Department of Mechanical Engineering

Project

Business case analysis for deployment of renewable power generation for Western Scotland industrial sites

Author: Valeria Khnykina

Supervisor: Prof John Counsell

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Abstract

This project is targeted at understanding of difficulties which renewable energy feasibility process, particular medium scale wind and solar PV, is accomplished with, including detailed energy resource assessment, analysis of energy demand data, choosing the size of the unit, and estimating economic and environmental benefits and drawbacks of different technologies and their combinations.

Wind and solar PV technologies are briefly overviewed In the first part of this paper, following by theoretical approaches to calculations of potential energy output at rural and industrial locations. Based on a case study of Barr Limited office and manufacturing territory at Killoch, a process of choosing a potential location of wind turbines and PV panels was described with a reference to local characteristics which affect the power generation.

The potential annual energy output was calculated and compared with the demand of the company. Using results from these calculations, proposed renewable energy generation types were compared between each other applying financial benefits calculations and evaluation of environmental and social impacts.

To sum up, each of the technology and unit size has own benefits. It was found that for wind energy with increasing of turbine size and hub height the financial outcomes are higher because of the greater wind speed. For PV technology is also beneficial to increase the power output, however about 75% of financial incomes for both – PV and wind energy depend on Feed-In tariffs which decrease with the size of the installed power capacity, so for example for PV it is less profitable to install more than 50kWp.

For wind energy negative environmental and social impacts are higher than for PV panels; however as for financial outcomes, they are higher for wind turbines. So the choice technology – wind or solar energy - should be accurately weighted with understanding of all problems that could occur during renewable energy system operation.

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Introduction

In the light of last economic crises, financial instability, and gradual increasing of energy tariffs, many companies try to stay afloat and increase their market share. To do that they decrease their expenditures, including work at their energy consumption. There are two well-known ways to cut energy payments. First one is energy management and saving technologies. The second one is having a renewable energy generation. Combination of both gives the highest efficiency for any industrial application.

This thesis is based on a case study of the Barr Limited, which is a large industrial company with a high range of production and services. The policy of Barr is targeted at decreasing of energy consumption and carbon footprint. Owing to information and help that the company supported this project with, it was possible to investigate technical, financial and environmental issues of renewable energy systems installation in Western Scotland industrial site.

Despite large distribution of renewable energy in present time, there is still a lack of information about technical issues, economic and environmental benefits. This happens because the scale of energy units for industrial applications is not well developed. Small-size renewables are easier to plan, install and operate; they usually do not require a detailed investigation of energy generation and consumption. Those systems are selling as a kit for households with all necessary equipment included. On the other hand, large utility-scale renewable energy plants need a very accurate energy prediction and operation, long planning and agreement process. Large scale renewables are developing by a few companies in the UK. This market is quite closed and does not share methods and technologies in use.

Medium-scale renewable energy market is exactly between domestic and commercial energy generation. Medium-scale renewables are not so well known which cause a lack of information and delusions about them. Dew to the profit orientation of industry and business, the prior investigation of energy output, economic and environmental effects should be detailed enough to understand whether green energy generation could be a goal for a business in Western Scotland to move towards.

1. Topic background

The energy policy of the UK and high prices on gas and electricity forces companies, communities and individuals to think about local renewable energy generation. The UK Government adopts different programmes to support them in this uneasy decision. Most of the problems with renewables are well known. For example, high cost and payback period, low efficiency and unpredictable energy output prevent many people from installation renewable energy generation equipment. However, using wind, solar, biomass or other green energy technologies could help solving current problems with high energy consumption and pollution.

1.1. Global interest in Renewable Energy

The fossil fuels era has begun more than a century ago. During that time the Humanity made an unbelievable leap upward in economy, technology and quality of life. Several generations in Europe and America were risen on the belief of inexhaustible energy from oil, coal and natural gas. People are lucky to live in this age. They have got everything they want – fast cars, airplanes, electronic devises, food from all over the world (Renewable Energy World, 2010). This wave of growth is so big that we refuse to understand that it is comes into break. The global oil demand expanded so much that the oil industry cannot maintain it any more. This calls the "peak oil" and many countries have reached it already (Rapier, 2010). To get oil companies should drill in hard-to-reach environments as north territories or ocean beds. They do it because of the high demand in oil to keep the same life-style that we built for the growing population.

The fossil fuels consumption already caused irreversible environmental problems, such as pollution and global warming. The world average temperature increased by 0.8 degrees Celsius (News, National Geographic, 2007) during the last 130 years and it continue growing. The Kyoto Protocol adopted in December 1997 was targeted at reducing greenhouse gas emissions by developed countries. To follow this aim, the Climate Action European Commission (DG CLIMA) was established in December

2010. It is working at building of an international carbon trading market and promotion low carbon technologies (The Directorate-General for Climate Action, 2010). For the EU this work is not only at reducing of energy consumption and carbon emissions, it is a work at decreasing of the total dependence of many European countries from oil and gas import, which cause high energy prices and limits in further developing.

To sum up, the World is now facing the most challenging situation connected with energy consumption. The fossil fuels reserves are decreasing and the world population and demand is growing together with complication of environmental problems. With present level of technologies the only way to surmount those global difficulties is to widespread using of renewable resources and significantly improve energy management.

1.2. Local Interest in Renewable energy

Many people care about oil and gas demand and pollution of the environment. However present economic situation makes people faster react to changes in energy industry. Recently British Gas has announced increasing of prices for electricity by 16% and gas by 18% from August 2011. This happened after only 8 months since the last prices increasing by 7% (King, 2011). Many households in the UK during the coming winter will suffer from new high bills. Between 2000 and 2010 the UK domestic electricity prices increased by 82% (from 7.09 to 12.89p/kWh) and domestic gas prices increased 2.5 times (from 1.66 to 4.15p/kWh) including taxes (Department of Energy & Climate change, 2011). The most significantly energy prices for domestic and industrial usage increased during last 5 years (Figure 1) despite the economic crises 2008-2009.

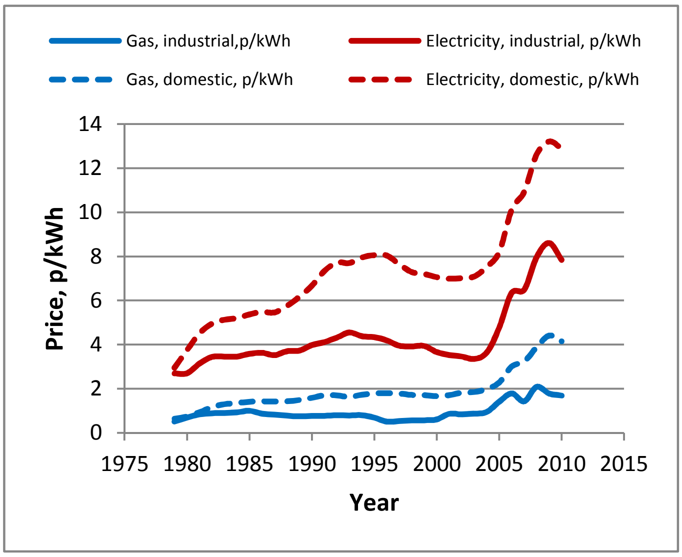


Figure 1 UK domestic (dashed line) and industrial (solid line) utilities price including taxes, 1979-2010 (Department of Energy & Climate change, 2011)

In present economic situation individuals try to decrease their energy bills and industries want to keep their business competitive. For both of them renewable energy could help to decrease expenditures on energy or even get an additional income from energy export to the grid. Local communities show a high interest in renewables. Thus in West Penwith the West Cornwall Local Action Group plans to move towards generating renewable energy in their community to protect themselves from fuel prices increasing (Community Energy Plus, 2011).

To conclude with, energy generation from renewable resources started to play a significant role in global and local environment. This process shows the great potential in Green Energy. The popular English proverb says “Little drops of water make the mighty ocean”. Similar, every locally installed solar PV panel, bio-fuel boiler or a wind turbine form the entire renewable energy industry.

1.3. Literature review

Renewable energy projects are running everywhere in the world, however most of them represents utility energy generation scale or micro generation. In both those cases the feasibility and pre-planning investigation differs from medium-scale industrial applications. For domestic usage the thoroughness of projects is not high. Short study and minimum information is usually required to install small-scale wind and solar energy system. For utility-size energy projects are more detailed for both – wind farms and large PV arrays. On the other hand, medium scale renewables need a project methodology that would allow an industrial or other large business company to analyse benefits and drawbacks of wind turbine(s) of PV system and start a planning and agreement process in case of positive decision about renewable energy generation. In addition, many existing studies about renewable energy overview only one resource, wind, solar or other. This paper compares possibilities of wind and PV power for the same location and discusses positive and problematic points for both of them.

