	Up to 300 MW
Fixed bed (updraft) gasifier	Chipped wood or hog fuel, rice hulls, dried sewage sludge	6 - 100 mm	< 20%	5 to 90 MW_{th}, + up to 12 MW_e
Downdraft, moving bed gasifier	Wood chips, pellets, wood scrapes, nut shells	< 50 mm	< 15%	~ 25 - 100 kW
Circulating fluidised bed, dual vessel, gasifier	Most wood and chipped agricultural residues but no flour or stringy materials	6 - 50 mm	15 - 50%	~ 5 - 10 MW
Anerobic digesters.	Animal manures & bedding, food processing residues, MSW, other industry organic residues	NA	65% to 99.9% liquid depending on type (i.e. from 0.1 to 35% solids)	

Figure 16: Biomass Power Generation Technologies and Feedstock Requirements (US EPA, 2007)

3.3.2 MARKET TRENDS

Power generation from biomass can be achieved with a wide range of feed stocks and power generation technologies. In each case, the technologies available range from commercially proven solutions with a wide range of technology suppliers such as direct combustion to those that are only just being deployed at commercial scale like gasification. There are other technologies that are at an earlier stage of development. Graph in figure 17 gives the degree of technology maturity. (EPRI, 2010)

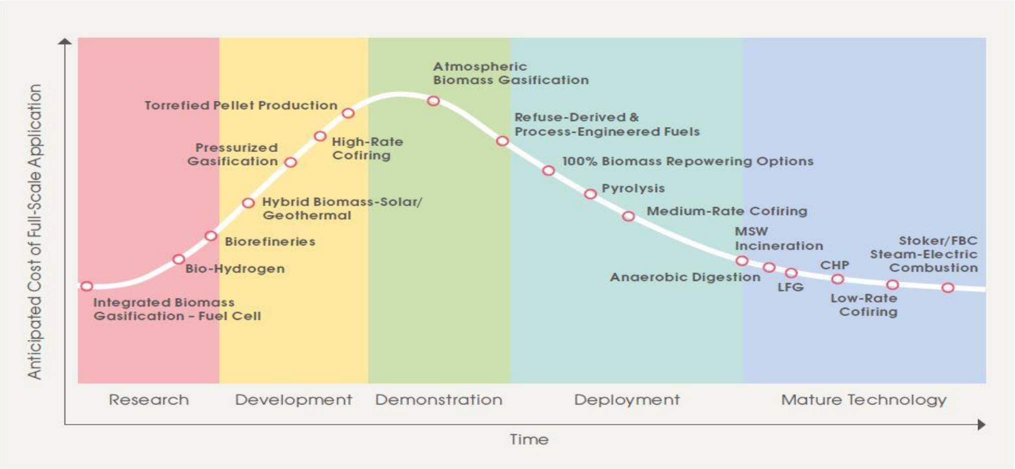


Figure 17: Biomass power generation technology maturity status (EPRI, 2010)

In 2010 the global installed capacity of biomass power generation plants was between 54 GW and 62 GW (REN21, 2011 and Platts, 2011) which shows that the power generation from biomass represents 1.2% of total global power generation capacity (Platts, 2011 and IEA, 2011). The graph in figure 18 shows the share of each region in the biomass energy market. It should be noted that biomass power generation is widely used for decentralized electricity generation.

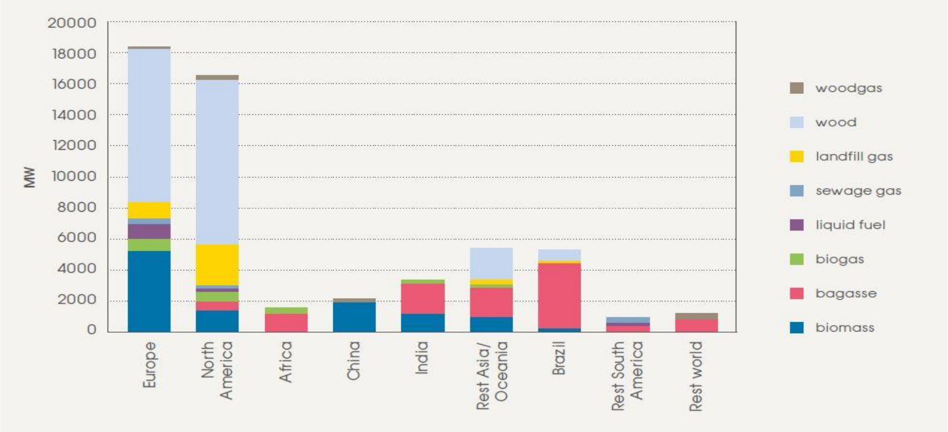


Figure 18: Global grid -connected biomass capacity in 201 0 by feedstock and country/region (MW) (Platts, 2011)

In Europe, 61% of total European installed capacity using solid biomass (excluding wood chips) is in England, Scotland and Sweden. Wood-fired biomass power capacity is concentrated in Finland, Sweden, England and Germany. Together these four countries account for 67.5% of European wood-fired biomass power generation capacity. Landfill gas capacity is concentrated in England with 45% of the European total, while biogas capacity is concentrated in Germany with 37% of total European capacity. In North America wood accounts for 65% of total installed capacity and landfill gas 16% (Platts, 2011). Wood is the prominently used feedstock followed by bagasse which is a by-product of sugarcane in the sugar industries. Bagasse is widely used for co-generation of heat and electricity for the sugar industries.

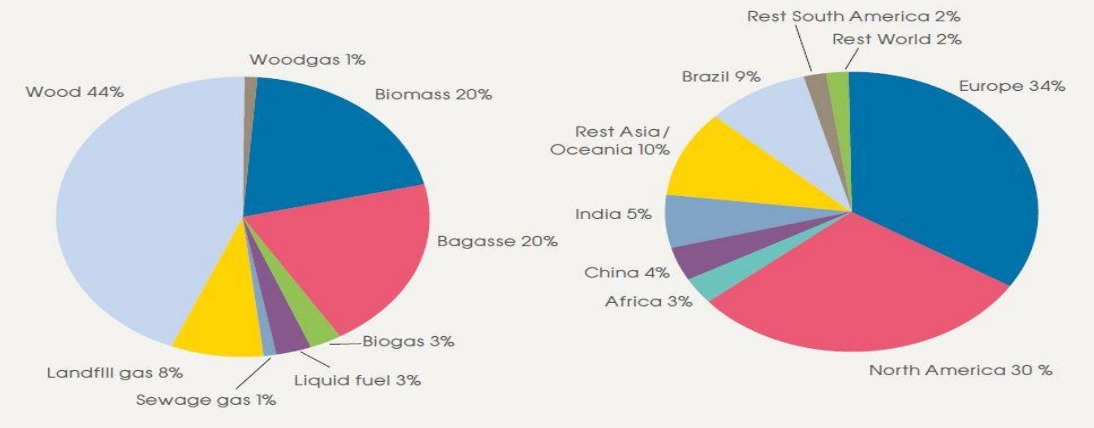


Figure 19: Share of global installed biomass capacity in 2010 by feedstock and country/region. (Platts, 2011)

Around 84% of total installed biomass power generation today is based on combustion with steam turbines for power generation from the solid fuels, with around half of this capacity also producing heat (combined heat and power) for industry or the residential and service sectors. By the end of 2011, around 45 GW of thermal capacity was being co-fired with biomass to some extent in Europe. In North America, around 10 GW of capacity is co-firing with biomass (IEA BioEnergy, 2012) With the research and development of gasification technologies, it is increasingly commercialized in the market. The producer gas is not only used for heat and electricity but in several chemical industries. The figure 18 shows the share of electricity generation by the nature of the feedstock.

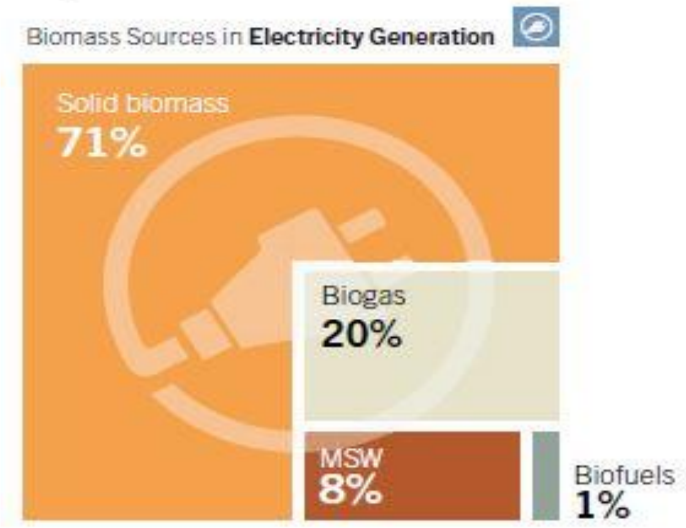


Figure 20: Share of bio sources 2015 (REN21, 2016)

3.3.3 LIFE CYCLE OF BIOMASS PLANT

The life cycle of biomass has the following phases as represented in the figure 21,

1. Production of fuels,

2. Construction of the plant,

3. Operation of the plant

4. The end of life.

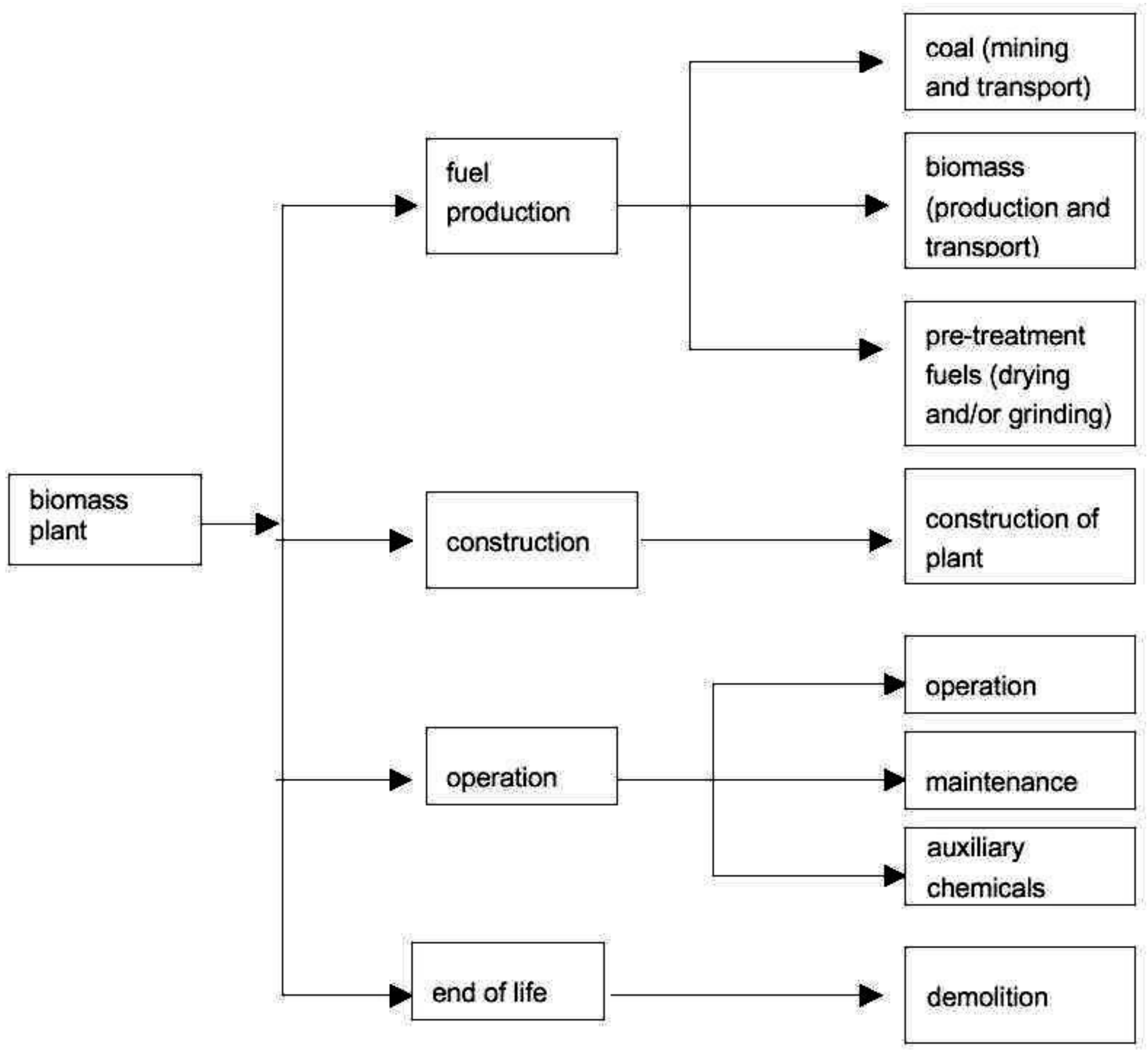


Figure 21: Life cycle phase of a biomass plant (Cuperus, 2003)

Since various types of biomass are available, the externality values are identified considering the woodchips feedstock. The life cycle stage starts from the fuel cutting, pruning, collection, transportation and pre-treatment of the fuel. The pre-treatment of the biomass involves grinding the woodblocks to chips according to the requirement of the combustion process involved. Certain feed stocks, especially with high moisture content, are torrified. The construction of the biomass plant includes the manufacturing of materials and metals as well as the use of electricity with all the respective upstream processes. Unlike other renewable sources, biomass operation process also emits several pollutants. In the life cycle phase operation, all these environmental effects which occur during the emission of the pollutants are considered. The maintenance of the plant undergoing wear and tear, the requirement of other auxiliary chemicals (such as bed material, lime stone for fluidized bed plants) are also considered. The end of life includes demolishing the plant and recycling the metal scrapes in the construction.

3.4 WIND

3.4.1 INTRODUCTION

Wind power technologies transform the kinetic energy of the wind into useful mechanical energy which is then converted into electrical energy. The kinetic energy of the air flow provides the required force to turn the wind turbine blades. That rotation, via a drive shaft, provide the mechanical energy to power the generator in the wind turbine. (IRENA, 2012). Wind Energy is one of the oldest known energy resources. Like biomass or hydro power, the available wind energy in most of the regions are finite and are highly dependent on the geographical location and the seasons. The average wind power not only varies greatly by site but also by the wind speed. The available wind energy is dependent on the function of cube of wind velocity. Hence, double the wind speed could yield eight times more available energy. Higher potential energy means lower cost per unit energy produced. While intermittency is a general characteristics of almost all the renewable resources, this high degree of dependency on the wind speed heavily challenges the wind energy technology.

The total wind resource potential depends on a several factors such as the average wind speed, turbine size, rotor diameter, density of turbine placement, land “free” for wind farms and so on. This is before consideration of whether the wind resource is located next to demand centres, transmission bottlenecks, economics of projects in different areas, etc. (Archer and Jacobson, 2005)

Wind power technologies are available in a range of sizes and styles and can generally be classified by whether they are horizontal axis or vertical axis wind turbines (HAWT and VAWT), by location as they are located onshore or offshore and the power generation capacity. (IRENA, 2012). An estimates global technical potential for energy production from both onshore and offshore wind installations are around 278 000 TWh. Assuming that only 10–15 % of this potential could be produced in a sustainable way, considering the urban and natural areas. The figure estimation of long-term wind energy output is approximately 39 000 TWh per year. (WBGU, 2003) The maximum energy conversion is proportional to the swept area of the rotor which is dependent on the rotor diameter. Hence, the blade design plays a key role in designing the wind turbine capacity and electricity output. The table 1 shows the impact of different design choices of turbine size, rotor diameter and hub heights in the electricity generated from wind in Denmark.

Generator Size (MW)	Rotor (m)	Hub Height (m)	Annual Production MWh
3.0	90	80	7089
3.0	90	90	7497
3.0	112	94	10384
1.8	80	80	6047

Table 1: Impact of turbine sizes, rotor diameters and hub heights on annual production (Nielsen et al, 2010)

The current average size of the grid connected wind turbines are around 1.16 MW (BTM Consult, 2011). Today’s utility-scale wind turbine generally has three blades, sweeps a diameter of about 80 to 100 metres, has a capacity from 0.5 MW to 3 MW and is part of a wind farm of between 15 and as many as 150 turbines that are connected to the grid. Small wind turbines are generally considered to be those with generation capacities of less than 100 kW. These smaller turbines are mostly used to power off-grid applications in rural areas. Intermediate-sized wind power systems of power capacity around 100 kW to 250 kW can electrify a cluster of small enterprises and can be grid-connected, mini-grid or off-grid. Small-scale wind are emerging as an important component of decentralized renewable electrification for rural communities in hybrid off-grid and mini-grid systems (IRENA, 2012)

Depending on the location of the wind turbine and their capacity they are primarily classified into three types,

1. Onshore wind systems
2. Offshore wind systems
3. Small turbine wind systems

ONSHORE WIND POWER SYSTEM

Onshore wind turbines are existing since long. In the recent years, it is one of the most affordable renewable energy sources. The onshore wind energy are getting cost competitive in many optimal sites. It can be scaled according to the power requirement and the local demand. Onshore wind farms are typically spread over a large land area. One of the reported issues is the avian fatality because of the large rotor blades of the wind turbines. While onshore wind farms are much cheaper compared to offshore turbines, the grid connectivity is also easier in the onshore cases.

OFFSHORE WIND POWER SYSTEM

The principal difference between the onshore and offshore wind turbines is the higher complex foundation required for the offshore wind turbines. Building such complex structures to bare the harsh marine environment increases the capital cost for the offshore wind systems. However, the key long-term constraint on wind in many countries is the growing difficulty in acquiring the approval for wind farms with high average wind speeds. With the right regulatory environment, offshore wind farms could help offset this challenge by allowing large wind turbines to be placed in high average wind speed areas in the marine. Thus, although offshore wind remains nearly twice as expensive to install as onshore wind, when built at appropriate sites, offshore wind installations can produce electricity 50% more than equivalent onshore wind farms because of the higher, sustained wind speeds which exist at sea leading to higher capacity factor (IEA, 2010)

Offshore wind farms are at the beginning phase of their commercial deployment. The reasons for the higher capacity factors and greater potential deployment are that offshore turbines can be,

1. Provision for taller and have longer blades, which results in a larger swept area and therefore higher electricity output.
2. Can be located at sites with higher average wind speeds and low turbulence.
3. Very large wind farms are possible. (IRENA, 2012)

SMALL WIND TURBINES

While there is no clear classification for small turbines, it is generally defined as a turbine with a capacity of 100 kW or lesser. Compared with utility-scale wind systems, small wind turbines usually have higher capital costs and lower capacity factors. They are primarily designed to meet the demand from un-electrified areas and can offer local economic and social benefits. Especially for off-grid electrification where these small systems can meet the local demands from small business hubs, farms and individual homes. They can be designed for capacity as low as 0.2 kW. Small wind turbines share of the total global wind power market was estimated at around 0.14% in 2010 and is expected to increase steadily to 0.48% by the year 2020 (Global Data, 2011)

3.4.2 MARKET TREND

Wind energy acquires significant share in the global electricity production. The global wind power generation at the end of 2015 was 432.9 GW, representing cumulative market growth of more than 17%. (GWEC, 2015) The graph in figure 21 shows the global cumulative installed capacity of wind power over the years from 2000 to 2015.

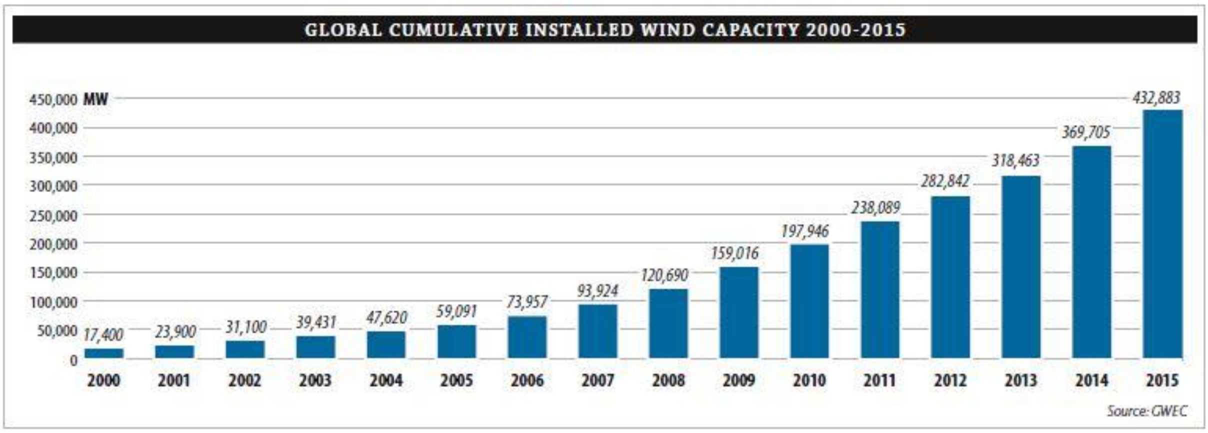
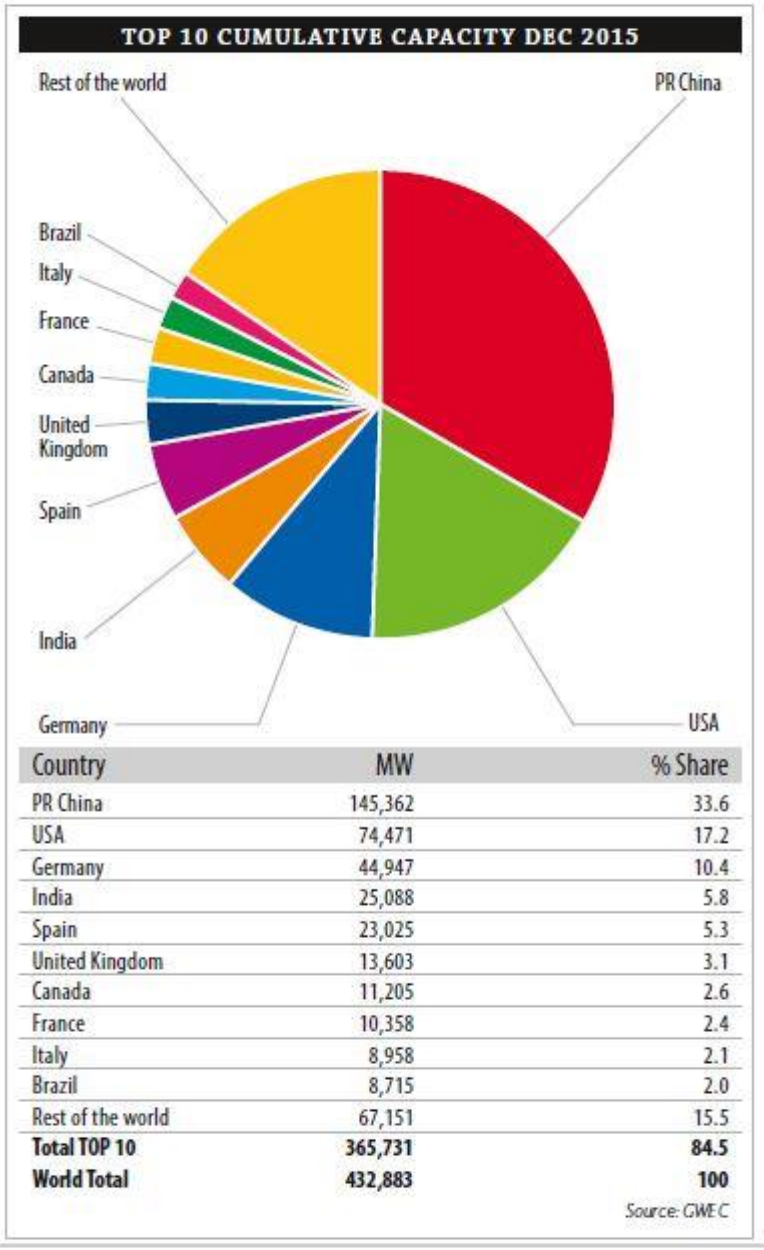


Figure 22: Global cumulative installed wind capacity from 2000 - 2015 (GWEC, 2015)

The market is still dominated by onshore wind and there remain significant onshore wind resources yet to be exploited. Offshore wind market is growing rapidly as they are in the early stages of commercial deployment, and reached a total installed capacity of 3118 MW at the end of 2010. (EWEA, 2009). Both developed and developing nations contributed to the wind energy market share. By the end of 2014, there were 26 countries with more than 1,000 MW installed capacity including 17 in Europe, 4 in Asia-Pacific (China, India, Japan & Australia), 3 in North America (Canada, Mexico, US) and 1 in Latin America (Brazil) and 1 in Africa (South Africa). (GWEC, 2015). The top ten countries and their cumulative installed capacity are listed below. While China takes the lead in the total market share, developing nations such as India and Brazil also have significant contribution.



Country	MW	% Share
PR China	145,362	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,205	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of the world	67,151	15.5
Total TOP 10	**365,731**	**84.5**
World Total	**432,883**	**100**

Source: GWEC

Figure 23: Top ten countries with high cumulative capacity in 2015 (GWEC, 2015)

Across Europe 13,805 MW of wind power was installed in 2015. The European Union members accounted for 12,800 MW in total.

In Europe, renewables accounted for 77% of new power plant installations in 2015 (22.3 GW out of 29 GW) of which wind accounted for 44% of renewable installations.

At the end of 2015, the EU had 142 GW of installed wind power capacity of which 131 GW was onshore and 11 GW offshore. EUR 26.4 billion was invested in wind energy in Europe in 2015, 40% higher than the total investment in 2014. While wind power led 2015 power installations, solar PV accounted for 29%; coal 16% and gas 6.4%. (GWEC 2015) The above statistics clearly depicts the growing market of wind power.

3.4.3 LIFE CYCLE OF WIND TURBINES

The life cycle of wind turbines consist of the following phases as represented in the figure 24,

1. Building
2. Operation and Maintenance
3. End of life

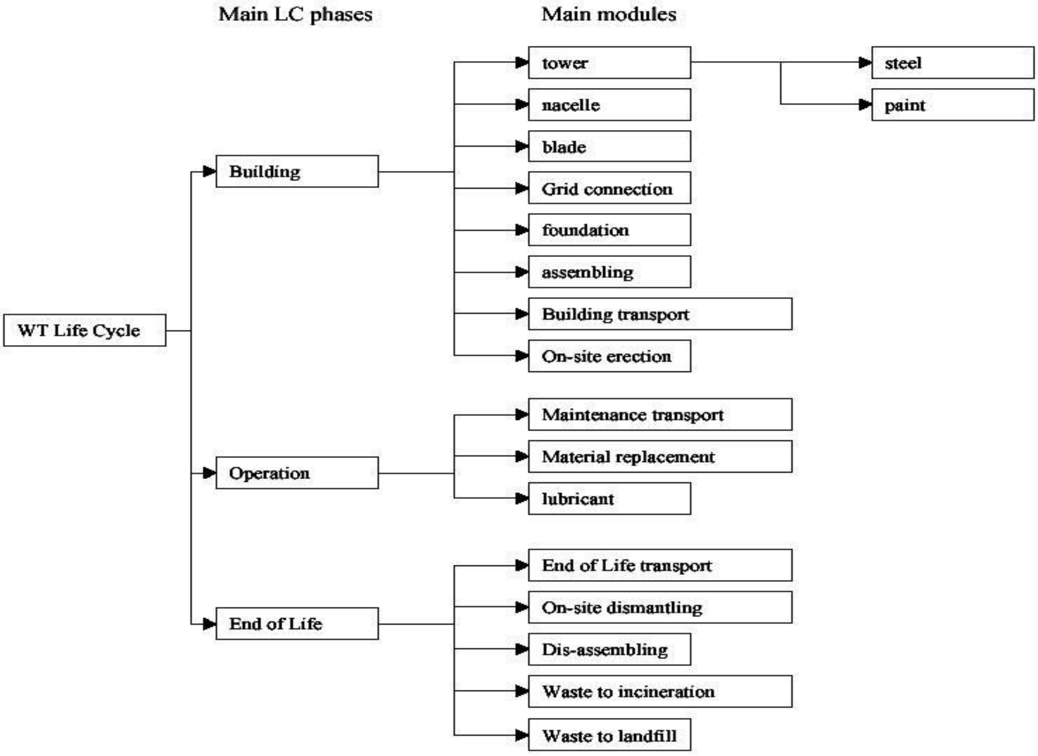


Figure 24: Life cycle phase of wind turbines (Chataignere at al, 2003)

The production of wind turbines include production of various components including tower, nacelle, blade, grid connection and foundation. The steel of the tower of wind turbine is usually galvanized steel whereas the steel for the foundation is generally secondary steel. For the grid connection, the transformer with its steel consumption is also taken into account. The assembling module includes the direct input (energy and water consumption but no raw materials) and output (such as emissions to air, waste and water) of the tower factory, the blade factory, the machine and controller factory, and the assembling factory as a part of their life cycle.

Most of the impacts are related to the building of the wind turbine. However, the end of life should also be taken into account. Most of the metal are recovered and the remaining scrape material are deposited on a landfill.

CHAPTER 4. REVIEW OF EXISTING EXTERNALITY STUDIES

The following externality studies are reviewed in this thesis.

1. External Costs of Energy (ExternE)
2. New Energy Externality Development for Sustainability (NEEDS)
3. Cost Assessment of Sustainable Energy Systems (CASES).

4.1 EXTERNAL COST OF ENERGY (EXTERNE)

In recent years there has been much progress in the analysis of public health risks of energy systems, thanks to several major projects to evaluate the external costs of energy in the USA and Europe. Of these, the ExternE (External Costs of Energy) Project of the European Commission has the widest scope and it is being continually updated to incorporate the latest scientific findings (the latest update at 2005). (NEA, 2001) Originally begun in 1991, the most recent ExternE studies were published between 2003 and 2005. ExternE includes a life cycle analysis and not only includes the externalities during the operation of the power plant but the whole life cycle. The ExternE methodology provides a framework for transforming impacts that are expressed in different units into a common unit – monetary values. (ExternE, 2005)

The ExternE studies utilize a bottom-up damage cost methodology to determine the social and environmental impacts of various pollutants emitted during the entire power generation lifecycle. The damages assessed include those from pollutants: particulate matter—both 'fine particles' of less than 2.5 microns diameter ($PM_{2.5}$) and 'inhalable coarse particles' of diameter less than 10 microns but more than 2.5 microns (PM_{10}); SO_2; NOx; Volatile Organic Compounds (VOC); ammonia; heavy metals; and radionuclides as well as damages related to greenhouse gas (GHG) emissions and accidents

METHODOLOGY

ExternE uses the Impact Pathway Approach. The impact pathway approach (IPA) is used to quantify environmental impacts as illustrated in Figure 25, the principal steps can be grouped as follows:

Emission: specification of the relevant technologies and pollutants, e.g. kg of oxides of nitrogen (NOx) per GWh emitted by a power plant at a specific site;

Dispersion: calculation of increased pollutant concentrations in all affected regions, e.g. incremental concentration of ozone, using models of atmospheric dispersion and chemistry for ozone (O_3) formation due to NOx ;

Impact: calculation of the cumulated exposure from the increased concentration, followed by calculation of impacts (damage in physical units) from this exposure using an exposure-response function, e.g. cases of asthma due to this increase in O_3;

Cost: valuation of these impacts in monetary terms, e.g. multiplication by the monetary value of a case of asthma. (ExternE 2005)

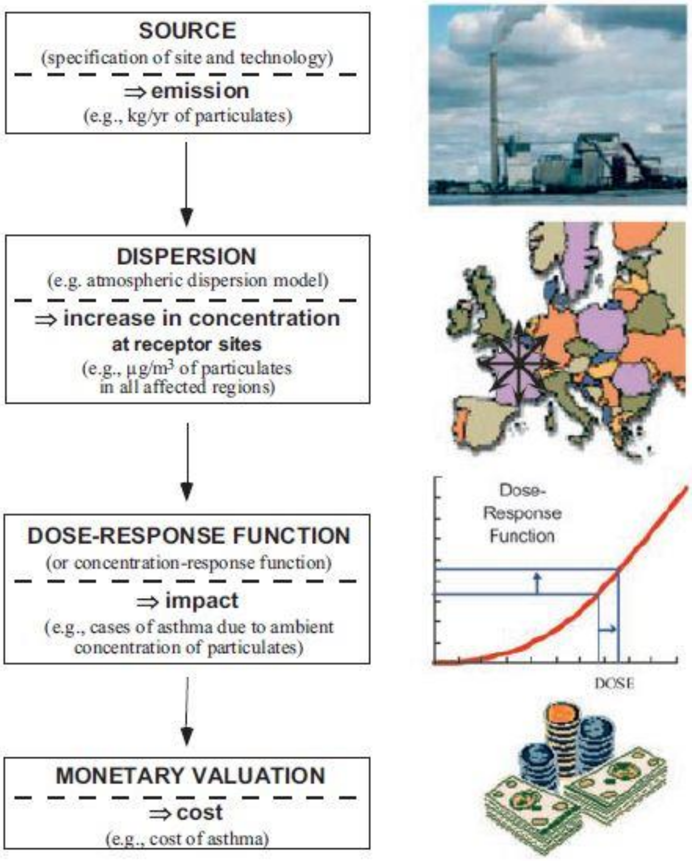


Figure 25: Impact Pathway Approach used in ExternE (ExternE, 2005)

The entire process is performed by the impact pathway EcoSense model. The model is site specific, and thus the distinct geologic, atmospheric, surrounding population density, land use and emission details of electricity generation sites can be modified to produce unique plant damage results. The monetary values are derived through techniques such as estimation of human health costs from public health records, lost work days, or epidemiology; market value of harvestable wildlife, timber, or plants; hedonic studies; or CV studies. The external cost of each technology was estimated at two different locations in each European country. The damages from a representative power plant were assessed at an ‘average’ location and a specific electricity generation plant.

For damages which are not calculated by the EcoSense model, such as GHG-related impacts and accidents related to transportation of fuel, the marginal costs of the damage and the lifecycle damages are assessed and then multiplied together to compute the total costs.