One of the recent studies took place in Canada southwest coast of Banks Island in the Amundsen Gulf. Initially the site was powered by diesel generator and that pre-planning work was targeted to investigate wind energy alternatives to diesel power. The energy load of the site was 907MWh/year with 68kW base load which is very close to the case study used in this project (1250MWh/year, 52kW respectively). For energy and economic analysis that study in Canada used 50kW turbine EW50 that could be located at one of three proposed in the project sites. Energy analysis was based on wind data from three sources including measurements at the local airport. Economic and environmental analysis compared wind energy with diesel generator worked as off-grid power station (Jean-Paul Pinard, 2009).

A few medium-sized wind energy projects were run by Wine Energy Direct in Ireland. In those projects wind turbines produced a part of necessary energy with an electrical grid as a primary energy resource. In the report a suitable site for a wind turbine describes as a company with permanent high base load and no dwellings within 300m from the site. Alco the area should have enough space for construction in lands with good wind resource. Another requirement is a far distance from airports. The report was based on a case study of a manufacturing site of “Munster Joinery” with two turbines 2MW rated power each installed in 2009 and covered 30% of the demand of the company. The timeline of the project shown, that the process from feasibility study to commissioning of turbines took 36 months. Additionally the project report described major financial and environmental benefits gained from wind turbines installation (Costello, 2010).

As for PV power solutions, industries are interested in solar energy and try to understand all issues of large scale system sizes. For example in 2009 Camco prepared a report for Renewables East that reviewed different aspects of solar PV as general trends on market, regulatory work in the UK, issues of site selection based on East of England as a case study, type of installation, environmental and planning criteria. The report was written when Feed-in tariffs were not adopted, so it does not review financial benefits from FITs payments (Hofmann, 2009).

Another paper about building-integrated PV energy managing of installation and it presents in depth stages of projects and timing, operation and maintenance using examples of 12 middle-size PV systems from 20 to 100kW power built under LSBIPV programme. This paper would be a good practice guide to those who want to understand all stages of PV installation process (Emily Rudkin, 2008).

A PV feasibility study that used 25kW PV system in Colorado, US as a case study calculated energy output and financial benefits accomplished solar PV system installation. Energy output calculations and energy demand analysis were introduced briefly following by financial analysis as return on investment calculations. In conclusions author outlined that PV technology is expensive and not mature enough in present time in comparison with other energy generation technologies. However the project took place in the US which has different from the UK support of renewables from the government (Nieh, 2010).

To sum up, there are many projects for PV and wind energy separately, however some of them are not detailed enough in data processing or concentrated on only one aspect of a middle-scale units as technical, financial or environmental aspects. This project targeted at unbiased investigation of all of those aspects for both – wind and PV energy generation.

2. Photovoltaic technology

The global photovoltaic market is growing rapidly. During the past decade it was growing by 30% annual mean rate (Sioshansi, 2010). At the period of 4 years since 2004 investments in PV technologies increased dramatically. Thus, the total US private investments rose from $200 million in 2005 to $1400 million in 2007. The third part of those investments were made in Thin-film PV technology. Similarly, during the same period the EU investments in PV increased from about $170 to nearly $800 a year. In 2007 the EU invested about 60% of total number in Poly-silicon technology. In addition to that, the price of PV systems decreased significantly. It was calculated that the price of PV decreases by 20% with doubling of the total installed capacity and this downward trend is expected to continue (Sioshansi, 2010, pp. 286-287). The cumulative PV capacity installed in Germany by 2007 reached 3800MW. Japan had twice lower cumulative capacity of PV, and this was the second highest result in the world. High support from governments in many countries together with costs decreasing make this technology the most interesting to invest in.

2.1. Solar resource

Solar radiation is the most important energy resource in the world. The amount of energy that our planet receives is 1.366kW/m^2 (the solar constant). Solar energy, that coming to a particular place, depends on Earth-Sun geometric position (including distance and declination angle), the place location (latitude, longitude) and position of the sun in the sky (solar altitude, azimuth). In clear days the amount of direct solar radiation is reaching 80% of the total insulation, this percentage is decreasing with increasing of humidity, clouds cover and atmospheric aerosols (Sioshansi, 2010, p. 274).

2.2. Types of PV

The Earth's surface consists from sand by 60%, which is quartzite or silicon dioxide SiO_2. Consequently, the supply of silicon is nearly endless. However to make a pure semiconductor-grade silicon which is used in PV production, the material should go through several purifying stages. First, in amounts of 600,000 tonnes a year the metallurgical-grade silicon is producing to make special still and alloys. The energy input of this process is only 50kWh/kg and the cost is about $2/kg (Markvart, 2000, p. 47). However the purity of 98-99% of metallurgical-grade silicon is not enough for electronic applications. For the industrial solar-grade silicon it purifies till 1ppma (or 99.9999% of pure silicon concentration). The price of this silicon is about $50/kg and in 2000 world production was 20,000 tonnes a year. During the production of pure silicon forms its crystallised structure. Different methods are applying at this stage, the most popular are – Czochralsky method, float-zone process and multi-crystalline method (Markvart, 2000, pp. 49-51).

The whole PV industry process has four major stages:

- From sand to pure silicon
- From silicon feedstock to silicon crystals and wafers
- From silicon wafers to solar cells
- From cells to modules.

2.2.1. <u>Monocrystalline silicon</u>

Made from single-crystal silicon this PV type is the most efficient because it does not have grain boundaries. Cells of those PV are made from single grown crystal, which was sliced, doped and etched. The efficiency range of panels made from monocrystalline is about 15-20% (Robert Foster, 2009, p. 129). For example, on market the maximum declared efficiency is 19.6% for SPR-318E-WHT model produced by "SunPower", USA (Posharp/a). The warranty for the 80% of power output is 25 years. Having the highest efficiency, monocrystalline PV panels are the most expensive to produce.

2.2.2. Polycrystalline silicon

These cells are made from various silicon crystals formed from an ingot. After that they have the same processing as monocrystalline PV cells. On the surface of the manufactured polycrystalline PV the portions of crystals could be seen easily. The efficiency of those PV is less than monocrystalline, usually between 13-15% (Robert Foster, 2009, p. 129). On market many companies produce polycrystalline PV with declared efficiency up to 17%, for example “SolarWorld” SW-200S has efficiency of 16.2% (Posharp/b). The efficiency of all crystalline cells is high; however it is necessary to reduce the cost and amount of the material used in PV production to make them more affordable on market (Markvart, 2000).

2.2.3. Thin-films

Thin-films solar cells have much higher rate of light absorption that allows making cells about 100 times thinner than cells from mono or poly crystalline. Thin-film cells are made from several layers of semiconductor material. The most common Thin-film technologies are amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium or gallium diselenide (CIS/CIGS) (Sioshansi, 2010, p. 277).

For example amorphous silicon has the lowest conversion efficiency among the crystalline types mentioned above; it is reaching 5-10% (Robert Foster, 2009, p. 129). Dew to the flexibility of the material, the number of applications of thin-films is much higher. Additionally those PV are the least expensive to produce. The main challenge of manufacturers is increasing the efficiency of thin-film material with maintaining low cost.

The cost of the final product is made up of 3 contributions each of them takes approximately 1/3 part: silicon in wafer form, fabrication of solar cells, encapsulation and construction of the module (Markvart, 2000). In 2007 the cost of the module was

$4.2/W (crystalline silicon) and $3.5/W (thin-film). The final cost of PV systems based on crystalline silicon varied between $7.2/W for commercial and $8/W for residential applications (Sioshansi, 2010, p. 286).

2.3. PV applications

PV systems can be used in many applications from small isolated systems (for example to power traffic lights, of charge mobile phones) to large installations of several MW connected to the grid.

2.3.1. Large–scale solar power

The major problem with large-scale solar power is energy diluteness. This causes necessity of large solar PV areas and associated infrastructure (Faiman, 2010). For example the 25kW of peak power plant would have 250m^2 of active PV array, and total occupied land area of 1000m^2 (Markvart, 2000). These space requirements lead large solar plants far from cities to remote areas in deserts. Those large territories cause additional expenditures for infrastructure building and a big number of service staff. Additionally, large-scale solar energy production is usually associated with exporting electricity to the grid. Therefore, it requires inversion from DC to AC electricity. Current inverters efficiency is about 95%. Additional losses occur in electrical wires between PV modules and in grid. On the other hand, systems, connected to the grid, does not require energy storages, this significantly improve economical values in comparison with stand-alone modules.