IMPACTS MEASURED

ExternE study measures the following impacts in its latest update in 2005:

1. Environmental impact

2. Global warming impact
3. Accidents

Environmental impacts:

“Environmental impacts here mean impacts that are caused by releasing either substances (e.g. fine particles) or energy (noise, radiation, heat) into the environmental media: air, soil and water. The substances and energy are transported and transformed and finally reach receptors (humans, plants, materials, ecosystems), where they cause risks and damage. Clearly, the methodology to use here is the impact pathway approach. Due to lack of knowledge, the pathway from emission to damage can sometimes not be quantified; in that case, other second best methods, e.g. marginal avoidance costs or restoration costs are used.” (ExternE, 2005)

Global warming impacts:

“For global warming, two approaches are followed. First, the quantifiable damage is estimated based on a top-down approach; i.e. the total damage of a scenario is calculated and then distributed on the emissions of greenhouse gases. However, due to large uncertainties and possible gaps concerning the possible impacts of global warming, an avoidance cost approach is used in addition. This means that the marginal avoidance costs to reach given emission reduction targets are used.” (ExternE, 2005)

Accidents

“Accidents are rare unwanted events in contrast to normal operation. A distinction can be made between impacts to the public and occupational accident risks. Public risks can in principle be assessed by describing the possible accidents, calculating the damage and by multiplying the damage with the probability of the accidents.” (ExternE, 2005)

RESULTS

The external cost of damages related to the emission of GHGs are determined to be between €18-46 per metric tonne CO_2 equivalent (tCO_2-eq), and for the ExternE central assessment a value of €19/tCO_2-eq is used.

The damage valuation of $PM_{2.5}$ emissions is of particular importance. $PM_{2.5}$ is either directly emitted during the combustion cycle or forms in the atmosphere after SO_2 and NOx undergo chemical reactions (Muller, 2011). The Eco Sense model uses the $PM_{2.5}$ dose-response as per (Pope et al, 2002) and (ExternE, 2005). However in has to be noted that other studies have found three times higher mortality rates per dose of $PM_{2.5}$ concentration than the Pope et al (2002) analysis (Schwartz et al, 2008). This could mean higher health damages have to be considered than estimated by the ExternE study. This uncertainty could affect the value of the health impacts assessed in the study considerably.

The Germany specific results of the Eco Sense model are used as a representative mid-point of the ExternE study. The coal external costs are determined to be 4.07 € cents/kWh, mostly from direct emissions of pollutants during electricity generation (ExternE-Pol, 2005). External costs of natural gas are determined to be from 1 to 1.55 € cents/kWh respectively, again mostly from direct emissions during electricity generation (ExternE-Pol, 2005). Nuclear external costs are calculated to be 0.19 €2000 cents/kWh, the majority of which stem from long-term, low-level radiation (ExternE-Pol, 2005). Renewable energy generation from PV has external costs of 0.41 € cents/kWh, while hydro (0.05 € cents/kWh), onshore wind (0.09 € cents/kWh), and offshore wind (0.12 € cents/kWh) have relatively small lifecycle external costs (ExternE-Pol, 2005). The ExternE studies clearly explicit the huge difference in the external cost between the fossil fuel and renewable energy technologies.

It is well noted in the study that the results are location specific and therefore it may not be possible to generalize. However, the results are useful to compare technologies (European Commission, 2003).

4.2 NEW ENERGY EXTERNALITIES DEVELOPMENT FOR SUSTAINABILITY (NEEDS)

INTRODUCTION

NEEDS is an extension of the ExternE project. Funded by the European Commission, the NEEDS project is developed by the joint work of several researchers and universities along different European countries. The quantification of external costs in NEEDS is based on the ‘impact pathway’ methodology which has been developed in the ExternE projects. The methodology is further improved within NEEDS such as improving the dispersion and modelling of pollutants in the environment, improvising the exposure-response relationships that are used to describe the response of receptors to an increased level of exposure, and to improve monetary valuation.

The technologies included in the NEEDS study which are relevant for this thesis are coal, biomass, PV, and offshore wind. The NEEDS also employs the bottom-up damage cost methodology as in ExternE, where the external costs from lifecycle pollutant emissions are calculated through the EcoSense model.

The damages assessed include lifecycle emissions of particulate matter including both $PM_{2.5}$ and PM_{10}, SO_2, NOx, VOC, ammonia, heavy metals and radionuclides, Green House Gas (GHG) emissions, biodiversity loss due to land use changes and accidents (NEEDS, 2009).

METHODOLOGY

The NEEDS study starts with the assessment of lifecycle damages and emissions of each technology. Next, the marginal costs of emissions emitted from average new plant configurations located in areas of average population density are calculated using the EcoSense model. The marginal costs are then multiplied by the lifecycle emissions per quantity of electricity generated (kg/kWh) to estimate the external costs associated with each generation technology. For damages which are not calculated by the EcoSense model such as GHG related impacts, land use change and accidents, a similar procedure of assessing the marginal costs of the damage and then multiplying by the lifecycle damage is followed. The marginal costs of GHG emissions are assessed with the FUND model developed by climate researcher Richard Tol (Tol, 2002).

One important aspect of the NEEDS project is that it estimates the future external costs for different energy generation sources. However, as the future generation costs are not relevant to our thesis, we consider only the current costs. To determine the future external costs, the energy system modelling MARKAL/TIMES is used to predict the changes in economy energy intensity, electricity generation mix by source and learning curves to predict the future external costs in 2025 and 2050.

Airborne pollutants

A number of impacts are quantified for various airborne pollutants on different receptors. The table 2 summarises the pollutants (not including GHG emissions) and impacts covered by the external cost assessment within NEEDS. It has to be noted that the impact from the emission of a pollutant during the fuel cycle depends on various factors such as location of the emission source, the release height, concentration of other pollutants in the atmosphere and further more. The damage costs are calculated for EU-27 average and assuming the pollutants are emitted at an average height (NEEDS, 2009).

Impact	**Pollutants**
Human Health	Fine particles (PM2.5, PM10), NOx, SO2, NMVOC, NH3, Cd, As, Ni, Pb, Hg, Cr, HCHO, Dioxin, Radionuclides
Loss of Biodiversity	NH3, NMVOC, NOx, SO2
Crop Yields	SO2, NOx
Material Damage	SO2, NOx

Table 2: Impact categories and pollutants covered by the NEEDS methodology for quantifying external costs from airborne pollutants (NEEDS, 2009)

Bio diversity losses due to land use

The monetary valuation for the biodiversity losses due to land use changes caused by energy generation and infrastructure is developed based on the costs for restoring different land use sectors. Information on replacement or restoration costs for different land use categories is derived from a meta-analysis of German studies which analysed the costs of restoring damaged habitats to mare valuable habitats. Restoration costs derived for Germany are transferred to other countries by adjusting them to income and price differences of the respective countries. (NEEDS, 2009)

Green House Gas emissions

The FUND climate impact module is used in the NEEDS project for evaluating the damage costs. This module covers the agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems (Tol, 2002). The estimates of damage cost from GHG emissions are fairly a large range and are highly sensitive to a number of parameters such as equity weighting, discount rate allocated. Hence, a large number of cost for carbon can be calculated form a single model by slightly varying some key assumptions assumed in the model. As the NEEDS external cost estimates are developed mainly to support European energy policies, the equity weighted results are normalised to Western European average per capita income.

Because of the large uncertainties of in evaluating the damage cost for the climate change, marginal abatement costs for achieving the CO2 reduction targets are considered as an option in the scenes with uncertain or non-quantifiable damage costs.

In the NEEDS project, a set of marginal abatement costs were suggested by Friedrich (2008). The lower range of abatement costs were calculated to a European target of reduction in the CO2 emissions by 20% by 2020, the upper values were estimated according to the long term target of global CO2 reduction to a level of 365 ppm. (NEEDS, 2009)

RESULTS

The externality results are in the range that is sensitive to the marginal damage cost of GHG emissions. The solar PV external costs is found to be 0.63 $€_{2000}$ cents/kWh and wind as 0.09 $€_{2000}$ cents/kWh. The values are separated into human health, biodiversity, biological resource, acidification, land use change and climate change costs. Most of the costs across all technologies are from climate change related damages and human health impacts. The NEEDS researchers acknowledge the need for future research to monetize other impacts left unconsidered as, “The report presents quantifiable external costs, which do not represent the total external costs related with electricity generation” (NEEDS, 2009).

4.3 COST ASSESSMENT OF SUSTAINABLE ENERGY SYSTEMS (CASES)

INTRODUCTION

Similar to NEEDS, the CASES study is a one-time extension of the ExternE assessment funded by the European Commission. The CASES study is developed in several countries over the years by multidisciplinary research teams at various universities and institutes across Europe. The CASES analysis was performed separately and in parallel to the NEEDS study.

However, in CASES, the social cost of the electricity generation by various sources is evaluated. This is done by calculating both the external and the internal cost of the European generation.

METHODOLOGY

Similar to ExternE, Impact pathway methodology is employed by the CASES for the estimation of external costs of generation technologies over the entire fuel life cycle. By fuel cycle, the entire lifecycle emissions and damages from material extraction to plant decommissioning are compiled. Then the marginal costs of emissions from different electricity generation are calculated through the

EcoSense model. Finally, the lifecycle emissions per quantity of electricity generated are multiplied by the marginal cost of emissions to calculate the external cost of the emission released. The external impacts to human health, agriculture, the built environment, and ecology are considered. The damage of GHG emissions are monetized through the FUND and PAGE (a similar model to FUND) models. The lower bound GHG marginal cost from the FUND and PAGE models is estimated to be €4/tCO2-eq and the upper bound is 53 € /tCO2-eq. The central value is taken to be the average of the median runs of the FUND and PAGE models as 23€/tCO2-eq.

For the private cost of the energy technologies, the Levelized cost of electricity (LCOE) is considered. LCOE represents the per-kilowatt hour cost of building and operating a generating plant over an assumed financial life and duty cycle. It has to be noted that the LCOE values in the CASES study are evaluated without taking into consideration of the countries policies which could vary the cost of electricity through taxations or subsidies. For the LCOE calculation, the capital costs (I), fuel (F) and operations and maintenance (M) costs of a plant are calculated and then, with a discount rate of 5% for future costs, the net present value (NPV) of total costs is calculated. Then, accounting for the plant capacity, expected lifetime, and capacity factor, the lifetime electricity generation is computed. The plant cost NPV is normalized by the expected lifetime electricity generation to obtain a levelized cost of electricity (LCOE). The formula to obtain the LCOE of an electricity generating plant can be calculated as,

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I(t) + M(t) + F(t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E(t)}{(1+r)^t}}$$

Where,

I(t) = Investment expenditure in the year t;

M(t) = Operations and maintenance in the year t;

F(t) = Fuel expenditure in the year t;

E(t) = Electricity generaion in the year t;

r = Discount rate

n = Economic life of the system.

With the external and the private costs, the social cost of the electricity generation technology is determined for the represented 2007 as the midpoint of the 2005-2010 study period of CASES project and also for 2020 and 2030. (Markandya et al, 2012).

RESULTS

According to the CASES study, the private costs for a new hard coal condensing plant are 3.33 $€_{2005}$ cents/kWh and external costs estimate is 3.14 $€_{2005}$ cents/kWh, for a total social cost of 6.47 $€_{2005}$ cents/kWh (Markandya et al., 2010). Nuclear has the lowest overall cost. The reason being the unquantified external costs such as long-term fuel storage. The private costs for nuclear are 3.10 €$_{2005}$ cents/kWh and the external costs are 0.21 €$_{2005}$ cents/kWh, for a social cost of 3.32 €$_{2005}$ cents/kWh (Markandya et al., 2010). Hydro has a social cost of 6.85 €$_{2005}$ cents/kWh with an external cost of only 0.07 €$_{2005}$ cents/kWh (Markandya et al., 2010). Onshore wind and offshore wind were found to have similar social costs of 6.21 and 6.45 €$_{2005}$ cents/kWh, respectively (Markandya et al., 2010). The external costs of wind power are 0.09 €$_{2005}$ cents/kWh for onshore and 0.10 €$_{2005}$ cents/kWh for offshore. The external costs of solar PV are about 0.89 €$_{2005}$ cents/kWh. (Markandya et al., 2010).

An important factor to be noted in the CASES study is that for wind and solar PV power, the private and external costs of backing-up up the power plants are included in the final social cost calculation. A CCGT plant was the assumed backup. While it is true that renewable power are variable generators which fluctuate generation periodically, all electricity generators come offline at some point for planned or unplanted maintenance. Thus, to integrate back-up costs for some technologies and not others is not valid. For this reason the CASES private and external costs of wind and solar are likely overvalued compared to its counter technologies in the assessment.

4.4 RESULTS OF EXTERNALITY STUDY COMPARISON

The results of the three studies discusses above are summarized in the table below. The table of different external cost for each energy technology is also graphically figured in the graph below.

TECHNOLOGY	EXTERNE	NEEDS	CASES
Unit	€c$_{2000}$/KWh	€c$_{2000}$/KWh	€c$_{2005}$/KWh
Source	(ExternE-Pol, 2005)	(NEEDS, 2009)	(CASES, 2008)
Coal	4.07	3.06	3.1352
oil	4.83	Not Studied	2.4654
gas	1.55	1.31	2.0845
Solar PV	0.41	0.63	0.888
Wind	0.09	0.09	0.1025
Biomass	0.18	2.5	0.6537
Hydro	0.02	Not Studied	0.0763
Nuclear	0.19	0.09	0.2141

Table 3: Externality values from the studies. Sources: (ExternE, 2005), (NEEDS, 2009), (Anil Markandya, 2012)

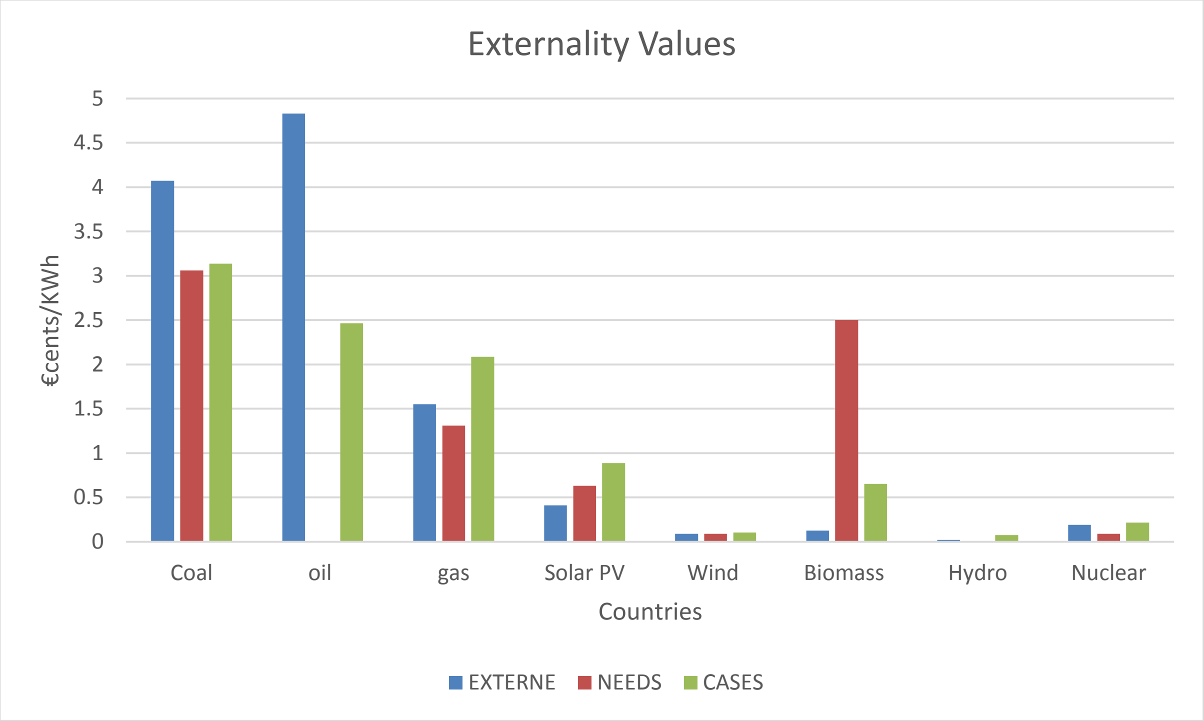


Figure 26: Externality values from the three studies for each technology.

The results vary considerably among the studies. However, in all the studies, the fossil fuels have very high externalities compared to the renewables. Among the renewables, solar holds the maximum amount of externalities compared to other renewable technologies. These externalities are primarily from the upstream process of solar manufacturing. It has to be noted that, solar has higher rate of technical growth and hence, with improvement in the material and efficiency, the externalities associated with solar will fall over time. The comparison may not be, however, so straightforward. In spite of the objective of comparing technologies, every nation has its own broad range of technologies, fuels, and abatement options. Therefore, due to the site- and technology-specificity of results, these will be sometimes very different. Among all the renewable technologies, differences are more prominent among countries in the case of nuclear and biomass technologies, since upstream process for these cycles (the extraction of the fuel, its transport, pre-processing) are highly variable among countries, and therefore their impacts will vary to a large extent. Hence, it is only appropriate to take site and technology specific case studies into consideration while assessing the externalities of energy systems.

Study	**Technologies Considered**	**Cost Considered**	**Damages Assessed**	**Model Used**
ExternE	All	External	SO_2, NOx, PM, VOC, Heavy Metals, Radio nuclides, Accidents, GHG	Eco Sense
NEEDS	Except Oil and Hydro	External	SO_2, NOx, PM, VOC, Heavy Metals, Radio nuclides, Land Use Change, Accidents, GHG	Eco Sense & MARKAL/TIMES
CASES	All	Private and External	SO_2, NOx, PM, VOC, Heavy Metals, Radio nuclides, Accidents, GHG	Eco Sense

Table 4: Overview of the methodology and model used in each externality studies. Sources: (ExternE, 2005), (NEEDS, 2009), (Anil Markandya, 2012)

Study	PM2.5 Dose-Response	CO2 Value	Total Value of Life (VSL)	Value of life per year lost (VSLY)
ExternE	Pope *et al.*, 2002	€18-46	€1,000,000	€ 50,000
NEEDS	Pope *et al.*, 2002	€7-98	€3,000,000	€ 40,000
CASES	Pope *et al.*, 2002	€7-99	€3,000,000	€ 40,000

Table 5: Overview of the methodology implemented in the externality studies. Sources: (ExternE, 2005), (NEEDS, 2009), (Anil Markandya, 2012)

In general, it may be concluded that fossil fuels have significantly high external costs, while renewable energies have small amount of external costs. The nuclear fuel cycle has small external costs, although it has to be noted that not all the significant impacts of this fuel cycle have been quantified. It can be well noticed that the external costs of fuel cycles are high enough to affect energy policy decisions. The methodology has a large number of uncertainties and impacts measured varies for each study. For an example, it the NEEDS estimate for biomass is higher than the other two studies because NEEDS include the impact of land use change while the other two studies don't. Especially with biomass, the CO_2 impact is very low owing to its carbon neutrality. Major proportion of the impact is from the nitrogen emission.

These uncertainties create some difficulties for using the results directly for policy-making. Several aspects should be taken a serious note, mainly the estimation of global warming damages. Atmospheric dispersion models, which, at least for some countries, should account for the complex topographic conditions are also a controversial aspect. Another important issue which should also be noted is the relationship between atmospheric pollution and chronic mortality, and the valuation of the deaths produced by atmospheric pollution. The table 5 gives the values of above mentioned parameters such as Value of Life per Year Lost (VSL), Total Value of Life (VSLY), damages assessed and the damage cost of CO_2 for each study, thereby, addressing the differences in the values.

All these uncertainties affect the individual fuel cycles studied. For the aggregation of results to the whole electricity sector, there are plenty of issues to be faced such as the transferability of results from one site to another or accounting the effects for which there is a threshold. The differences in damages per tons of pollutant emitted between different sites are quite large, so the direct transfer of results from one site to another is not reasonable. Hence, it is recommended by the studies to use the results provided only as background information. This background information might be very useful for establishing economic incentive tools, such as environmental taxes, or subsidies for renewable energies and for energy planning. However, it is advised that the results are better not used directly, until the methodology is refined. (ExternE, 2008)

In the further part of the thesis, externality costs from the CASES study is used owing to the facts that the country data for each technology is available clearly explaining the impacts and the damage cost used.

CHAPTER 5. EUROPEAN RENEWABLE POLICY BENEFITS & COST

5.1 INTERNALIZATION OF THE EXTERNALITIES

The main objective of numerous studies in estimating the external costs is to create policies that alter the price of energy in such a way to take into account both the private and the external cost, thereby, "level the playing field." Generally, renewable forms of energy have high private costs as most of the technologies are not mature but they have far lower external costs than energy generated from fossil fuels, but the market, which doesn't take this fact into account, would feature a huge price gap between the fossil fuel–derived energy and renewables-derived energy. It is through the policies, that the external costs can be "internalized" for the energy systems, making renewables competitive with fossil fuels on an economically justified basis(PSG AG, 2014). Several political instruments have been proposed to achieve internalization of external costs. "The optimal instrument for internalization creates no distortions on the market. Furthermore it should be efficient and fair, minimize costs and uncertainty and have low administrative costs" (CASES, 2008). There are several economic instruments employed to directly or indirectly internalize the external costs since early 19th century.

In theory, the use of an economic instrument is to regulate the level of an externality generating activity to its optimal point where any reduction in the additional damage caused by the activity is equal to the cost of abating that additional amount of the activity. This optimal point can be achieved directly or indirectly through a number of policy instruments. These are,

1. An order to the polluter to limit the emissions, which is a direct or command and control solution. It has practical difficulties in the energy sector as the marginal cost of abatement curve is derived from the activities of lots of polluters, and the reductions along it are not undertaken at only one plant.
2. A tax or charge per unit of emissions. Such charges will act as an incentive to reduce the emissions to the point where the costs of abatement are less than the tax implied on the emissions.
3. Instead of a charge, the polluter could be given a subsidy for each unit of reduction in the emissions. This acts in the same way as a charge where the polluter finds it pays to make reductions because the subsidy it receives exceeds the costs of abatement. Beyond that point the subsidy does not cover the costs of abatement.
4. Tradable permits allow polluters to emit as much as they like, as long as they are in possession of a permit. It can be shown that in such a situation a market will develop for permits. Plants, whose costs of abatement exceed emissions permit costs, will buy permits to cover those costs while the plants who can afford to reduce the emissions will be incentivised to reduce further (Anil Markandya, 2012).

The main purpose of these support instruments is to encourage the large scale deployment of the renewable energy generation and energy efficiency among the consumers. Large scale take-up of

RES would help technologies to mature, learning rates to improve and integration of RES within traditional market arrangements to be tested and refined. (CEER, 2015)

5.2 POLICY SUPPORT FOR RENEWABLE ENERGY TECHNOLOGIES

Policy supports for investment in renewable energy are usually based on a combination of different policy types. The policies can be differentiated according to their characteristics such as regulatory or voluntary, direct or indirect, investment-focused or generation- based, and more. The following policy types are distinguished into major and secondary instruments as follows,

Major support instruments

Feed-in tariffs (FIT)

Feed-in premiums (FIP)

Tenders (TN)

Quota obligations with trade-able green certificates (QO)

Secondary support instruments

Investment Incentives (II)

Tax Exemptions (TE)

Net Metering (NM)

Financial Incentives (FI) (Lena Kitzing et al. 2012)

A quick overview of the support instruments existing in Europe is given below,

Feed In Tariffs (FIT)

Feed in tariff system has several elements such as priority dispatch to eligible generation, long- term perspective and guaranteed prices. These prices are guaranteed for a specific period of time or to certain production capacity. In most implementations of FIT (especially earlier ones), the producers of renewable electricity are exempt from market participation, and receive the guaranteed price by delivering the power to an obliged off-taker.

Feed in Premium (FIP)

Feed in premiums are guaranteed premiums paid as a fixed top up over the market price. In addition to selling the electricity to the market, the producer also receives a premium amount per unit production. These premiums are either guaranteed for a fixed period of time or production capacity.

Tenders (TN)

In tenders, the public responsible organisation launches tenders for renewable system projects for specific capacity. Potential investors win the tender by competing with other investors submitting their requested support level and performance details. The most appropriate bid wins the tender, thereby the support from the government.

Quota Obligations (QO)

Also called as Renewable Portfolio Standards with green certificates. Under this scheme, the producer should have a specific share of their production form the renewable energy. This is a quantity control scheme unlike FIT, FIP. When complying with the share requirement, certificates are issued which can be materialized in the market under the compliance period.

In certain countries like Sweden, the certificates can be transferred over the compliance years, making them bankable. This creates a stable market for the certificates.

Investment Incentive (II)

These are the financial support granted to the renewable energy investors as a non-reimbursable payment during the construction phase of the project. Indifferent to the generation of renewable electricity after deployment, this scheme aims at easing the high initial investment cost of the renewable energy systems.

Financial Incentive (FI)

These are equity investments or venture capital investments by the government institutions targeted at renewable energy producers. Unlike investment incentive, these incentives are reimbursable.

Tax Exemptions (TE)

Tax exemption mainly involve fiscal support. They are in the form of income tax relief, electricity tax relief and reduced VAT.

Net Metering (NM)

Net metering for self-consumption can aid in tax relief of all forms imposed on the energy producers and consumers. Small residential production and consumption through renewable systems can be highly beneficial form this scheme.

While one or the other form of policy support instrument promoting renewable energy systems and thereby indirectly curb the activities producing external costs has been long existing, the EU nations started implementing defined schemes in the late 20th century. Prior to 2000, fifteen EU nations provided defined explicit policy support tools for renewables. By 2007, all the EU nations had implemented some form of policy support instruments, usually combination of schemes. The table 6 describes how the EU nations has adapted policy tools over the decades. By the end of 2011, nearly all the countries implemented at least one of the major support tools. Among primary support instruments, FIT was the most adapted scheme. Among the secondary support instruments, investment grants scheme has been prominently employed. (Lena Kitzing et al, 2012).

	Number of countries that has implemented the scheme			
	2000	**2005**	**2010**	**2011**
Major Support Schemes				
Feed-In Tariff (FIT)	7	16	23	21
Feed-In Premium (FIP)	-	4	7	7
Tenders (TN)	2	2	6	5
Quota Obligations (QO)	1	6	6	6
Secondary Support Schemes				
Investment Incentive (II)	5	10	20	20
Tax Exemptions (TE) & Net Metering (NM)	9	10	12	13
Financial Incentives (FI)	4	4	9	9

Table 6: Number of countries implementing renewable support policies over the decades (Lena Kitzing et al, 2012)

5.3 ANALYSIS OF BENEFITS AND COSTS OF RENEWABLE POLICY SUPPORT

Almost all the EU nations have enacted support schemes in order to promote renewable electricity, correct the market failure and achieve desired level of renewable penetration into the electricity generation mix. However, concerns have been raised in many studies on the cost of promotion of these renewable energy systems. While promotion of renewable aids to indirect reduction of the externalities generated, it is also being well noted that the support costs have increased significantly in the recent years. The support cost for renewable electricity have increased by 144% from 2009 to 2012 (CEER, 2015). It has to be noted that the costs are borne by the consumers of the electricity in the end through the electricity bills. The growing penetration of the renewable systems and their increasing support costs has raised concerns of the policy makers of the EU nations about the cost of the promotion of renewable systems and their usefulness.

A quantification of the cost and the benefit of the support costs of the renewable energy promotion can helping in gaining a perspective of the usefulness of these policy support costs. This analysis could contribute to the debate on the renewable energy targets and their promotion. The studies addressing the benefits and costs of the different technologies among the EU nations are scarce with few exception such as Garcia-Redondo et al (2014), European Commission (2014), Marcantonini et al, 2014 and Margarita Ortega-Izquierdo et al (2016). Among the studies, Garcia-Redondo et al (2014) compares benefits associated with carbon dioxide emissions avoided with the cost of FIT systems in Spain. Margarita Ortega-Izquierdo et al (2016) extends the study and performs the analysis of the benefits of avoided carbon dioxide cost and the fossil fuel savings with the policy support costs for all the EU member states. As it is noted, GHG emissions are one of the several externalities in the energy generation. Hence, in this thesis, an analysis of the benefits of the avoided external costs by the renewable penetration and the benefits of fossil fuel savings are compared with the support costs of the renewable promotion schemes. It has to be noted that this cannot be considered as a cost-benefit analysis of the renewable technology, as performing a thorough cost benefit analysis will require the system costs.

This aim of this analysis is to understand the usefulness of the policy support costs by comparing them with the quantifiable benefits achieved through the renewable deployment.

5.3.1 BENEFITS CONSIDERED

Two main benefits from the promotion of renewable energy is discussed in this thesis. They are,

1. Externality reduction
2. Fossil fuel savings.

Externality Reduction

The studies prove that the externalities generated from renewable energy is far lesser than the externalities generated by the fossil fuels. This avoided external cost by the renewable energy penetration is considered.

Fossil Fuel Savings

The current energy demand in the EU is 55% covered by imported energy sources. Energy dependence renders the EU vulnerable, particularly in terms of the potential loss of energy supply. While pollution represents mainly an environmental risk, the energy dependence represents predominantly economic and socio-political risk as well as a challenge to restructure the EU energy sector (Matevž Obrecht 2014). Penetration of renewables into the electricity generation mix of the nations have significantly increased the fossil fuel consumption and hence this fossil fuel savings are considered as one of the benefits.

Other benefits such as merit-order benefit, employment creation are not considered in this analysis due to lack of EU-wide data availability. Merit-order benefit is the reduction of the pool energy price due to the increasing penetration of renewable energy.

5.3.2 COST CONSIDERED

Since this is an analysis to identify the usefulness of the policy support costs, only the policy instrument costs of the EU nations are considered and not the system costs which would involve the plant construction cost, operation, maintenance costs. As argued by Claudio Marcantonini et al (2014) “cost data on actual capital outlays are not available for either renewable or competing fossil generation for all the EU nations. A more accessible metric is the price paid for the output, which can be expected to cover all relevant costs in well-functioning markets, as well as extra profit and unanticipated losses in some instances. The payments to producers are real expenditures and they are the starting point for devising any relevant metric of cost”. The support costs are taken from the Council of European Energy Regulators (CEER, 2015) and for the year 2012. Hence, the benefits are also calculated for the year 2012. For a clear definition, support costs are the incentives paid for the renewable energy generation through different schemes as discussed earlier.

Apart from the system costs, other costs related to the electricity system such as cycling costs, balancing costs are not considered in this analysis. The Cycling costs are the extra operation costs incurred due to the varying load due to the intermittent nature of the renewable systems. Balancing costs are costs incurred to meet the demand with the varying supply because of the non-predictable nature of the renewable systems. These costs are not considered as the studies show that such costs are negligible with low percentage mix of renewable energy systems. As mentioned by (Claudio Marcantonini et al, 2014), the balancing costs represent only a tiny average of 2% of the net remuneration costs. Hence, these costs are neglected for the analysis because of the following reasons as mentioned by (Margarita Ortega-Izquierdo et al, 2016).

- The aim of the analysis is to compare the costs and the benefits of policy support costs and not a holistic cost-benefit analysis.
- System costs and cycling costs for all the EU nations are not available as they are difficult to calculate
- As studies have shown that these costs are very low for low penetration levels of renewable energy into the nation's electricity generation mix, they are ignored at this period of time.

5.3.3 THE METHODOLOGY

The costs and benefits are calculated for the year 2012. Literature data from (CEER, 2015) are taken for the policy costs while the avoided external costs are calculated from the CASES study. The fossil Fuel savings are adapted from the calculation devised by (Margarita Ortega-Izquierdo et al, 2016). The comparison is done as mentioned in the table below.

Benefits	**Calculation**	**Source of the data**
Fossil Fuel Savings	Adapted from the literature	(Margarita Ortega-Izquierdo et al, 2016)
Avoided External Costs	Own Elaboration	(Markandya, 2012)
Policy Support Costs	Data from the literature	(CEER, 2015)
Population	Data from the Literature	(Eurostat, 2013)

Table 7: Cost and benefit calculation sources.

Benefits

Fossil Fuel Savings:

Near-zero variable costs of generation of renewables indicate that it displaces conventional fossil fuel generation from coal, natural gas or oil. The displaced cost of the fossil fuel required to generate the electricity is a cost saving. Consequently, it must be subtracted from the payment to generators to isolate the additional cost for abating externalities generated. This cost saving depends on the quantity and prices of the coal or natural gas imported, but figuring out what is displaced precisely when a technology like wind or solar generation is injected into the grid is not easy. Hence, some approximations are adapted. The quantities of each fuel displaced are indicated by the difference between the scenario calculated to replicate observed load for the year 2012 with and without renewables in the generation mix. The quantities calculated form the difference are multiplied by the fuel prices, to determine the fuel cost savings. Since natural gas prices are higher than coal, cost savings are greater per MWh of displaced natural gas generation than for coal generation. However, it should be noted that the efficiency of conversion of the primary energy to electricity by the plant also comes into role in deciding the amount of fuel used to produce the unit MWh. (Claudio Marcantonini et al, 2014). Thus, in order to calculate the fossil fuel savings as a result of renewable penetration, the electricity is converted to primary energy using the respective efficiency rates (η) for the fossil fuels derived from (European Commission, 2011). The primary energy consumption is given by,

$$\textbf{Primary Energy Consumption (MWh)} = \mathbf{(1/\eta)}\textbf{*Final Energy Consumption (MWh)}$$

The following conversion rates are followed. Coal – 1 MWh = 0.21 tons ; Oil – 1 MWHh = 0.61 barrels; Natural gas – 1MWh = $3.44*10^6$ BTU (Margarita Ortega-Izquierdo et al, 2016).

The table 8 shows the fossil fuel savings because of the renewable penetration for the year 2012. An analysis per country reveals that the four largest countries (Germany, France, Spain and Italy) plus Sweden are the ones having the largest fossil fuel savings as a result of renewable deployment. Almost half (46%) of fossil fuel savings can be attributed to the deployment of hydro power, followed by wind (26%), biofuels (18%), PV(9%) and the rest for a small proportion of less than 1% (Margarita Ortega-Izquierdo et al, 2016).