During last 3 years a number of large PV plants were built in different countries. The cumulative power of them accounts for 3GW, including 1GW power installed in Germany which is the absolute leader of the market followed by Italy and the Czech Republic (PVResources (a)). In present time the biggest Solar PV operates in Canada, Sarnia. The capacity of the plant is 98MW, and it was constructed between 2009 and 2010. At the same time two plants of 84.2MW and 70.6MW were constructed in Italy. The other two large PV plants with the capacity of 80.2MW and 71.8MW are situated in Germany. Most of the biggest PV plants are ground-mounted without solar-tracking systems (PVResources (a)). The biggest roof-mounted PV plant was installed in 2010 in Kallo, Belgium. The Power output of the system is 13MW (PVResources (b)). A large PV power plant installation significantly improves a public image of the country and local city. Producing green energy means care about the environment and people.

2.3.1. Small and medium-size solar power

Energy generation is not only about huge power plants as many people consider it. There are lots of applications where a medium, small or even micro power generation is required, for example, for traffic lights, bus stops, small electronic devises. When power generates near consumers, many losses that occur because of the long chain between generation and load could be dismissed. Especially micro generation is highly applicable with PV technologies because of their cells and modules structure. In 2006/2007 the UK transmission losses were 1.8%, this is 6.1 TWh (National Grid, 2008). Thus, remote large PV station would loss about 2% of generated electricity in the grid. When PV panels are installed on a roof of a building, those 2% are consumes on site, which is very important for the technology with initially low efficiency.

Additionally, in some systems DC currency produced by PV could be used directly, without conversion to AC, so not only grid transmission losses could be avoided, but about 10% of losses in double conversion too. This could be applied to all electronic devices such as cell phones, netbooks, iPods, photo cameras, mp3 players and many others. It is not a pioneering technology; for instance calculators on solar energy were designed decades ago. Currently, when the cost of PV materials decreased, businesses are returning to this idea. For example “Suntrica” from Finland produces portable charges for Apple electronics as iPhone and iPod. After 4 hours under direct solar the mobile phone gives 1.2 hours of talking or 32 hours of standby time. This could be used not only occasionally when the grid is not available, but for permanent charging as well.

3. Wind energy technology

Wind energy is a promising technology that rapidly developing on market. Large wind farms and domestic turbines produce electricity for local applications and export it to the grid. In present time there are 307 operational wind farms in the UK, 293 of them are onshore and have installed capacity of 4,212.90MW, and 14 offshore wind farms have capacity of 1,524.80MW (see annex, Table 21) (RenewableUK, 2011).

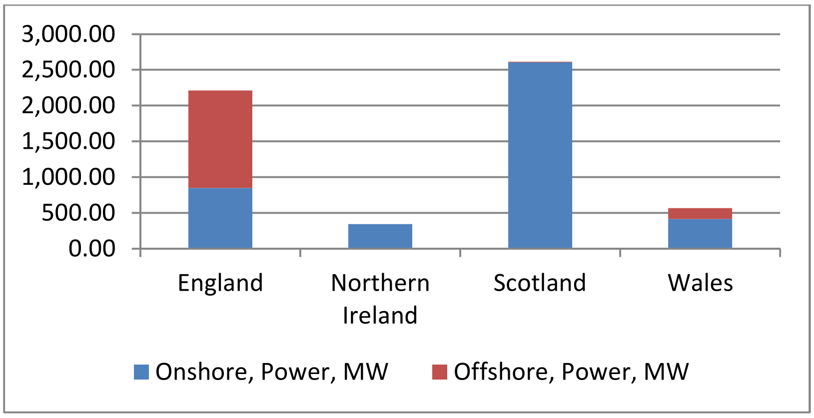


Figure 2 Onshore and offshore operational wind farms capacity (RenewableUK, 2011)

In Scotland, where the wind resource is the best in Europe, the cumulative capacity of currently operated wind farms is 2,614.73MW, it is based on onshore technology. In England, the capacity of all wind farms is 15% lower than in Scotland. Thus, more than half of it generates offshore. All in all, the UK policy is targeted at fast development of renewable resources including wind energy. Wind power generation is more suitable for large-scale farms, the size of existing turbines reaching 5MW per unit.

3.1. Power from wind

To find a power output from wind turbines it is essential to understand what it depends upon. The well-known equation (1) shows that the most significant contribution into wind power gives wind speed U.

$$P = \frac{1}{2} * C_p * \rho * A * U^3; \quad (1)$$

Additionally, power output depends on power coefficient C_p, air density ρ and swept area A of the turbine.

The power output from wind is limited by C_{pmax}=16/27=0.59, which is known as Betz limit for lift-driven turbines and means that a wind turbine actuator absorbs a maximum of approximately 59% of the power available in free stream wind (Mertens, 2006). C_{pmax} is only a theoretical maximum, in practice C_p of wind turbines is in-between 0.25-0.45 (Olimpo Anaya-Lara, 2009) and determines by losses in power extraction and transmission machinery.

3.2. Wind data

Because power output from wind turbines highly depends on wind speed, it is critical to use trustworthy wind data in calculations. Collecting wind data is a part of analysis of the proposed site for a wind turbine. Firstly, wind data could be collected from nearby weather station. The advantage if this method is short time for collecting and analysing of data. However, the relationship of the site and weather station to local terrain is very important. Different surface roughness and elevation could significantly affect the wind speed. This method only works in flat terrain where average annual wind speeds are 10mph or greater (Harry L. Wegley, p. 35).

Another method of wind data collection is taking limited onsite measurements. This method could be used when nearby weather stations can not represent wind speed conditions of the site properly, for example when they are too far away. Measurement instruments (anemometer) should be located is near as possible to the proposed site for a wind turbine and at the same height as in nearby weather station. The collection period should correspond to the same period of the weather station. After the data from both sites have been collected, it should be analysed and compared. It helps to predict more accurately wind speed and direction on the site using data from the weather station. Additionally collected data analysis could identify that the weather station indicates site conditions insufficiently. Among drawbacks of the short-term data collection is seasonal and annual variations in data. (Harry L. Wegley, p. 37).

The third site analysis method is extended onsite wind speed and direction data collection. This involves measurements for at least a full year. This method is more reliable, and it works for all types of terrain. However there are three disadvantages: additional cost of the measuring equipment, long realization time and the data collection period should represent typical wind conditions (Harry L. Wegley, p. 38).

3.2.1. Logarithmic wind profile

There are two mathematical models that describe wind speed vertical profile. The first model is called "Lag law". It is based on boundary layer flow in fluid mechanics and in atmospheric research. At low roughness surfaces wind speed U at height above surface z is defined as:

$$U(z) = \frac{U^*}{K} \ln\left(\frac{z}{z_o}\right); \qquad (2)$$

Where U^* is a friction velocity, K=0.4 as a Von Karman constant and z_o is the earth's surface roughness length (Mertens, 2006). In terrains with high roughness and built environment the Log law transforms to:

$$U(z) = \frac{U^*}{K} \ln\left(\frac{z-d}{z_o}\right); \qquad (3)$$

Where the displacement height d could be found from average height of roughness elements $\overline{H}$ and the percentage of the total area occupied by roughness elements A_H (ESDU 82026 cited in (Mertens, 2006)):

$$d = \overline{H} - 4.3 * z_o(1 - A_H); \qquad (4)$$

Typically A_H = 42% for cities as a total area occupied with buildings. Roughness length is defined as a height above ground where wind speed theoretically equals zero

Types of roughness are defined by Roughness Classes, that could be calculated using roughness length (M.Ragheb, Wind Shear, Roughness Classes and Turbine Energy Production, 2011):

$$RC = 1.699823015 + \frac{ln\, z_o}{\ln 150} \quad for\ z_o \leq 0.03 \qquad (5)$$

$$RC = 3.912489289 + \frac{ln\, z_o}{\ln 3.3333} \quad for\ z_o > 0.03 \qquad (6)$$

Values of the surface roughness length z_o, Roughness Class with land type descriptions are given in annex, Table 22.
Another method is the Power law. It represents a simple model for the vertical wind speed profile:

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha}$$

From this equation, the wind speed *U* at height *z* could be found from known reference wind speed U at height z_r, and wind shear exponent α (J.F. Manwell, 2009, p. 44). The exponent α varies with such parameters as elevation, time of day, season, nature of the terrain, wind speed, temperature, and various thermal and mechanical mixing parameters. The value of exponent α could be estimated for different terrain or surface roughness coefficient, if known (annex, Table 22). For flat terrains wind shear exponent α = 1/7, that fits many of surfaces, due to the law calls 1/7 power law (Gipe, 2004). Additionally, the wind shear exponent could be calculated as a function of reference wind velocity U_{ref} in m/s at height z_{ref} in m (Justus (1978) cited in (J.F. Manwell, 2009)):

$$\alpha = \frac{0.37 - 0.088 * \ln(U_{ref})}{1 - 0.088 * \ln\left(\frac{z_{ref}}{10}\right)}$$

Another way to calculate α is through surface roughness (Counihan (1975) cited in (J.F. Manwell, 2009)):

$$\alpha = 0.096 * \log_{10} z_o + 0.016 * (\log_{10} z_o)^2 + 0.24$$

Additionally, *α* could be calculated using methodology based on both surface roughness and the wind speed at the reference elevation ((D.A.Spera, 1979) mentioned in (J.F. Manwell, 2009)):

$$\bar{\alpha} = \alpha_o \frac{1 - \left(\frac{log\ V_1}{log\ V_h}\right)}{1 - \alpha_o \left(\frac{log\ \left(\frac{z_1}{z_r}\right)}{log\ V_h}\right)}\ ; \tag{7}$$

In this equation $\alpha_o = \left(\frac{z_o}{z_r}\right)^{0.2}$; in which α_o – surface roughness exponent, V_h – homogeneous wind speed ($\bar{\alpha} = 0$), m/s; V_1 – steady wind speed at elevation z_1; z_r – reference elevation 10m, x_o – surface roughness length in meters.

In open areas with few windbreaks such as coastal sites the logarithmic model produces result similar to 1/7 power law. Farther inland, results from the two methods diverge. For inland sites, the logarithmic model finds more energy in the wind then does 1/7 power law (Gipe, 2004).

The effect of height on wind speed is so great, that sometimes it is necessary to make measurements of wind speed at hub height. However, without measurements Log and Power laws give a reasonable estimation of wind speed.

3.2.2. Turbulence intensity

High turbulence intensity (I) affects the life-time of the turbine and noise emissions. Fluctuations in wind depend on roughness and obstacles on lands surface (Mertens, 2006):

$$I \approx \frac{1}{\ln\left|\frac{z-d}{z_o}\right|} \quad if\ \ z > z_{min} \tag{8}$$

Where z_0 is the surface roughness, z is height above the ground, d – displacement height and could be calculated using equation 4. This equation is applicable if height above the ground is more than minimum height for log law z_{min}, which equals to 1.5d. The equation for turbulence intensity shows that turbulence intensity is growing with increasing roughness and decreasing height z.(Mertens, 2006).

3.2.3. Wind direction

On a site with rough terrain, hills or buildings it is important to know wind direction distribution to locate a wind turbine. Turbulence from obstacles has different impact on power output of a turbine located upwind or downwind from it. Wind direction data could be collected from nearest weather station, or measured on site. Hills, mountains or large buildings could change wind direction significantly. Collected wind data should be analysed to make a wind rose with wind speed at prevailing directions.

3.3. Wind turbines range

Current market analysis shows clear wind turbines sizes deviation according their possible applications (Table 1).

Table 1 Wind turbines scale (materials from (Gipe, 2004))

Turbines	Rotor diameter, m	Power rate, kW	Applications
Micro Mini	up to 1.25 1.25…3	0.020…1.5	Energy generations for small appliances, small households
Small (household-size)	3… 10	1.5- 20	Households, farms, communities
Medium-scale	10…40	20 - 500kW	Large farms, communities, industries
Large-scale	40…100	From 500kW	Commercial/industrial power generation

Currently, on market small and large are the most popular turbines sizes. Small scale turbines are adopted for usage to power households, they are simple in construction and reliable, they do not require professional monitoring and operation. For example, The UK company “Proven” produces small wind turbines from 2.5kW (3.5m rotor diameter) to 12.2kW (8.5m rotor diameter) for domestic usage (Proven Energy).

Large turbines occupied commercial wind energy sector. Turbines of this type are usually used at wind-farms on large territories to generate dozens and hundreds of megawatts. A number of companies share the market of large wind turbines, for instance Vestas, GE wind, Siemens, Enercon, Gamesa and others.

3.4. Wind power control systems

The type of the control system affects the power output from the turbine. There are two types of control systems to regulate power output from wind turbines. First of them is based on C_p definition (see equation 1). Power coefficient of turbines depends of a tip speed ratio λ, which could be calculated as:

$$\lambda = \frac{\omega R}{\nu} \quad (9)$$

Where ω is a rotational speed of rotor, R – radius to tip of rotor, ν – upwind free wind speed (m/s) (Olimpo Anaya-Lara, 2009). The tip speed ratio and the power coefficient are dimensionless and can be used to describe the performance of any size of wind turbine rotor. The maximum power coefficient is only achievable at single tip-speed ratio (Figure 3 Illustration of power coefficient/tip-speed ratio curve, C_p/λFigure 3).

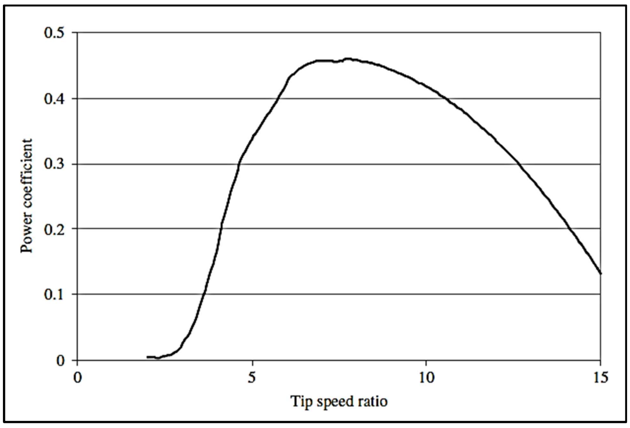


Figure 3 Illustration of power coefficient/tip-speed ratio curve, C_p/λ (Olimpo Anaya-Lara, 2009, p. 5)

In stall control system, after reaching the rated speed, the system keeps the same rotational speed of blades. The pitch angle is fixed, so it is important to set the angle of blades initially correctly. The advantage of this control system is its simplicity. However, wind turbines with stall-control have reduced C_p on rated speeds, higher loads on construction, higher noise and wake turbulence.

The stall control is based on changing angle of blades of the turbine, which affects drive forces and keeps rated power output. Stall-controlled turbines have variable rotational speed and C_p. The construction of these turbines is more advanced. Stall control could be realized mechanically, where the centrifugal force of rotating force blades to rotate around pivots, and electronically, when the controller senses power output and gives signals to rotate blades. The third part of all installed wind turbines has a pitch control type (M.Ragheb, 2009).

Stall control system could be passive and active. Passive stall control designed to reduce speed of rotation when the wind speed exceeds maximum value, so it works as protection. Active stall control is targeted at operating a wind turbine with different blades angles in order to get maximum torque from lower wind speeds.

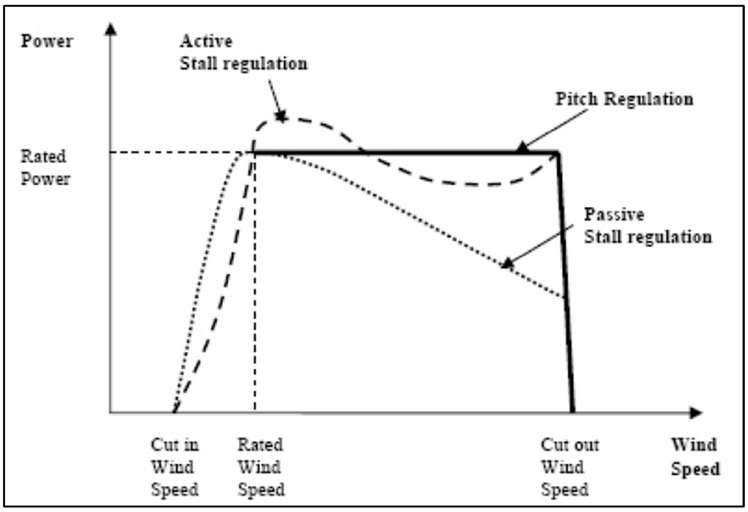


Figure 4 Passive and active stall regulation and pitch power control (M.Ragheb, 2009)

The type of power control could be easily seen from a power curve of the turbine (Figure 4), because each of them has a typical curve objectively to the rated power level.

A wind turbine could have mixed control of two types – stall-pitch regulation (fixed speed), and pitch-stall regulation (variable speed). First one uses stall control on slow wind speeds, and after reaching rated power output the pitch regulation system adjusts blades to a more “negative” angle to keep the rotational speed constant. Turbines with this control have slightly higher noise than at the next type. In pitch-stall control system on slow wind blades are adjusted using pitch control. After the rated speed was reached, blades are moving to a more "positive" setting angle to reduce forces on turbine construction and keep power level. At higher wind speeds the pitch angle keeps constant to maintain a maximum power specified. Pitch-stall regulation provides low noise that could be obtained by special regulation. (M.Ragheb, 2009).

4. Methodology

This project is targeted at investigation the pre-planning process and methodology of renewable energy unit for industrial application on the basis of a case study. Two popular renewable resources – wind and solar PV will be assessed and analysed (Figure 5). After that annual amount of energy will be calculated using different sets of equipment. Then, the demand-supply analysis will show how renewables cover the consumption of the case study. At the end, economic and environmental analysis will show benefits and drawbacks of each variant of equipment.

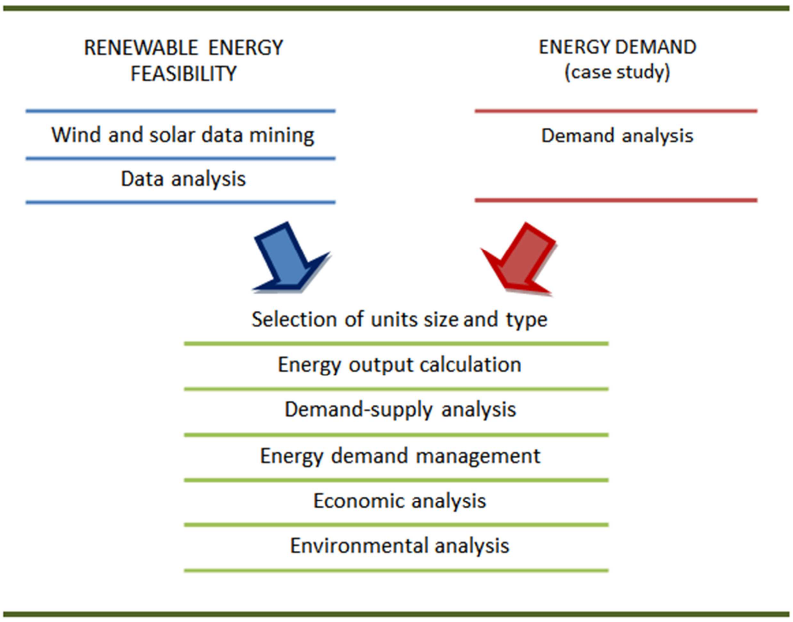


Figure 5 Project methodology diagram

This methodology could be used for a pre-planning process of a renewable energy system for any industrial of community site.

Case study

In this project a specific place was used to perform the energy feasibility study. This is Barr Limited office and industrial site in Killoch, Western Scotland. There are a few buildings at this location that are related to the activity of the company: the main office building, IT building, garage, training area, storage spaces, and an asphalt plant and other buildings on site.

5. Weather data - mining and analysis

Using trustworthy weather data is essential for a renewable energy feasibility study. Wind and solar energy output totally depends on climate data. Because of high costs and long-time of measurements, at the first step of renewable energy feasibility study businesses feel dubiously about new investments. However knowledge of small spatial and temporal data variability could validate using available data measured at nearby meteorological station (Stephen Wilcox). If after the first step of the assessment renewable energy proofs its profitability, taking weather measurements on site could be the next stage of work.

As any climate parameter, solar radiation varies from year to year. In best years direct normal radiation could increase by 8-15%, in worst cloudy years it could decrease by 13-23%. However changes in global horizontal solar irradiance normally limited by ±5%. Additionally solar radiation varies with distance because of microclimate effects of topography. For example, on a territory of 30x30km it could vary between 0.12% on plane territories as central Missouri, USA, and 11.5% on coastal territories with mountains as along a corridor between Los Angeles and San Bernardino, California, USA (Stephen Wilcox). Glasgow is situated about 40km away from the case study location (Figure 39). Assuming generally flat topography of the Western Scotland territory, “Merit” software was used in this project for solar energy estimations with climate data of Glasgow 1972.

5.1. Wind speed data

In comparison with solar radiation, wind speed and direction highly depends on type of terrain and height (see p.28). The closest meteorological station that measured wind speed and direction hourly is located in Prestwick airport, Ayrshire (station id 1006) at the distance of approximately 13km far from the case study site (NERC Data). Wind data was recorded on the height of 10m during 8 years from 1984 to 1992.

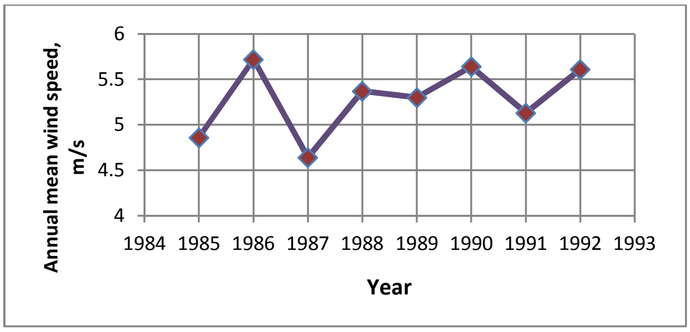


Figure 6 Annual mean wind speed, Prestwick airport, m/s (NERC Data)

The lowest annual average of 4.64m/s was reached in 1987, and the highest – 5.72m/s, in 1986. The average wind speed during 8 years was accounted for 5.3m/s. The wind speed data of 1989 was closest to the average at this site, thus it was taken to calculate energy output from wind turbines in this project. According to the wind speed distribution shown at Figure 7, about 36% of the time a year wind speed is at the range between 3 and 6 m/s.

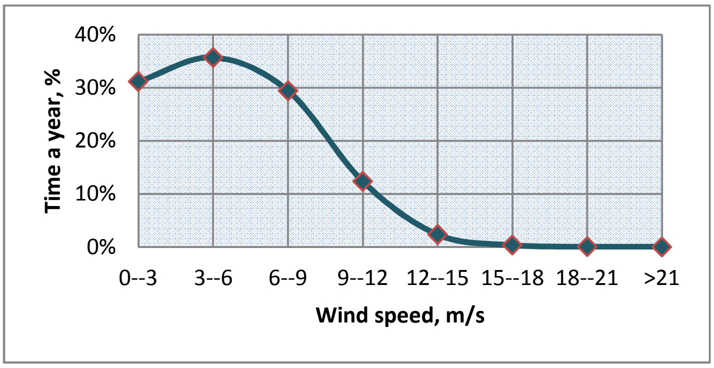


Figure 7 Wind speed distribution, Prestwick airport, 1989

To calculate the wind speed at Killoch site using Prestwick data it was necessary to consider differences between two locations. First of all, according to a wind speed data available at (Department of energy and climate change (A)), at the territory of one square kilometre around each location and height of 10m, the average wind speed at Killoch is higher by 9.6% then in Prestwick airport (Figure 8).

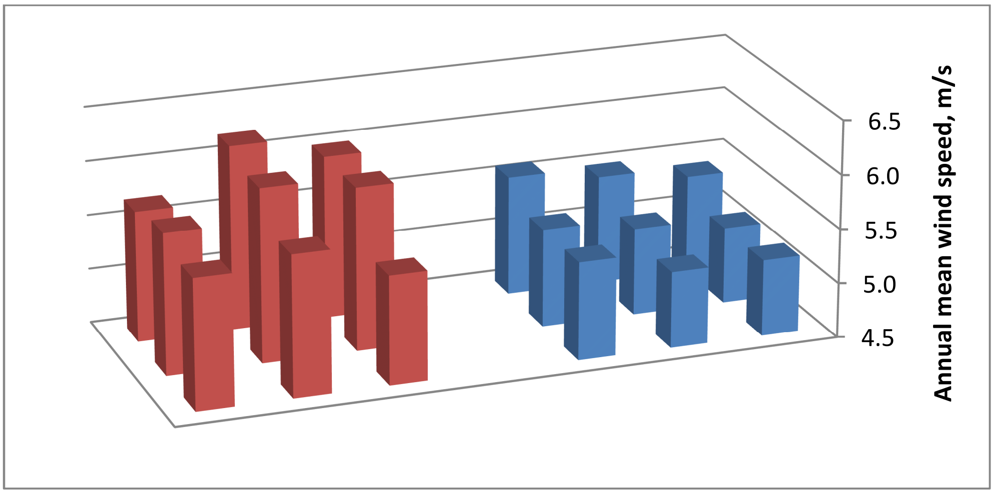


Figure 8 Annual mean wind speed in 1km square at Killoch (red) and Prestwick Airport (blue) locations at the height of 10m (Department of energy and climate change (A)), see annex Table 23

At Figure 8 was used data collected using air flow model to estimate the effect of topography on wind speed, however it does not take account topography on a small scale, or local surface roughness (such as tall crops, stone walls or trees) (Department of energy and climate change (A)).