	Fossil Fuel Savings (Million €) at 2012			
	Solar	**Wind**	**Biomass**	**Hydro**
EU	2619	7646	5159	11529
Austria	11	79	147	1527
Belgium	79	101	187	61
Czech	77	15	111	103
Germany	993	1901	1556	1027
Denmark	4	378	152	1
Estonia	0	18	35	2
Spain	300	1818	180	894
Finland	0	16	341	536
France	118	443	137	1850
UK	55	793	576	332
Hungary	0	29	61	8
Ireland	0	177	19	44
Italy	830	594	530	1925
Lithuania	0	25	9	42
Netherlands	12	227	316	5
Poland	0	196	381	101
Portugal	16	406	113	264
Romania	0	95	7	438
Sweden	0	177	292	1935

Table 8: Fossil fuel savings by renewable deployment in Europe in 2012 (Margarita Ortega-Izquierdo et al, 2016)

Avoided External Cost

The external cost per unit electricity production is taken from the aforementioned CASES study. Among the three studies discussed in the thesis, CASES study is the latest study inclusive of the final improvisations to ExternE. The electricity generation mix for each European country is taken from the database of (EUROSTAT, 2016). The table 9 shows the electricity generation mix of various EU nations.

	Electricity Generation Mix (TWh) at 2012										
	Total	**Solid Fuels**	**Gases**	**oil**	**Solar**	**Wind**	**Biomass**	**Hydro**	**Nuclear**	**Geothermal**	**Wastes**
EU	3297.5	901.0	616.0	73.9	71.2	206.0	148.5	366.6	882.4	5.8	21.1
Austria	72.6	4.4	11.6	0.7	0.3	2.5	4.6	47.7	0.0	0.0	0.8
Belgium	82.9	3.4	25.6	0.3	2.1	2.8	5.2	1.7	40.3	0.0	1.3
Bulgaria	47.3	22.9	2.4	0.2	0.8	1.2	0.1	4.0	15.8	0.0	0.0
Czech	87.6	44.4	3.9	0.1	2.1	0.4	3.4	2.9	30.3	0.0	0.1
Germany	629.8	277.1	87.5	7.6	26.4	50.7	44.6	27.8	99.5	0.0	6.6
Denmark	30.7	10.5	4.2	0.4	0.1	10.3	4.4	0.0	0.0	0.0	0.7
Estonia	12.0	9.8	0.6	0.1	0.0	0.4	1.0	0.0	0.0	0.0	0.0
Spain	297.6	55.1	74.2	15.3	12.0	49.5	5.0	24.2	61.5	0.0	0.7
Finland	70.4	10.8	7.2	0.3	0.0	0.5	11.2	16.9	23.0	0.0	0.2
France	565.7	18.9	24.4	6.2	4.0	14.9	4.9	63.6	425.4	0.0	2.2
UK	363.6	143.2	100.8	2.5	1.4	19.8	14.7	8.3	70.4	0.0	2.6
Hungary	34.6	6.3	9.5	0.2	0.0	0.8	1.7	0.2	15.8	0.0	0.1
Ireland	27.6	7.5	14.4	0.2	0.0	4.0	0.4	1.0	0.0	0.0	0.0
Italy	299.3	49.1	134.0	18.9	18.9	13.4	12.5	43.9	0.0	5.6	2.3
Lithuania	5.0	0.0	2.9	0.2	0.0	0.5	0.2	0.9	0.0	0.0	0.0
Netherlands	103.3	24.2	59.7	1.1	0.2	5.0	7.2	0.1	3.9	0.0	1.8
Poland	162.1	134.6	8.1	2.0	0.0	4.7	10.1	2.5	0.0	0.0	0.0
Portugal	46.6	13.1	10.7	2.2	0.4	10.3	3.0	6.7	0.0	0.1	0.3
Romania	59.0	22.9	8.7	0.8	0.0	2.6	0.2	12.3	11.5	0.0	0.0
Sweden	166.6	0.9	1.3	0.6	0.0	7.2	12.2	79.1	64.0	0.0	1.3

Table 9: Electricity generation mix at 2012 (TWh) (EUROSTAT, 2016)

The avoided external cost for each KWh of electricity generated from the renewable technology is given by,

Avoided external cost $_{\text{renewable technology}}$ **= Weighted Average** $_{\text{fossil}}$ **- External Cost** $_{\text{renewable technology}}$

Where,

$$\boldsymbol{Weighted\ Average\ Cost\ (F)} = \frac{\sum \mathbf{El\ (F) * Ex(F)}}{\boldsymbol{El}}$$

Where,

Weighted Average Cost (F) = Weighted Average External Cost of Fossil Fuels generation in a country (€ cent /KWh)

El (F) = Electricity generated by each fossil fuel in the year 2012

Ex(F) = External cost per unit electricity generated from each fossil fuel at 2012

El = Net electricity generated from all the fossil fuels at 2012. Applying the above, the Avoided external costs for each renewable technology for the year 2012 was calculated as,

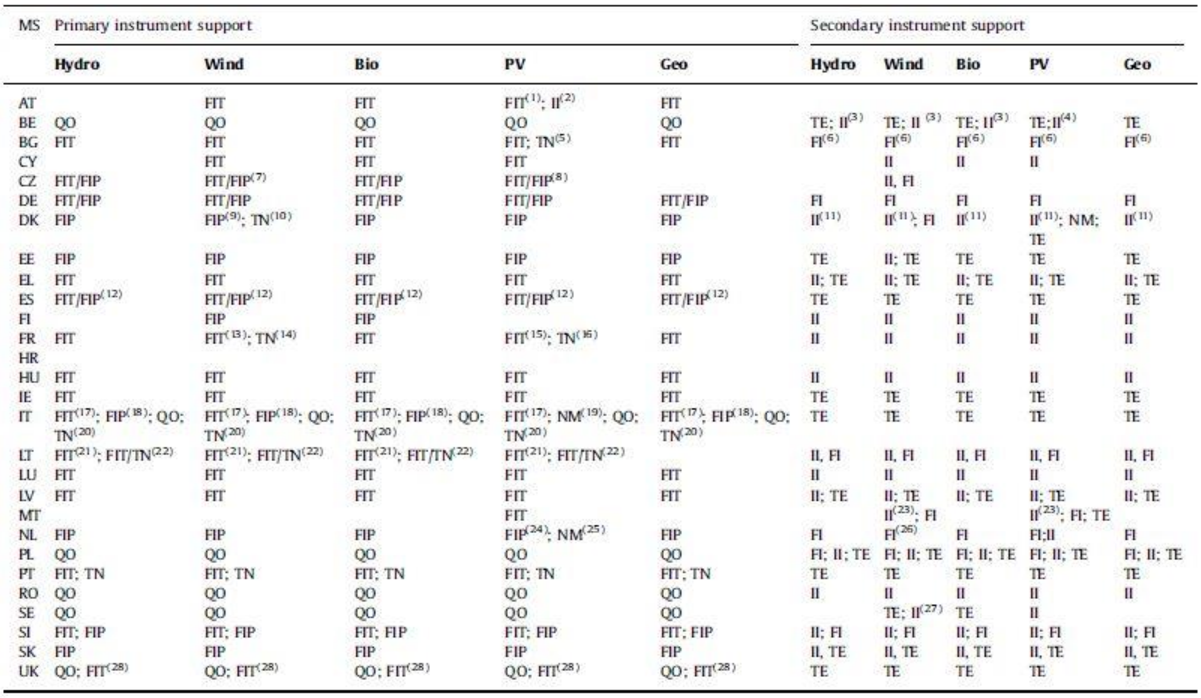
Avoided External cost for a renewable = (avoided external cost /KWh) * (electricity generated by the renewable)

	Avoided External cost at 2012 (Million €)			
country	**Solar**	**Wind**	**Biomass**	**Hydro**
AT	5.85	67.10	88.69	1316.00
BE	28.28	64.95	89.00	39.44
CZ	54.75	14.51	93.41	100.75
DE	610.30	1706.93	1155.78	945.49
DK	1.88	246.12	88.76	0.41
EE	0.00	10.05	20.25	0.98
ES	175.21	1004.60	83.87	496.61
FI	0.09	9.61	189.28	332.20
FR	74.09	411.44	102.62	1774.37
UK	22.08	469.34	282.98	196.84
HU	0.16	23.61	36.47	6.60
IE	0.01	82.57	7.35	21.16
IT	295.50	329.00	226.82	1087.69
LT	0.02	9.79	3.06	17.27
NL	3.36	130.46	138.26	2.74
PL	0.02	145.84	252.94	76.42
PT	5.27	189.30	47.25	124.04
RO	0.22	107.94	6.26	509.88
SE	0.27	137.64	194.05	1539.09

Table 10: Avoided External costs for each technology for the year 2012 by EU nations are given in the table below.

Policy Support Cost

As discussed above, each nation in EU had employed several forms of policy support schemes to promote renewable energy. Complied data on the different forms of support each renewable technology at different EU member states are taken from the source (Margarita Ortega-Izquierdo et al, 2016).



MS	Primary instrument support					Secondary instrument support				
	Hydro	**Wind**	**Bio**	**PV**	**Geo**	**Hydro**	**Wind**	**Bio**	**PV**	**Geo**
AT		FIT	FIT	FIT(1); II(2)	FIT					
BE	QO	QO	QO	QO	QO	TE; II(3)	TE; II (3)	TE; II(3)	TE;II(4)	TE
BG	FIT	FIT	FIT	FIT; TN(5)	FIT	FI(6)	FI(6)	FI(6)	FI(6)	FI(6)
CY		FIT	FIT	FIT			II	II	II	
CZ	FIT/FIP	FIT/FIP(7)	FIT/FIP	FIT/FIP(8)			II, FI			
DE	FIT/FIP	FIT/FIP	FIT/FIP	FIT/FIP	FIT/FIP	FI	FI	FI	FI	FI
DK	FIP	FIP(9); TN(10)	FIP	FIP	FIP	II(11)	II(11); FI	II(11)	II(11); NM; TE	II(11)
EE	FIP	FIP	FIP	FIP	FIP	TE	II; TE	TE	TE	TE
EL	FIT	FIT	FIT	FIT	FIT	II; TE	II; TE	II; TE	II; TE	II; TE
ES	FIT/FIP(12)	FIT/FIP(12)	FIT/FIP(12)	FIT/FIP(12)	FIT/FIP(12)	TE	TE	TE	TE	TE
FI		FIP	FIP			II	II	II	II	II
FR	FIT	FIT(13); TN(14)	FIT	FIT(15); TN(16)	FIT	II	II	II	II	II
HR										
HU	FIT	FIT	FIT	FIT	FIT	II	II	II	II	II
IE	FIT	FIT	FIT	FIT	FIT	TE	TE	TE	TE	TE
IT	FIT(17); FIP(18); QO; TN(20)	FIT(17); FIP(18); QO; TN(20)	FIT(17); FIP(18); QO; TN(20)	FIT(17); NM(19); QO; TN(20)	FIT(17); FIP(18); QO; TN(20)	TE	TE	TE	TE	TE
LT	FIT(21); FIT/TN(22)	FIT(21); FIT/TN(22)	FIT(21); FIT/TN(22)	FIT(21); FIT/TN(22)		II, FI	II, FI	II, FI	II, FI	II, FI
LU	FIT	FIT	FIT	FIT	FIT	II	II	II	II	II
LV	FIT	FIT	FIT	FIT	FIT	II; TE	II; TE	II; TE	II; TE	II; TE
MT				FIT			II(23); FI		II(23); FI; TE	
NL	FIP	FIP	FIP	FIP(24); NM(25)	FIP	FI	FI(26)	FI	FI;II	FI
PL	QO	QO	QO	QO	QO	FI; II; TE	FI; II; TE	FI; II; TE	FI; II; TE	FI; II; TE
PT	FIT; TN	FIT; TN	FIT; TN	FIT; TN	FIT; TN	TE	TE	TE	TE	TE
RO	QO	QO	QO	QO	QO	II	II	II	II	II
SE	QO	QO	QO	QO	QO		TE; II(27)	TE	II	
SI	FIT; FIP	FIT; FIP	FIT; FIP	FIT; FIP	FIT; FIP	II; FI	II; FI	II; FI	II; FI	II; FI
SK	FIP	FIP	FIP	FIP	FIP	II, TE	II, TE	II, TE	II, TE	II, TE
UK	QO; FIT(28)	QO; FIT(28)	QO; FIT(28)	QO; FIT(28)	QO; FIT(28)	TE	TE	TE	TE	TE

Figure 26: Policy instruments for the deployment of renewables in Europe (Margarita Ortega-Izquierdo et al, 2016)

The annual support costs for the year 2012 is obtained from the study (CEER, 2015). As shown in the table below, the level of support differs for each renewable technology and each nation. With a general average of 261.6 €/MWh for the EU countries taken into account, PV has the highest level of support among the renewable technologies. The lowest level of support is given to hydro which has an average of 40.8 €/MWh with wind a little higher average of 48 €/MWh. Biofuels have an average of 66.4 €/MWh. It has to be noted that the above mentioned values are non-weighted average and the incentives vary vastly among the nations depending on their local targets and resources (Margarita Ortega-Izquierdo et al, 2016).

	Policy Support Cost (Million €) 2012			
	Solar	**Wind**	**Biomass**	**Hydro**
EU	21407	10329	10236	1714
Austria	34	74	248	5
Belgium	802	257	417	14
Czech	965	27	221	54
Germany	8118	3108	4827	231
Denmark	0	202	86	0
Estonia	0	4	13	1
Spain	2614	2053	385	187
Finland	0	9	37	0
France	1709	550	143	86
UK	377	1418	783	164
Hungary	0	43	52	3
Ireland	0	42	11	1
Italy	6161	1018	1612	681
Lithuania	1	28	17	3
Netherlands	12	324	343	7
Poland	0	315	583	139
Portugal	66	508	177	30
Romania	0	148	7	31
Sweden	0	165	258	72

Table 11: Policy support costs at 2012 for different renewables (CEER, 2015)

5.3.4 RESULTS

An analysis of the costs associated with the public support for renewables and the benefits from fossil fuel savings and the avoided external costs is presented in the tables below for the renewable technologies solar, wind, biomass and hydro separately. The per capita benefits and policy cost are also drawn out to understand and compare each country's renewable technology cost and benefits. The total population of each European member state is taken from Eurostat (2013).

	Solar (Million €)			
country	**Avoided External Cost**	**Fossil Fuel Saving**	**sum of benefits**	**Policy Support Cost**
AT	5.85	11.00	16.85	34.00
BE	28.28	79.00	107.28	802.00
CZ	54.75	77.00	131.75	965.00
DE	610.30	993.00	1603.30	8118.00
DK	1.88	4.00	5.88	0.00
EE	0.00	0.00	0.00	0.00
ES	175.21	300.00	475.21	2614.00
FI	0.09	0.00	0.09	0.00
FR	74.09	118.00	192.09	1709.00
UK	22.08	55.00	77.08	377.00
HU	0.16	0.00	0.16	0.00
IE	0.01	0.00	0.01	0.00
IT	295.50	830.00	1125.50	6161.00
LT	0.02	0.00	0.02	1.00
NL	3.36	12.00	15.36	12.00
PL	0.02	0.00	0.02	0.00
PT	5.27	16.00	21.27	66.00
RO	0.22	0.00	0.22	0.00
SE	0.27	0.00	0.27	0.00

Table 12: Summary of benefits and cost for solar renewable deployment in Europe at 2012

	Wind (Million €)			
country	**Avoided External Cost**	**Fossil Fuel Saving**	**Sum of Benefits**	**Policy Support Cost**
AT	67.10	79.00	146.10	74.00
BE	64.95	101.00	165.95	257.00
CZ	14.51	15.00	29.51	27.00
DE	1706.93	1901.00	3607.93	3108.00
DK	246.12	378.00	624.12	202.00
EE	10.05	18.00	28.05	4.00
ES	1004.60	1818.00	2822.60	2053.00
FI	9.61	16.00	25.61	9.00
FR	411.44	443.00	854.44	550.00
UK	469.34	793.00	1262.34	1418.00
HU	23.61	29.00	52.61	43.00
IE	82.57	177.00	259.57	42.00
IT	329.00	594.00	923.00	1018.00
LT	9.79	25.00	34.79	28.00
NL	130.46	227.00	357.46	324.00
PL	145.84	196.00	341.84	315.00
PT	189.30	406.00	595.30	508.00
RO	107.94	95.00	202.94	148.00
SE	137.64	177.00	314.64	165.00

Table 13: Summary of benefits and cost for wind renewable deployment in Europe at 2012

	Biomass (Million €)			
country	**Avoided External Cost**	**Fossil Fuel Saving**	**Sum of Benefits**	**Policy Support Cost**
AT	88.69	147.00	235.69	248.00
BE	89.00	187.00	276.00	417.00
CZ	93.41	111.00	204.41	221.00
DE	1155.78	1556.00	2711.78	4827.00
DK	88.76	152.00	240.76	86.00
EE	20.25	35.00	55.25	13.00
ES	83.87	180.00	263.87	385.00
FI	189.28	341.00	530.28	37.00
FR	102.62	137.00	239.62	143.00
UK	282.98	576.00	858.98	783.00
HU	36.47	61.00	97.47	52.00
IE	7.35	19.00	26.35	11.00
IT	226.82	530.00	756.82	1612.00
LT	3.06	9.00	12.06	17.00
NL	138.26	316.00	454.26	343.00
PL	252.94	381.00	633.94	583.00
PT	47.25	113.00	160.25	177.00
RO	6.26	7.00	13.26	7.00
SE	194.05	292.00	486.05	258.00

Table 14: Summary of benefits and cost for biomass renewable deployment in Europe at 2012

	Hydro (Million €)			
country	**Avoided External Cost**	**Fossil Fuel Saving**	**Sum of Benefits**	**Policy Support Cost**
AT	1316.00	1527.00	2843.00	5.00
BE	39.44	61.00	100.44	14.00
CZ	100.75	103.00	203.75	54.00
DE	945.49	1027.00	1972.49	231.00
DK	0.41	1.00	1.41	0.00
EE	0.98	2.00	2.98	1.00
ES	496.61	894.00	1390.61	187.00
FI	332.20	536.00	868.20	0.00
FR	1774.37	1850.00	3624.37	86.00
UK	196.84	332.00	528.84	164.00
HU	6.60	8.00	14.60	3.00
IE	21.16	44.00	65.16	1.00
IT	1087.69	1925.00	3012.69	681.00
LT	17.27	42.00	59.27	3.00
NL	2.74	5.00	7.74	7.00
PL	76.42	101.00	177.42	139.00
PT	124.04	264.00	388.04	30.00
RO	509.88	438.00	947.88	31.00
SE	1539.09	1935.00	3474.09	72.00

Table 15: Summary of benefits and cost for hydro renewable deployment in Europe at 2012

The results show that the benefits are lower than the support costs for solar and biomass while wind and hydro have higher benefits to cost of policy incentives, on an EU wide. When noticed in detail, it widely varying among the countries and among each technology. The graphical representation of results of each technology are presented below.