5.1.1. Roughness and height factors

Another factor that affects wind speed is surface roughness. In Prestwick, where the data was collected, the wind shear exponent is close to α=1/7 which is typical for airports and corresponds to the surface roughness length of z_o=0.03m (see p.27).

On the other hand, the surface type of Killock site has RC=2 and could be described as "Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500 meters", and according to Table 22, the roughness length

z_o=0.1m. Using this data and equation (9) the wind shear exponent α could is calculated as:

$$\alpha = 0.096 * log_{10}z_o + 0.016 * (log_{10}z_o)^2 + 0.24$$
$$= 0.096 * log_{10}0.1 + 0.016 * (log_{10}0.1)^2 + 0.24 = 0.16\ (m) \quad (10)$$

After that, for two locations, the relationship between wind speeds at different roughness could be defined using log law (see p.27):

$$\frac{U_k(z)}{U_p(z)} = \frac{\frac{U^*}{K}\ln\left(\frac{z}{z_{ok}}\right)}{\frac{U^*}{K}\ln\left(\frac{z}{z_{op}}\right)};$$

Where $U_k(z)$ and $U_p(z)$ are wind speeds in Killock and Prestwick airport respectively, z_{ok} and z_{op} are surface roughness lengths, z – height (for this example – 10m). The value of (U*/K) in both locations is the same, so it could be removed from the equation:

$$\frac{U_k(z)}{U_p(z)} = \frac{\ln\left(\frac{z}{z_{ok}}\right)}{\ln\left(\frac{z}{z_{op}}\right)}$$

Solving it for $U_k(z)=f(U_p(z))$ using values of surface roughness length gives the result of:

$$U_k(z) = U_p(z) * \frac{\ln\left(\frac{z}{z_{ok}}\right)}{\ln\left(\frac{z}{z_{op}}\right)} = U_p(z) * \frac{\ln\left(\frac{10}{0.1}\right)}{\ln\left(\frac{10}{0.03}\right)}$$
$$= U_p(z) * 0.793$$

The coefficient of 0.793 was applied for wind speed values for each hour. Next, a wind speed at hub height could be found using the power law (see p.28). In this project the range of wind turbines at different height was used. Using logarithmic function of wind speed with height it is possible to design a graph which can be used for each height.

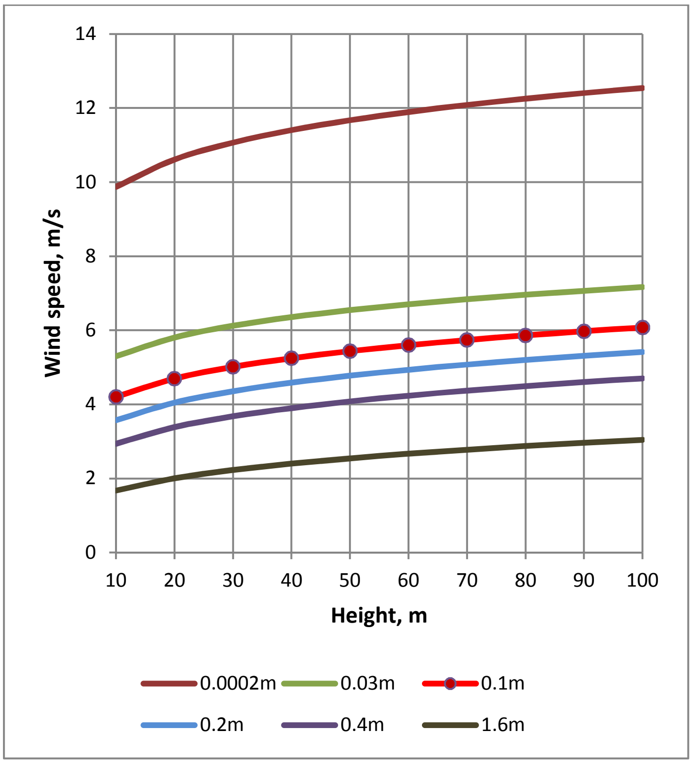


Figure 9 An example of logarithmic profile of wind speed with height for different roughness lengths

At Figure 9, the red line displays the wind speed changes with height at Killoch. Starting with the average annual wind speed of 4.2 at 10m, the wind speed on each height could be identified. A part of table with wind speed calculations for each hour could be found in annex, Table 24.

5.2. Wind direction

Having a wind direction data for 8 years (1985-1993) measured at Prestwick Airport, and using the fact that between two locations there is no mountains that could change this data significantly, wind direction in Killock assumed as equal. Wind rose, based on cumulative 8 years data is presented at Figure 10, where the wind speed range is shown in different colours. The scale indicates percentage of occurrence. At this figure it could be seen that wind coming from South-East has speed of 0-3m/s that cannot be captured by most of wind turbines, as they have cut-in speed 3.0-4.0 m/s.

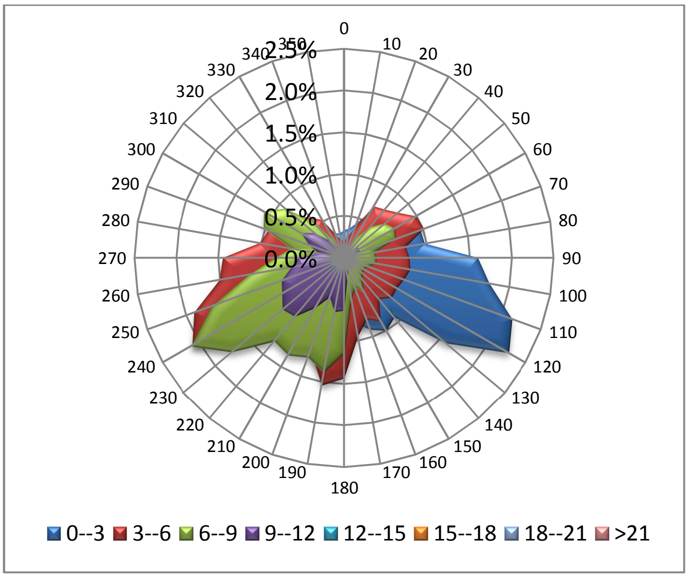


Figure 10 Wind rose, Prestwick Airport, illustrates from which direction wind streams are coming).

The prevailing wind direction is South-West, about 38% of all useful (>3m/s) wind blows from direction between 180 and 270 degrees. This data is used further to calculate effect of obstacles at Killoch location.

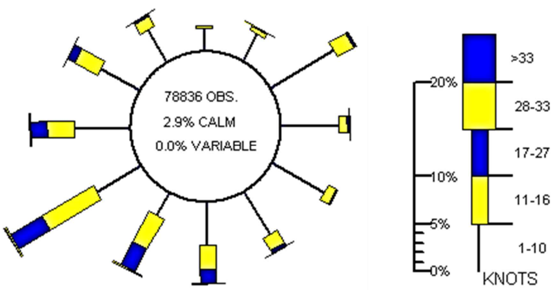


Figure 11 Wind rose for Prestwick, Gannet at altitude of 27m, annual (Met Office, 1996-2005)

Comparing the data for 1985-1993 (Figure 10) and data from Met Office for 1996-2005 (Figure 11) it could be seen that the prevailing wind direction is the same.

5.3. Obstacles

The effect of obstacles – high trees or buildings – on wind energy production depends on size and distance from it. Each obstacle in area around a turbine location generates a turbulence zone that reduces power output and life-cycle of the turbine. Distance from any obstacle to the wind turbine, if it is located downwind, should be 10, preferably 20 heights of the obstacle, to minimize turbulence effect. The size of the turbulence zone is shown at Figure 12:

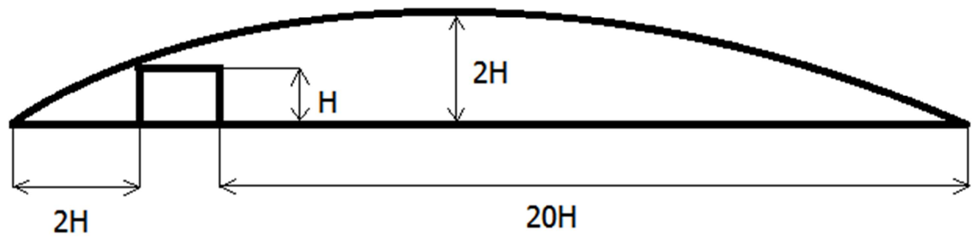


Figure 12 Turbulence zone behind obstacles with height H (Harry L. Wegley)

Percentage of wind speed and power output decreases for obstacles with different shape and different distance is introduced at Table 25 Wake behaviour of Variously Shaped Buildings (Meroney, 1977 cited in)Table 25 (see annex). Using wind rose and Table 25 the power output decreasing could be calculated for the wind coming from specific directions.

5.4. Wind turbines and aviation

The role of wind energy in Scotland is radically increasing this time. Often, during the planning process of a wind farm or single wind turbine, interests of developers encounter with interests of military and civil aviation. To get more power from wind turbines they are installed on tall towers with long rotating blades to increase the swept area. Because of that, wind turbines could pose hazards for approaching and landing aircrafts, be dangerous for a low flying airplanes and train aircrafts, and be an obstacle for radars and navigation systems. Low flying hazards (training areas are not included) could occur only with large utility-scale wind turbines with total height more than 250ft (76.2m). In training areas fast jet aircrafts could fly down to 100ft

(30.5m), so wind turbines higher than that height could not be installed at those sites (Wind Energy, Defence and Civil Aviation Interests working group, 2002). Training areas that are situated in Scotland are shown in a map at Figure 13:

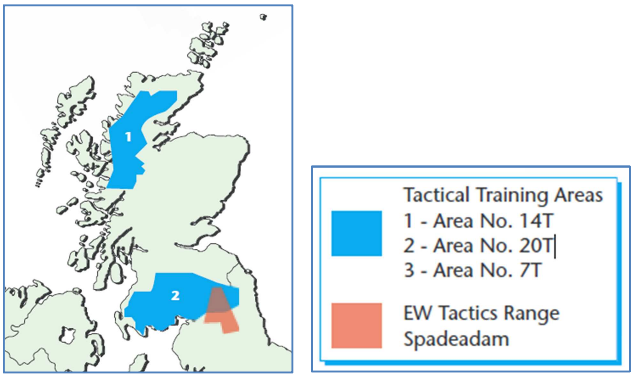


Figure 13 Map of tactical training areas and Spadeadam range in Scotland (Wind Energy, Defence and Civil Aviation Interests working group, 2002)

As Figure 13 shows, training areas occupy large territories in south, south-west and north lands of Scotland. Additionally areas around military and civil airports have restrictions for wind turbines installations because of radars. To investigate the impact of wind turbines on radars in is necessary to undertake a pre-planning assessment, because radars restriction sites depend on height of wind turbines and take significantly larger territories than tactical training lands.

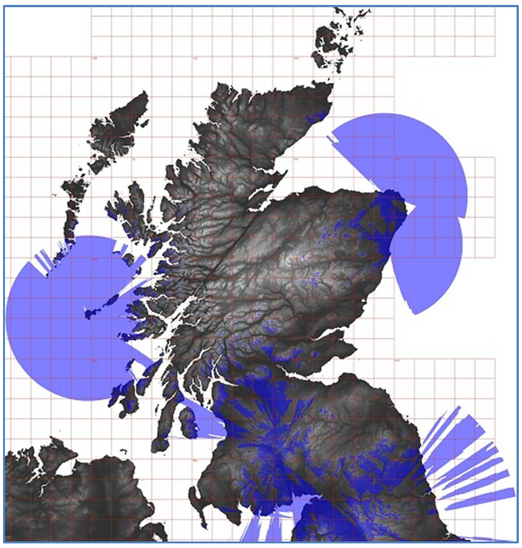


Figure 14 Introductory map of radar restricted zones (blue areas) for wind turbines with up to 60m height (NATS)

At the example of the self-assessment map for turbines up to 60m high in could be seen that large territories on the South and South-west of Scotland have limitations for wind energy because of radars. Together with training areas they form serious restrictions for wind industry growing in Scotland. For example, Scottish and Southern Energy Renewables planned to install 152 utility-scale turbines 35 miles east of Prestwick. However the project was delayed for 1.5years because “Wind farms can degrade the performance of voice communications facilities and en-route navigation aids”. The company was asked to build a new traffic tower to neutralize wind turbines negative effects (Prestwick Airport, 2010). Verification of possibility of joint work of wind turbines and radars should be a part of pre-planning process to prevent any harmful effect on aviation safety.

6. Energy demand analysis

Analysis of the demand data gives the first conception about energy generation that is necessary. The size of renewable energy unit depends on the type of the system. For example off-grid systems need entire energy demand coverage, and systems with a grid connection could use renewable energy for a partial supply of total energy needs.

The best way to estimate energy demand is measurement. A year of hourly or even daily data would give information about the base load of the company and energy consumption peaks. For the case study of Barr at Killoch, the real electricity consumption was measured from 06/2010 to 05/2011. The data averaged for day-time (from 7am to 6pm) and nights (7pm-6am) is presented at Figure 15:

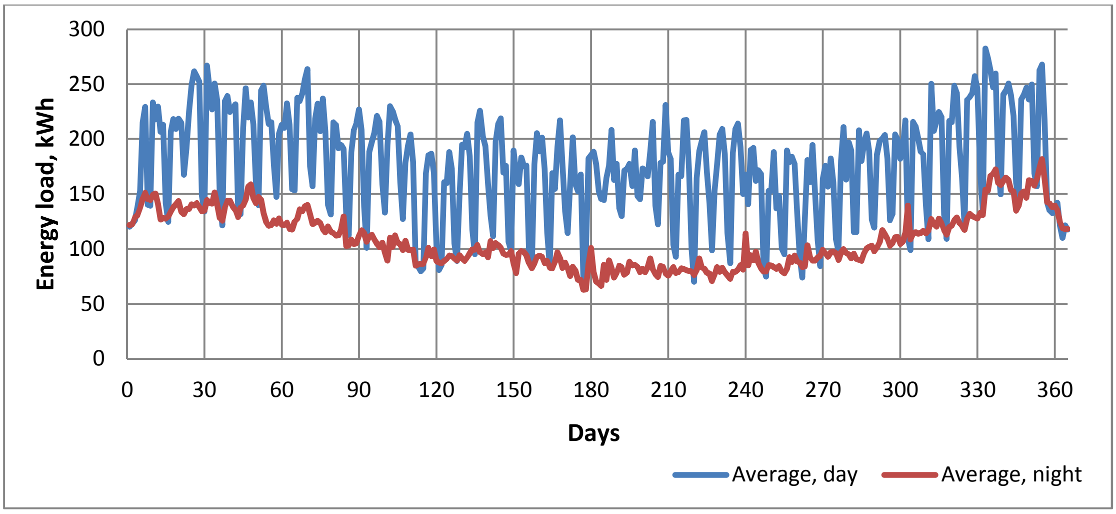


Figure 15 Average energy load during days (blue line) and nights (red line), Killoch site

The base load of the site is accounts for 52kWh in summer, and in winter it is reaching 100kWh. These values are caused by high electrical consumption by heating in winter and air conditioning systems in summer, additionally electricity is using in asphalt manufacturing process. The total energy load reached 1251MWh annually.

Work days and weekends have clear difference in electricity consumption. An example of a typical summer week (1-7th August 2010) is shown at Figure 16:

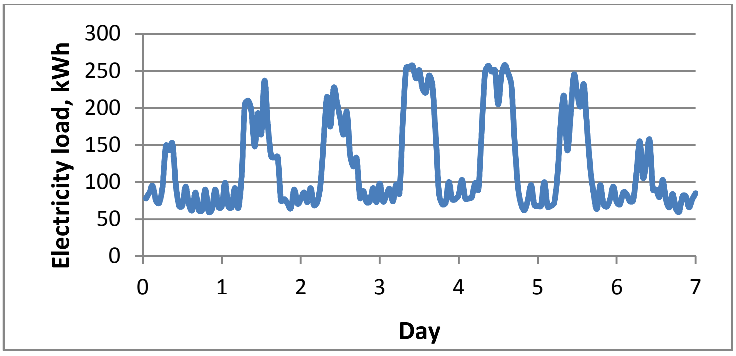


Figure 16 Typical summer week (1-7th August, 2010), electricity load, kWh

It is clear that during the weekend, 1st and 7th of August, electricity consumption is 30% lower than during work-days (2-6 August).