Solar Energy

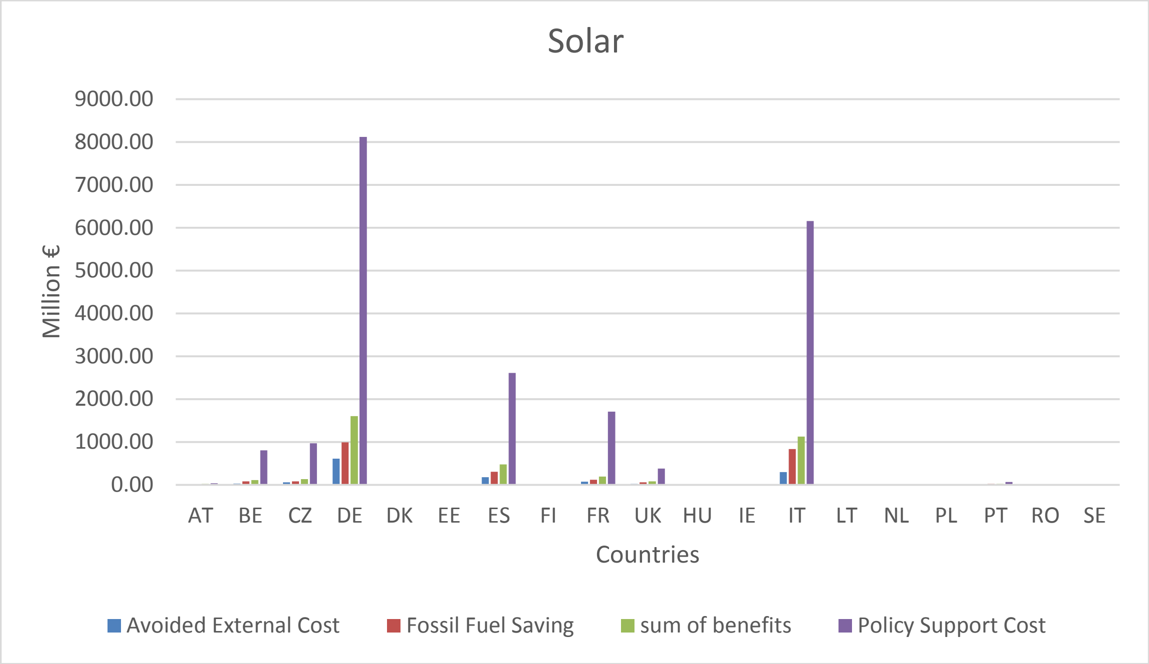


Figure 27: Comparison of benefits and costs of policy support for solar.

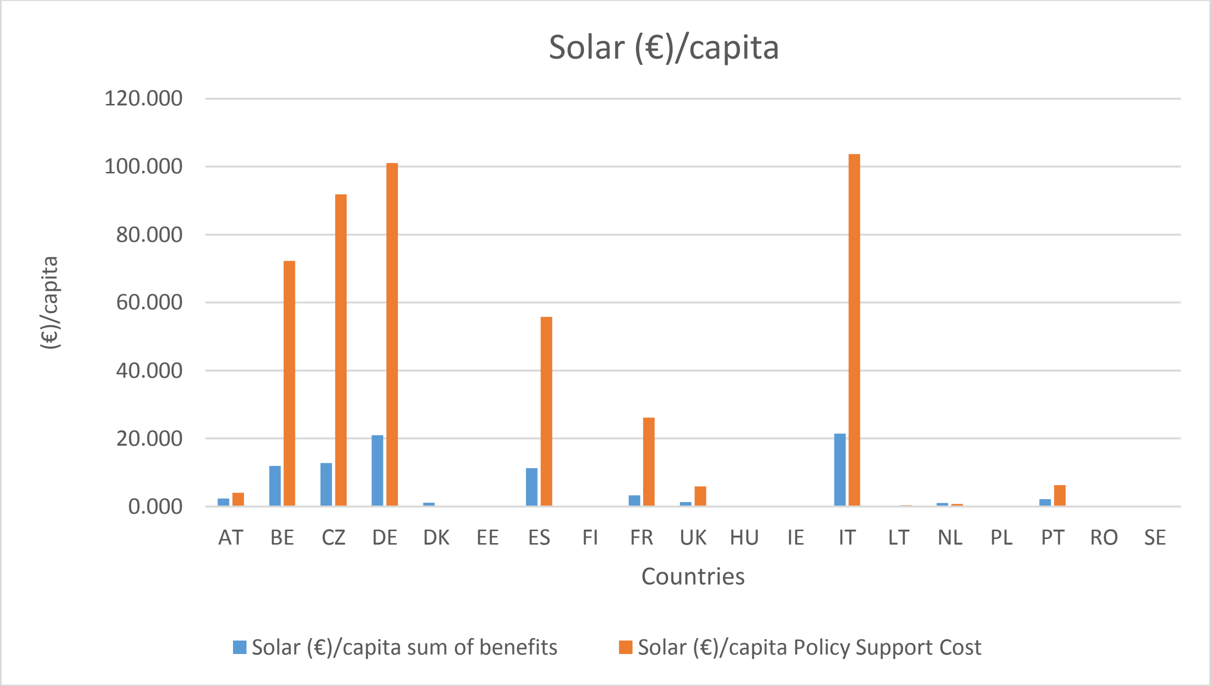


Figure 28: Per capita benefits and policy cost for solar energy

Solar has very high policy support cost compared to the benefits obtained from the avoided external costs and fossil fuel savings. Several countries such as Hungary, Poland and Sweden do not have significant policy support instruments actively employed. Solar, besides being a mature technology, has high cost to the benefits. However, considering the high technology growth in solar industry, with considerable increase in the efficiency of the technology, the externalities may still come down, thereby increasing the possibility of benefits from the avoided external costs.

Biomass Energy

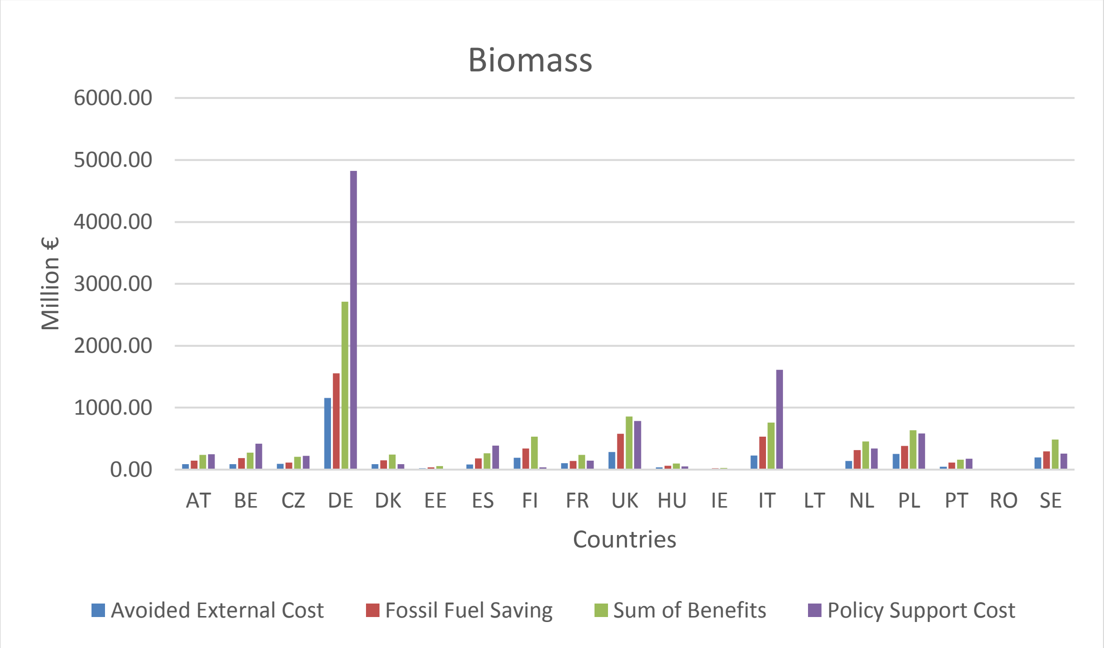


Figure 29: Comparison of benefits and costs of policy support for biomass.

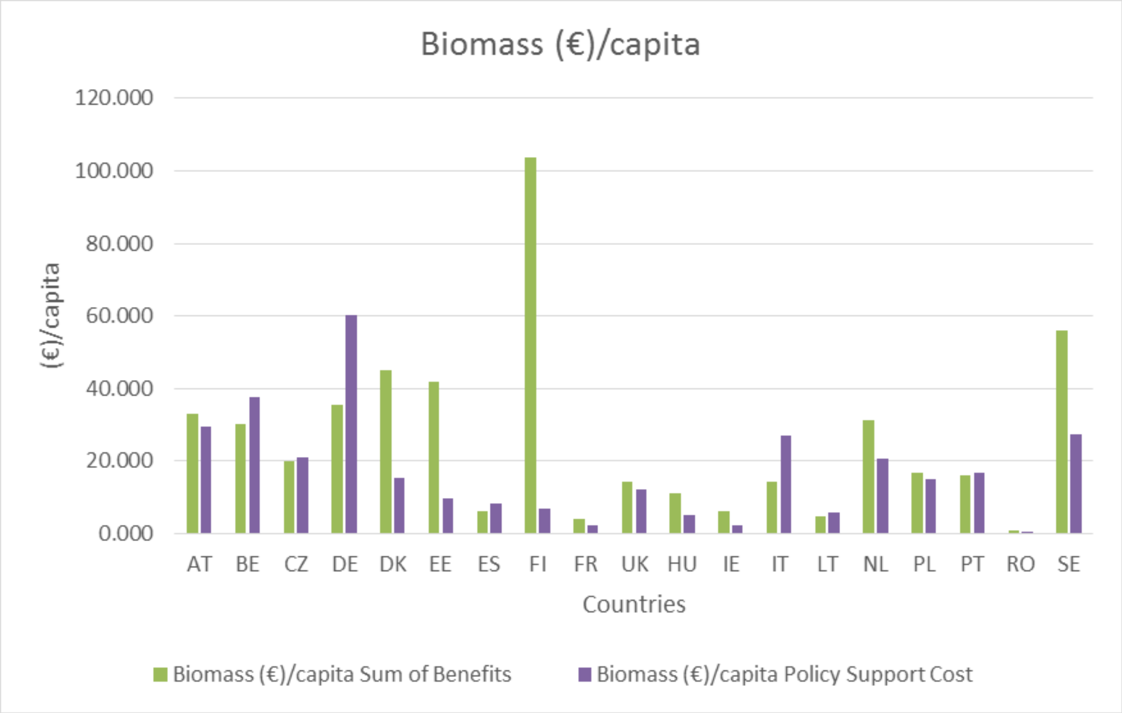


Figure 30: Per capita benefits and policy cost for biomass energy

Biomass has a mixed result to the benefit and cost comparison. Germany, Belgium, Italy, Estonia and Portugal have higher policy costs to the benefits obtained with Germany and Italy exhibiting huge difference. It has to be noted that for biomass, an assumption on the fuel is made. Woodchips is considered as the fuel for the calculation of the avoided external costs. This could considerable affect the results presented, especially in case of Germany, the biomass is the second largest renewable energy source in the energy mix. Of all the nations, Finland exhibits very high benefits to the policy support cost. In Finland, amongst all the renewable sources, biomass received the maximum policy support cost of 37 million €, however, it has to be noted that biomass is contributed to nearly 24% of the net electricity mix.

Wind Energy

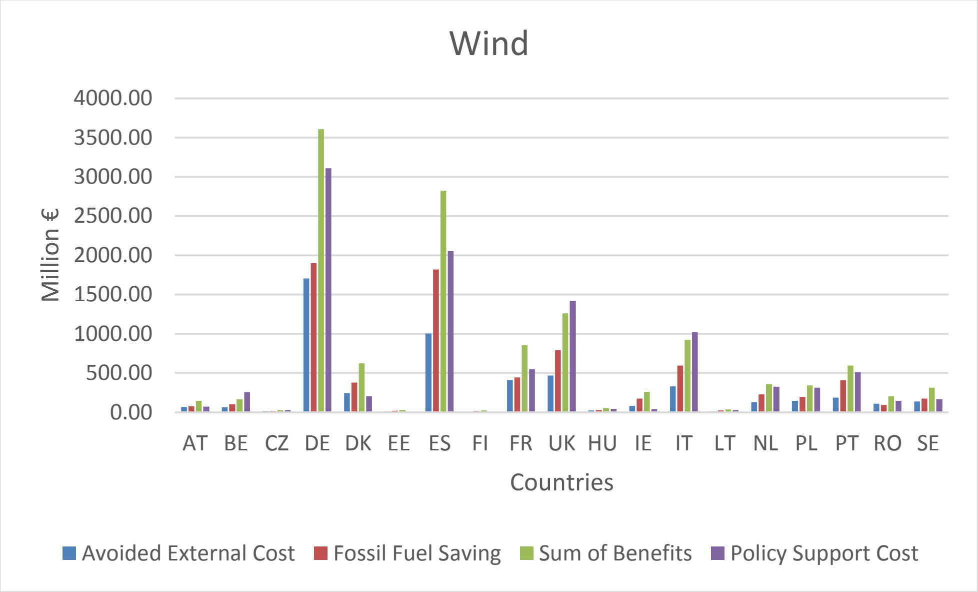


Figure 31: Comparison of benefits and costs of policy support for wind energy.

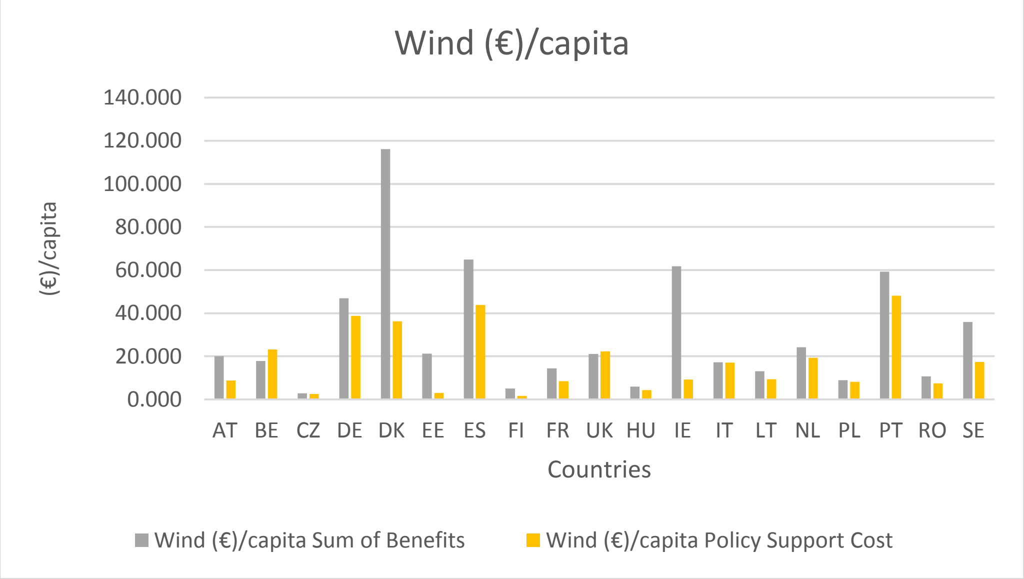


Figure 32: Per capita benefits and policy support cost for wind energy

The benefits obtained from the wind energy is higher than the policy support costs in most of the countries with an exception of UK, Belgium and Italy. In Denmark, the benefits are threefold higher than the costs involved. Denmark has employed FIP, tendering and both financial and investment incentives to promote wind energy.

Hydro Power

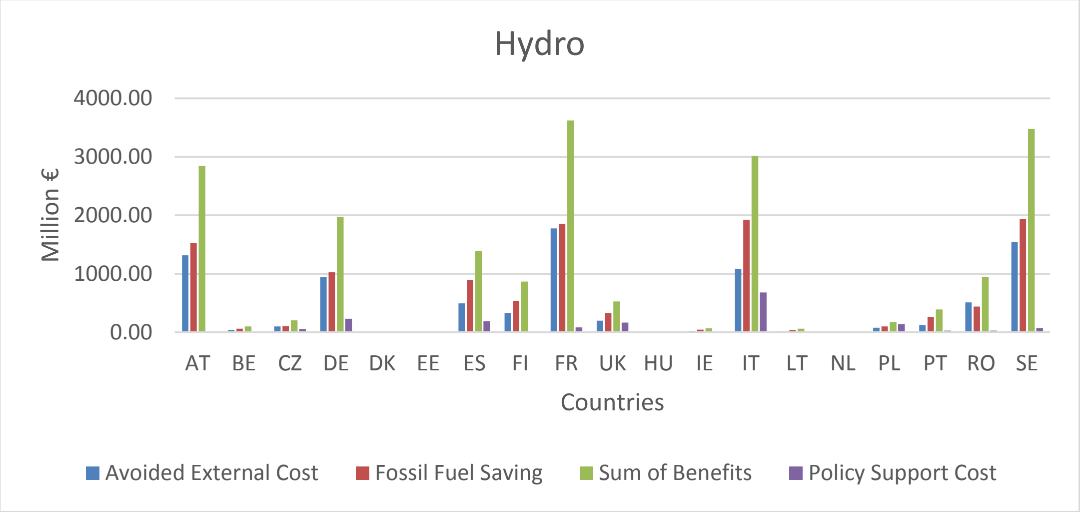


Figure 33: Comparison of benefits and costs of policy support for hydro power.

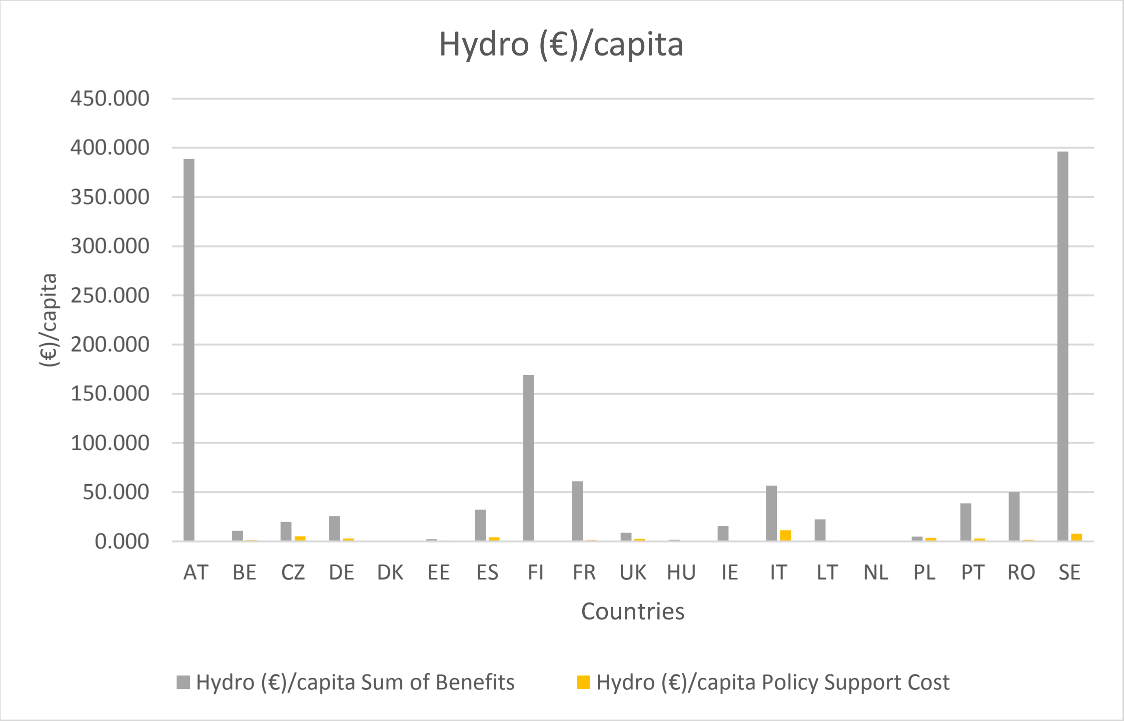


Figure 34: Per capita benefits and policy support for hydro power.

The benefits from hydro outweigh the support costs in all the countries. This is also because, hydro is a very mature technology prevalent for decades. In countries like Sweden, Austria, Germany, France and Italy, the benefits are at least threefold than the policy costs. With the pumped storage system, the hydro is also used to meet the demand fluctuations in the day. Among all the four renewables, hydro has a steady high benefits to cost.

This analysis shows the summary of benefits and costs from the policy support for renewable penetration in the Europe. These support cost, which are paid by the electricity consumers ultimately, have led to the benefits of externality reduction and fossil fuel savings, thereby, contributing to energy security. While Solar has higher policy costs compared to the benefits on an average, other renewables have a mixed results with hydro mainly holding higher benefits than the policy costs. Hence, it is only reasonable to do a country wise research of their resource availability and the policy schemes to understand the usefulness of promoting the renewable technologies in each nation. It should also be noted that, with increasing renewable penetration in the energy mix, the cycling and balancing costs have to be taken into account.

Margarita Ortega-Izquierdo et al (2016) have performed similar analysis comparing the policy costs with fossil fuel savings and the Externality avoided from GHG emissions (during the operation of the power plant alone). The results are considerably different compared to the analysis performed in this thesis. While in the above mentioned study, on an average, benefits are more relevant to the policy costs for hydro and wind and they are below the policy costs for bioenergy and solar PV. Taking a closer look, the country level values differed in certain cases. For an example, Netherlands had higher policy costs for hydro compared to their benefits in the study Margarita Ortega-Izquierdo et al (2016). However, in the analysis above, Netherlands have higher benefits to the policy cost for hydro. Such difference in the results are primarily because of taking into account the entire fuel cycle externalities into account in the analysis.

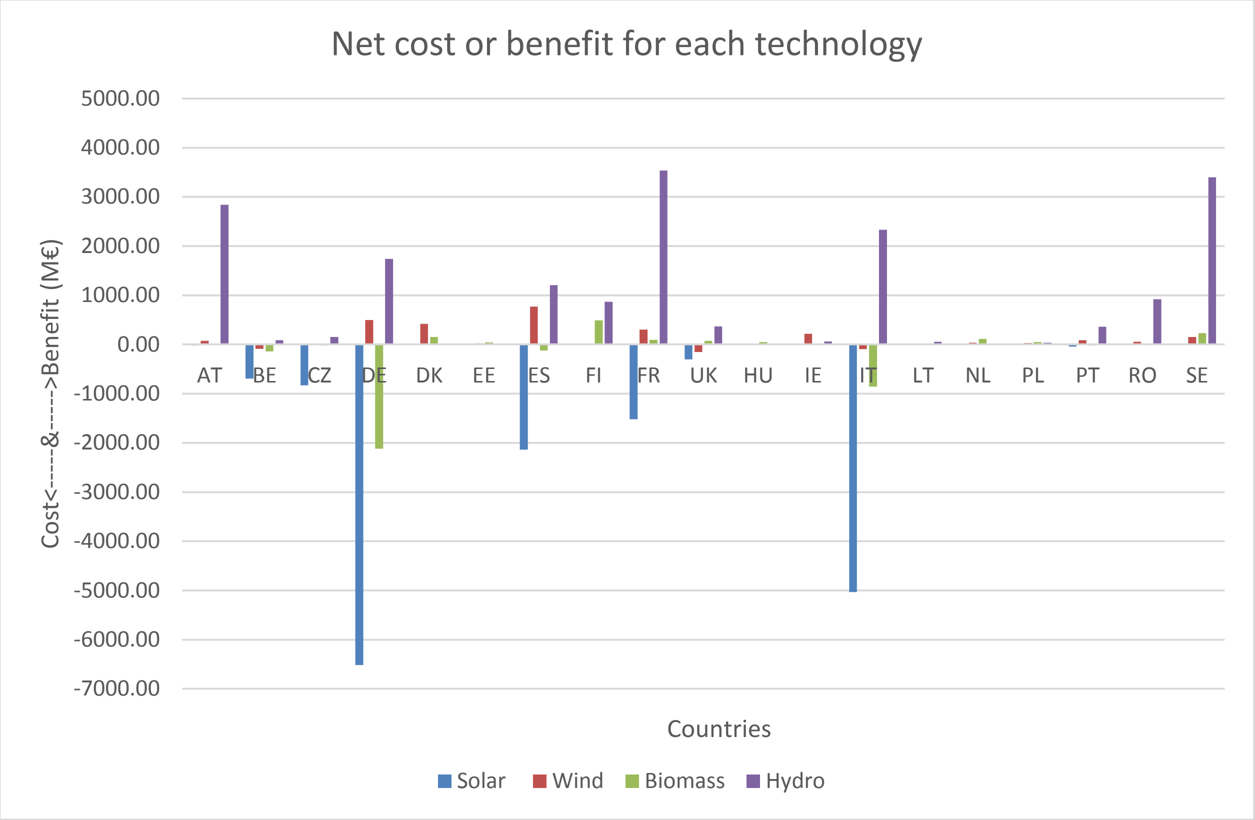


Figure 35: Comparison of the net costs and benefits by the renewable energy promotion. The Positive axis shows the benefits over the costs and the negative axis vice versa.

The figure above, shows that mostly, promotion of solar energy has been costly. Hydro energy has well stabilized establishing more benefits over the policy support costs followed by wind. Biomass has mixed results. On the whole, except solar, the benefits have been on the higher value to the policy incentives employed to boast the renewable energy into the electricity market. While the results give an overview of the costs and benefits, separate analysis has to be done for each country considering their availability of fuel resources to obtain a sustainable electricity generation mix.

The empirical findings bring out some policy implications,

- Considerable social benefit is induced by every cent of renewable support aided by the electricity consumers in their bills.
- The costs of support have increased significantly for some countries and technologies over the years, leading to the implementation of cost-containment measures in FIPs and FITs (including capacity caps, generation caps) which in some cases may have come too late to limit those costs.
- While FITs certainly have issues on their own as discussed by many studies, the results show that, at least in the EU, they have also brought significant social benefits. Despite the criticism, FITs continue to be widely recognised as a bench-mark for effective policy design in support of renewable energy expansion (Margarita Ortega-Izquierdo et al, 2016).

- The valuation of externality plays a pivotal role is in affecting the estimation of the benefits obtained from each the renewable energy technology.
- The fossil fuel savings from each technology signifies the political benefits attained in its contribution to the security of energy supply of the nation.

CHAPTER 6. CONCLUSION

This thesis work aims at identifying the externalities of the renewable energy technologies from various studies and from the externalities of each technology, the benefits and the costs involved in the public promotion of renewables was discussed. In this respect, this study can be regarded as confirming the climate benefits of replacing the fossil fuel power plants with the cleaner renewable technologies.

With respect to the externalities studies chapter, the study attempts to identify the external costs of various power generation technologies in order to support the decision-making process of future power plant investments under the framework of a sustainability. Along with the external costs, the uncertainties involved in the monetary valuation and hence the need for a site specific and technology specific study is stressed.

In order to level the economic playing field between several energy technologies, the external costs should be internalized and the existing subsidies on conventional and mature technologies have to be gradually reduced. From the policy perspective, there are several ways to achieve this goal with their own benefits and demerits. In this thesis, with the established external costs, the socio-economic effectiveness of promoting renewable energy through the policy incentives was discussed. With the exception of solar and biomass in certain countries, the EU wide average of the promotion of renewables have proven to be beneficial in terms of the avoided external costs and the fossil fuel savings. Behind the broader picture, significant differences between each country and technology emerge which has to be taken into account for the nation-wide decision making. Continuous assessment of the policy support tools to create cost effective and market based incentives are important.

The chief short coming of the thesis and hence an area for future research is the inclusion of private cost, cycling cost and balancing costs in the net cost of renewable penetration especially in the future when the penetration of renewable in the electricity mix increases. System cost are highly dependent on technology, location, size of project and cost of capital and it is extremely difficult to assess as a single figure. Furthermore, private costs, especially those of developing technologies such as solar PV and offshore wind, are not static, as they are subject to market forces and technological advancement. Hence, it is important to continuously update the studies and use market and site specific data for the analysis of cost and benefits of policy.

However, the current empirical findings and the analysis bring out the political and social benefits attained by the renewable energy technologies compared to the fossil fuel technologies in terms of the health and environmental benefits, climate change mitigation, social well-being and energy supply security.

BIBLIOGRAPHIC REFERENCES

Angeliki Menegaki (2007): Valuation for renewable energy: A comparative review, Renewable and Sustainable Energy Reviews, pp. 2422–2437.

Anil Markandya (2012): Environmental Taxation: What Have We Learnt in the Last 30 Years? Environmental Taxes and Fiscal Reform, pp.9-56

Anil Markandya (2012): Externalities from electricity generation and renewable energy. Methodology and application in Europe and Spain, Basque Centre for Climate Change, pp. 85–100,

Archer and Jacobson (2005): Evaluation of global wind power, Journal of Geophysical Research 110,D12110.

Athanasios Rentizelas, Georgakellos D (2014): Incorporating life cycle external cost in optimization of the electricity generation mix, Energy Policy 65, pp. 134–149.

Carneiro, Patrícia; Ferreira, Paula (2012): The economic, environmental and strategic value of biomass. Renewable Energy 44, pp. 17–22.

CASES (2008): D.06.1 Database of Full costs for EU, with external and private costs, Deliverables CASES. Available online at http://www.feem-project.net/cases/downloads_deliverables.php.

CASES (2008): WP 9 Report on policy assessment of instruments to internalise environment related external costs in EU member states, via promotion of renewables, Deliverables CASES. Available online at http://www.feem-project.net/cases/downloads_deliverables.php.

CEER (2015): Status Review of Renewable and Energy Efficiency Support Schemes in Europe in 2012 and 2013. The Council of European Energy Regulators Ref: C14-SDE-44-03.

Chataignere, A., Le Boulch, D. (2003): ECLIPSE Wind turbine (WT) systems. Internet publication. Available online at http://www.ECLIPSE-eu.org/zip/wind.zip.

Claudio Marcantonini and A. Denny Ellerman (2014): The implicit carbon price of renewable energy incentives in Germany, EUI Working Paper RSCAS.

Coutts, Erin M. (2014): Renewable energy econ module.

Cuperus, M.A.T. (2003): ECLIPSE Biomass systems. In Internet publication. Available online at http://www.ECLIPSE-eu.org/zip/biomass.zip.

D. Feldman, R. Margolis, and A. Goodrich: NREL; G. Barbose, R. Wiser, and N. Darghouth: LBNL (2014): Photovoltaic (PV) Pricing Trends: Historical, Recent, and Near-Term Projections, National Renewable Energy Laboratory.

Delucchi, Mark A.; Jacobson, Mark Z. (2011): Providing all global energy with wind, water, and solar power, Part II. Reliability, system and transmission costs, and policies, Energy Policy 39 (3), pp. 1170–1190.

EBIONET (2003): Biomass Co-firing: an efficient way to reduce greenhouse gas emissions,EBIONET,EU

EPIA (2012): Market Report 2011, European Photovoltaic Industry Association, EU

EPRI (2010): Power Generation Technology Data for Integrated Resource Plan of South Africa, Electric Power Research Institute, EU

European Commission (2011): Commission implementing decision 2011/877/EU of 19 December 2011 establishing harmonised efficiency reference values for separate production of electricity and heat in application of directive 2004/8/EC of the European Parliament and of the council and repealing commission decision 2007/74/EC (notified under document C(2011)9523).

European Commission (2014): Energy Economic Developments in Europe, Directorate-General for Economic and Financial Affairs. European Commission

Eurostat (2013): Eurostat News release, Eurostat Press office, STAT/13/173, European Commission.

Eurostat (2015): Electricity production, consumption and market overview, European Commission.

Eurostat (2016): Country Datasheets June 2016, European Commission.

Eurostat (2016): Electricity production and supply statistics, European Commission.

Evans, Annette; Strezov, Vladimir; Evans, Tim J. (2010): Sustainability considerations for electricity generation from biomass, Renewable and Sustainable Energy Reviews 14 (5), pp. 1419–1427. DOI: 10.1016/j.rser.2010.01.010.

EWEA (2009): The Economics of Wind Energy, The European Wind Energy Association.

ExternE (2005): Bickel, P & Friedrich, R., editors: Externalities of energy; methodology 2005 update. Directorate-General for Research: Sustainable Energy Systems.

ExternE (2008): Volume 10 National Implementation, Directorate-General for Research: Sustainable Energy Systems.

ExternE-Pol (2005): Externalities of energy, extension of accounting framework and policy applications, Work Package 6 new energy technologies.

Frankl, P., Gamberale, M. (1998): Simplified life-cycle analysis of Energy and CO2 aspects of building integration of photovoltaic systems. Progress in Photovoltics 6, pp. 137–146

Friedrich, R. (2008): Note on the choice of values of marginal external costs of greenhouse gas emissions. NEEDS Working Paper.

Garcia-Redondo AJ, Román-Collado R (2014): An economic valuation of renewable electricity promoted by feed-in system in Spain. Renew Energy, 68, pp. 51–7.

GlobalData (2011): Small Wind Turbines (less than 100kW) - Global Market Size, Analysis by Power Range, Regulations and Competitive Landscape to 2020.

Green M.A, Emery K, Hishikawa Y, Warta W (2011): Solar Cell Efficiency Tables (Version 37), Progress in Photovoltaic: Research and Applications 19, pp. 84–92.

GWEC (2015): Global wind report: annual market update 2015, The Global Wind Energy Council

IEA (2010): IEA Wind: 2009 Annual Report, International Energy Agency.

IEA Bio Energy (2012): Bioenergy – a Sustainable and Reliable Energy Source: A review of status and prospects, International Energy Agency.

IEA PVPS (2016): Snapshot of global photovoltaic markets, International Energy Agency Photovoltaic Power Systems Programme.

Intergovernmental Panel on Climate Change (IPCC) (2014): Climate Change 2014: Synthesis Report: Contribution of Working Group I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

International Energy Agency (2015a): World Energy Outlook 2015 - Executive Summary - English Version.

International Energy Agency (2015b): Energy and Climate Change - World Energy Outlook Special Report.

IRENA (2012a): Renewable Energy Cost Analysis: Biomass for Power Generation, International Renewable Energy Agency.

IRENA (2012b): Renewable Energy Cost Analysis: Solar Photovoltaic, International Renewable Energy Agency.

IRENA (2012): Renewable Energy Cost Analysis: Wind Power, Volume 1: Power Sector, International Renewable Energy Agency.

Kovach-Hebling, Anne (2016): Photovoltaic Report.

Lena Kitzing; Catherine Mitchell; Poul Erik Morthorst (2012): Renewable energy policies in Europe Converging or diverging? Energy Policy 51, pp. 192–201.

Margarita Ortega-Izquierdo; Pablo del Río (2016): Benefits and costs of renewable electricity in Europe, Renewable and Sustainable Energy Reviews 61, pp. 372–383.

Matevž Obrecht (2014): Would internalisation of external costs change cost-competitiveness of different energy sources? JCEBI 1, pp. 55–66.

Murphy, D. J. & C. A. S. Hall. (2010): Review: energy return on investment, Annals of the New York Academy of Sciences.

NEA (2001): Externalities and energy policy: The life cycle analysis approach, The OECD Nuclear Energy Agency.

NEEDS (2009): External costs from emerging electricity generation technologies. Deliverable n° 6.1 – RS1a, Sustainable Energy Systems.

Nielsen et al (2010): Economy of Wind Turbines (Vindmøllers Økonomi).

Peter Berrill; Anders Arvesen; Yvonne Scholz; Hans Christian Gils; Edgar G Hertwich: Environmental impacts of high penetration renewable energy scenarios for Europe, Environmental Research Letters, Volume 11.

Platts (2011): Data base description and research methodology UDI world electric power plants data base.

Pope, C. A., III, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002): Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, The Journal of the American Medical Association, 287(9), 1132-1141.

PSG AG (2014): Photovoltaic report, Fraunhofer Institute for Solar Energy Systems, Projects in Solar Energy.

REN21 (2016): Renewables 2016 Global Status Report, Renewable Energy Policy Network for 21st Century.

Setterwall, C., Münter, M., Sarközi, P., Bodlund, B (2003): ECLIPSE Bio-fuelled Combined Heat and Power Systems. In Internet publication. Available online at http://www.ECLIPSE-eu.org/zip/bio_fuelled.zip.

Susaeta, Andres; Lal, Pankaj; Alavalapati, Janaki; Mercer, Evan (2011): Random preferences towards bioenergy environmental externalities. A case study of woody biomass based electricity in the Southern United States. In Energy Economics 33 (6), pp. 1111–1118. DOI: 10.1016/j.eneco.2011.05.015.

Tol, R. S. J. (2002): Estimates of the damage costs of climate change. Part 1: Benchmark estimates. Environmental and Resource Economics, 21(1), 47-73.

UNIDO (2009): Deployment of Technologies for Sustainable Bioenergy: Towards an Agenda for International Cooperation.

US DOE (2010): Worldwide Gasification Database, US Department of Energy

US EPA (2007): Biomass combined heat and power catalog of technologies, U. S. Environmental Protection Agency Combined Heat and Power Partnership, Volume 1.1.

WBGU (2003): World in Transition – Towards Sustainable Energy Systems, German Advisory Council on Global Change.

APPENDIX

1. Solar Energy Benefits and Policy Support Cost

Country	Population*	Solar (Million €)			
		Avoided External Cost	Fossil Fuel Saving	sum of benefits	Policy Support Cost
AT	8408100	8.850	11.000	19.850	34
BE	11094900	52.935	79.000	131.935	802
CZ	10505400	56.990	77.000	133.990	965
DE	80327900	694.410	993.000	1687.410	8118
DK	5580500	2.125	4.000	6.125	0
EE	1333800	0.000	0.000	0.000	0
ES	46818200	228.183	300.000	528.183	2614
FI	5401300	0.107	0.000	0.107	0
FR	65327700	97.852	118.000	215.852	1709
UK	63495400	27.361	55.000	82.361	377
HU	9931900	0.228	0.000	0.228	0
IE	4582700	0.021	0.000	0.021	0
IT	59394200	441.168	830.000	1271.168	6161
LT	3003600	0.041	0.000	0.041	1
NL	16730300	5.467	12.000	17.467	12
PL	38538400	0.023	0.000	0.023	0
PT	10542400	6.381	16.000	22.381	66
RO	20096000	0.258	0.000	0.258	0
SE	9482900	0.338	0.000	0.338	0

2. Solar Energy Per Capita Benefits and Policy Support Cost

Country	Solar (€)/capita			
	Avoided External Cost	Fossil Fuel Saving	sum of benefits	Policy Support Cost
AT	1.053	1.308	2.361	4.044
BE	4.771	7.120	11.891	72.285
CZ	5.425	7.330	12.754	91.858
DE	8.645	12.362	21.007	101.061
DK	0.381	0.717	1.098	0.000
EE	0.000	0.000	0.000	0.000
ES	4.874	6.408	11.282	55.833
FI	0.020	0.000	0.020	0.000
FR	1.498	1.806	3.304	26.160
UK	0.431	0.866	1.297	5.937
HU	0.023	0.000	0.023	0.000
IE	0.004	0.000	0.004	0.000
IT	7.428	13.974	21.402	103.731
LT	0.014	0.000	0.014	0.333
NL	0.327	0.717	1.044	0.717
PL	0.001	0.000	0.001	0.000
PT	0.605	1.518	2.123	6.260
RO	0.013	0.000	0.013	0.000
SE	0.036	0.000	0.036	0.000

3. Biomass Energy Benefits and Policy Support Cost

Country	Wind (Million €)			
	Avoided External Cost	Fossil Fuel Saving	Sum of Benefits	Policy Support Cost
AT	89.005	79.000	168.005	74.000
BE	96.531	101.000	197.531	257.000
CZ	14.946	15.000	29.946	27.000
DE	1868.477	1901.000	3769.477	3108.000
DK	270.396	378.000	648.396	202.000
EE	10.247	18.000	28.247	4.000
ES	1223.578	1818.000	3041.578	2053.000
FI	10.909	16.000	26.909	9.000
FR	499.687	443.000	942.687	550.000
UK	546.824	793.000	1339.824	1418.000
HU	30.102	29.000	59.102	43.000
IE	105.892	177.000	282.892	42.000
IT	432.536	594.000	1026.536	1018.000
LT	14.109	25.000	39.109	28.000
NL	177.000	227.000	404.000	324.000
PL	148.842	196.000	344.842	315.000
PT	218.237	406.000	624.237	508.000
RO	120.448	95.000	215.448	148.000
SE	163.409	177.000	340.409	165.000

4. Biomass Energy Per Capita Benefits and Policy Support Cost

Country	Biomass (€)/capita			
	Avoided External Cost	Fossil Fuel Saving	Sum of Benefits	Policy Support Cost
AT	15.422	17.483	32.905	29.495
BE	13.404	16.855	30.259	37.585
CZ	9.226	10.566	19.792	21.037
DE	16.160	19.371	35.530	60.091
DK	17.789	27.238	45.027	15.411
EE	15.525	26.241	41.766	9.747
ES	2.262	3.845	6.107	8.223
FI	40.514	63.133	103.647	6.850
FR	2.018	2.097	4.115	2.189
UK	5.358	9.072	14.429	12.332
HU	5.078	6.142	11.219	5.236
IE	2.159	4.146	6.305	2.400
IT	5.443	8.923	14.366	27.141
LT	1.601	2.996	4.597	5.660
NL	12.287	18.888	31.174	20.502
PL	6.729	9.886	16.615	15.128
PT	5.271	10.719	15.990	16.789
RO	0.361	0.348	0.710	0.348
SE	25.089	30.792	55.881	27.207

5. Wind Energy Benefits and Policy Support Cost

Country	Wind (Million €)			
	Avoided External Cost	Fossil Fuel Saving	Sum of Benefits	Policy Support Cost
AT	89.005	79.000	168.005	74.000
BE	96.531	101.000	197.531	257.000
CZ	14.946	15.000	29.946	27.000
DE	1868.477	1901.000	3769.477	3108.000
DK	270.396	378.000	648.396	202.000
EE	10.247	18.000	28.247	4.000
ES	1223.578	1818.000	3041.578	2053.000
FI	10.909	16.000	26.909	9.000
FR	499.687	443.000	942.687	550.000
UK	546.824	793.000	1339.824	1418.000
HU	30.102	29.000	59.102	43.000
IE	105.892	177.000	282.892	42.000
IT	432.536	594.000	1026.536	1018.000
LT	14.109	25.000	39.109	28.000
NL	177.000	227.000	404.000	324.000
PL	148.842	196.000	344.842	315.000
PT	218.237	406.000	624.237	508.000
RO	120.448	95.000	215.448	148.000
SE	163.409	177.000	340.409	165.000

6. Wind Energy Per Capita Benefits and Policy Support Cost for Countries

Country	Wind (€)/capita			
	Avoided External Cost	Fossil Fuel Saving	Sum of Benefits	Policy Support Cost
AT	10.586	9.396	19.981	8.801
BE	8.700	9.103	17.804	23.164
CZ	1.423	1.428	2.851	2.570
DE	23.261	23.666	46.926	38.691
DK	48.454	67.736	116.190	36.197
EE	7.683	13.495	21.178	2.999
ES	26.135	38.831	64.966	43.850
FI	2.020	2.962	4.982	1.666
FR	7.649	6.781	14.430	8.419
UK	8.612	12.489	21.101	22.332
HU	3.031	2.920	5.951	4.329
IE	23.107	38.624	61.730	9.165
IT	7.282	10.001	17.283	17.140
LT	4.698	8.323	13.021	9.322
NL	10.580	13.568	24.148	19.366
PL	3.862	5.086	8.948	8.174
PT	20.701	38.511	59.212	48.186
RO	5.994	4.727	10.721	7.365
SE	17.232	18.665	35.897	17.400

7. Hydro Energy Benefits and Policy Support Cost

Country	Hydro (Million €)			
	Avoided External Cost	Fossil Fuel Saving	Sum of Benefits	Policy Support Cost
AT	1740.524	1527.000	3267.524	5.000
BE	58.486	61.000	119.486	14.000
CZ	103.731	103.000	206.731	54.000
DE	1034.284	1027.000	2061.284	231.000
DK	0.452	1.000	1.452	0.000
EE	1.004	2.000	3.004	1.000
ES	603.556	894.000	1497.556	187.000
FI	376.672	536.000	912.672	0.000
FR	2150.677	1850.000	4000.677	86.000
UK	229.077	332.000	561.077	164.000
HU	8.400	8.000	16.400	3.000
IE	27.058	44.000	71.058	1.000
IT	1426.362	1925.000	3351.362	681.000
LT	24.764	42.000	66.764	3.000
NL	3.717	5.000	8.717	7.000
PL	77.981	101.000	178.981	139.000
PT	142.832	264.000	406.832	30.000
RO	568.320	438.000	1006.320	31.000
SE	1823.477	1935.000	3758.477	72.000

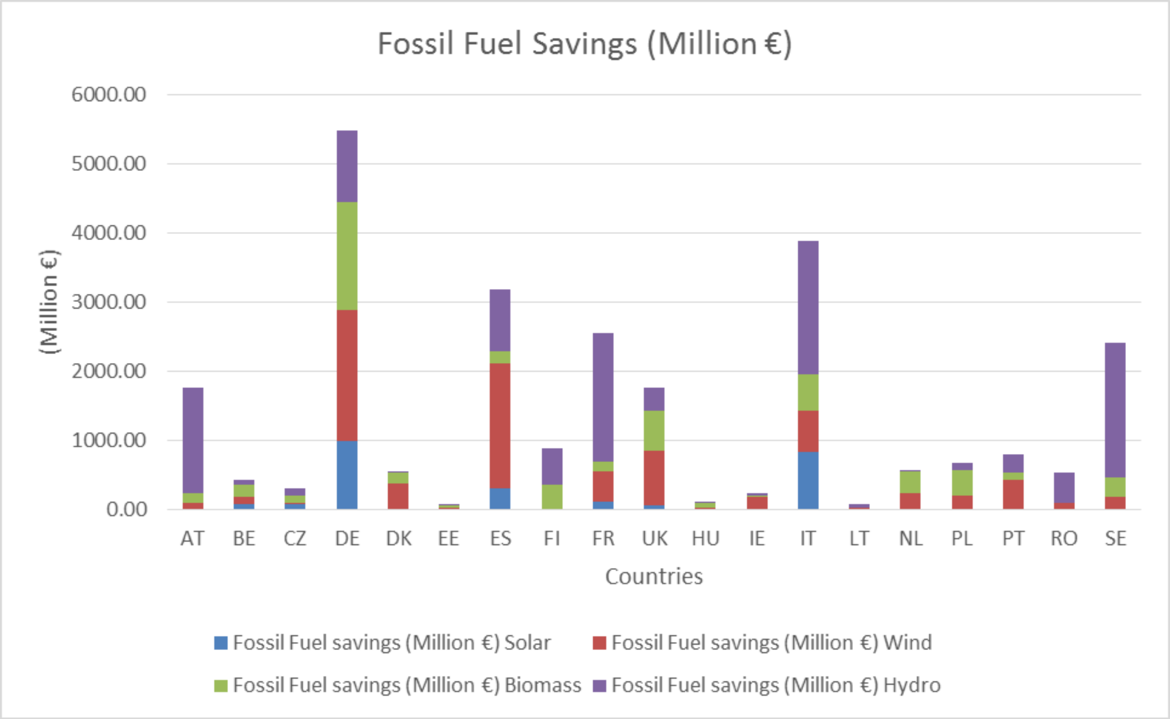
8. Hydro Energy Per Capita Benefits and Policy Support Cost for Countries

Country	Hydro (€)/capita			
	Avoided External Cost	Fossil Fuel Saving	Sum of Benefits	Policy Support Cost
AT	207.006	181.611	388.616	0.595
BE	5.271	5.498	10.769	1.262
CZ	9.874	9.804	19.679	5.140
DE	12.876	12.785	25.661	2.876
DK	0.081	0.179	0.260	0.000
EE	0.753	1.499	2.252	0.750
ES	12.891	19.095	31.987	3.994
FI	69.737	99.235	168.973	0.000
FR	32.921	28.319	61.240	1.316
UK	3.608	5.229	8.836	2.583
HU	0.846	0.805	1.651	0.302
IE	5.904	9.601	15.506	0.218
IT	24.015	32.411	56.426	11.466
LT	8.245	13.983	22.228	0.999
NL	0.222	0.299	0.521	0.418
PL	2.023	2.621	4.644	3.607
PT	13.548	25.042	38.590	2.846
RO	28.280	21.795	50.076	1.543
SE	192.291	204.052	396.343	7.593

9. Avoided External Cost by Renewable Energy in Europe

	Avoided External cost at 2012 (Million €)			
country	**Solar**	**Wind**	**Biomass**	**Hydro**
AT	5.85	67.10	88.69	1316.00
BE	28.28	64.95	89.00	39.44
CZ	54.75	14.51	93.41	100.75
DE	610.30	1706.93	1155.78	945.49
DK	1.88	246.12	88.76	0.41
EE	0.00	10.05	20.25	0.98
ES	175.21	1004.60	83.87	496.61
FI	0.09	9.61	189.28	332.20
FR	74.09	411.44	102.62	1774.37
UK	22.08	469.34	282.98	196.84
HU	0.16	23.61	36.47	6.60
IE	0.01	82.57	7.35	21.16
IT	295.50	329.00	226.82	1087.69
LT	0.02	9.79	3.06	17.27
NL	3.36	130.46	138.26	2.74
PL	0.02	145.84	252.94	76.42
PT	5.27	189.30	47.25	124.04
RO	0.22	107.94	6.26	509.88
SE	0.27	137.64	194.05	1539.09

10. Net Fossil Fuel Savings by Renewable Energy in European Countries



11. Net Policy Support for Renewable Energy in European Countries