Currently, for Barr the cost of electricity that was consumed on site is 10p, and sent to the grid – 3p. Consequently, it is more profitable for the company to consume more electricity, generated by renewables, by itself and reduce electricity load from the grid. In order to find the most economically advantageous variant of renewable energy equipment, the rated power off units starts from 50kW power for PV panels and wind turbine to be 100% consumed on site. Additionally, to estimate benefits from export of electricity, the size of assessed wind turbines is increased to 100 and 330kW power.

7. Renewable energy equipment

Many international companies produce similar solar PV panels and wind turbines. For any customer it is easy to be lost in this range. There are several rules that would help do decide what equipment to use and what company to work with:

1. First of all the equipment should be introduced locally. It would guarantee that it certified and approved to use in the UK. Additionally it would give an advantage to see it before buying and probably monitor it in work at already existing installations.

2. It is more convenient to work with a company which offers a complex of services for the whole life-cycle of renewable energy equipment – from planning, supplying, installation to operation, monitoring, and decommissioning.

3. Monitoring already existing installations and talking with owners would help to understand what challenges they meet running particular PV panels and wind turbines.

In this project, one type of PV panels and three different wind turbines were chosen with respect to energy demand profile, to show their energy performance, advantages/drawbacks, economical results and environmental issues.

7.1. Photovoltaic panels

In this project the PV system was planned on the basis of Hyundai Solar modules, SF-series. To let all produced electricity be consumed on site, the size of the system was chosen with regards to the base load of the company, which is 52kWh, so the energy usability factor would be 100%. Selected PV system should produce about 50kWh of electricity at peak power. To do that Mono-crystalline PV series HiS-S218SF was chosen because of the highest efficiency of 15% and power output 218W of this type of panels. The quantity of PVs could be calculated as 50,000W/218W=229 PV, which produce 229*218W=49,922W of peak power. The size of each PV is 983x1476x35 mm (38.7"x58.11"x1.38"). Each panel contains 54 cells (6x9 matrix) and has a total weight of 17kg (Hyundai Solar, 2010).

Because PV panels produce DC electricity in is necessary to install inverters DC/AC for a grid connection. As an example, "Sunny Tripower" 2 x STP 17000TL-10 and 1 x STP 10000TL-10 inverters were chosen as widely used in PV systems. The nominal power of STP 17000TL-10/10000TL-10 is 17/10kW converted to AC – 230/400V (Sunny Tripower (A)), (Sunny Tripower (B)). More detailed description of PV and inverters could be found in annex Figure 40, Figure 41 (see annex).

7.2. Wind turbines

Current market of wind turbines is oriented towards small domestic applications or large commercial turbines (see Table 1). For this project it is necessary to use medium-scale wind turbines which are not so widespread. The range of turbines was taken as:

- 50kW of rated power wind turbine Endurance E-3120. Most of electricity produced by this turbine would be consumed on site because of the annual base load of 52kW.

- 100kW of rated power turbine Northern Power. In winter, when the base load of the company increases to 100kW, all produced electricity would be consumed on site, and in summer some surplus electricity would be exported to the grid.

- 330kW of rated power turbine Enercon E-33. This turbine would produce a lot of surplus electricity because its rated power exceeds the maximum energy consumption of the company.

Major technical parameters of all turbines are summarized in Table 2. More detailed description could be found in annex (Figure 42, Figure 43 and Figure 44).

Table 2 Wind turbines technical data (Enercon, 2010), (Endurance), (Northern wind).

Wind Turbine	50kW Endurance E-3120	100kW Northern Power	330kW Enercon E-33
Type	3 blades, horizontal axis, downwind	3 blades, horizontal axis, upwind	3 blades, horizontal axis, upwind
Rated power	55kW	100kW	330kW
Rated wind speed	11m/s	14.5m/s	12.5m/s
Cut-in wind speed	3.5m/s	3.5m/s	3.0m/s
Cut-out wind speed	25m/s	25m/s	28-34m/s
Rotor diameter	19.2m	21m	33.4m
Hub height	25/37m	37m	44/50m
Control type	Stall control, constant speed	Stall control, variable speed	Active pitch control, variable speed
Rotation speed	43 rpm	59 rpm maximum	18-45 rpm

8. Local site assessment

Placing wind turbines and PV panels is a key factor of success in reliable and profitable energy generation. Wrong placing of PV would cause reduction of energy generation. As for wind turbines, wrong placing, apart from low energy output, would cause high noise, turbulence and frequent breakdowns.

8.1. PV system location

For PV solar panels it is important to avoid any shading that would reduce energy output. Positively, for PV systems the best option is roof-mounted installation. Most of roofs are high enough to surpass any vegetation and other shadings on site in height. Of course the ability of a building to endure all PV mounted on it should be investigated during the pre-planning process.

Another factor that affects energy output from PV panels is orientation. For northern regions as Scotland, PV panels should be oriented south to maximize energy generation. The tilt angle of PV is important as well. For Glasgow area the tilt angle is around 40 degrees. The right tilt angle and orientation could be checked using “Merit” software. For example, for investigated system of 229 PV HiS-S218SF oriented south the energy outputs at different tilt angles are summarized in a graph at Figure 17:

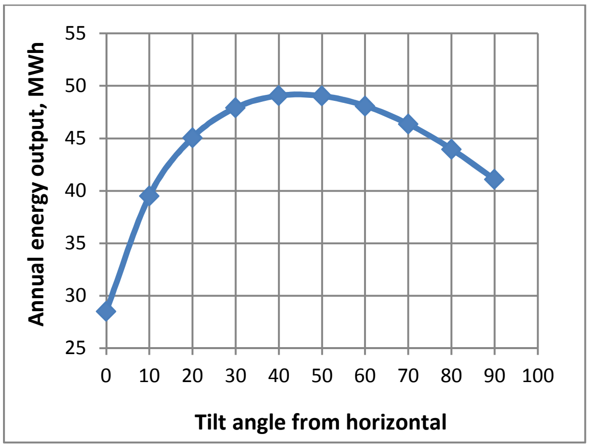


Figure 17 Annual energy output at different tilt angles

It could be seen that the tilt angle of 40-50 degrees from horizontal gives maximum power from PV. To investigate how orientation affects the power output from chosen system tilted at 40 degrees it was oriented towards different sides using "Merit" software. Results of this experiment are introduced at Figure 18:

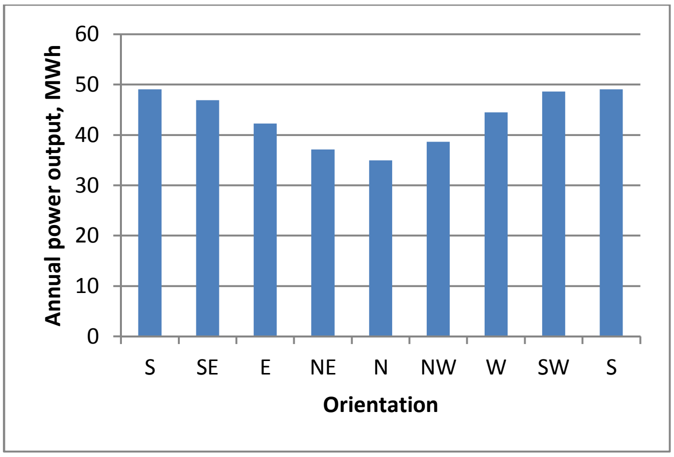


Figure 18 Annual power output at different orientations.

At this figure it is clear that orientation towards south maximizes power output from PVs, however orientation South-West is also acceptable.

The size of the single PV is 1.45m^2, it was used in calculations of necessary area for the PV plant of 50kW. If 229 PV panels are planned to install, it would require $229 * 1.45 = 332m^2$. Many buildings on site have appropriate size. However, some of the roofs of garages and storages are not appropriate for PV mounting or increase complexity of operation and maintenance works.

Figure 19 Potential PV location (dashed red line).

Finally, the roof of building stores was chosen for a possible PV installation. The size of the roof is about 25x60m apart from 4 holes of 7x17m, which gives about 1024m2 of free space which is enough for 229 PV (332m2) with additional space for maintenance and operation works.

8.2. Wind turbine location

Correct location of a wind turbine in peri-urban or industrial environment is more challenging process than location of PV panels. Many factors contribute to final site of the turbine. They could be technological, economical or environmental (J.F. Manwell, 2009).

A wind turbine should be located on a site with access roads and free area that will be used for installation and operation purposes. The size of access roads depends on blades and tower sections length and weight. Grades and curves should be gentle enough that bulk and heavy equipment could reach the site. Additionally, the wind turbine should be connected to the grid, so it should have a switch gear and transformer as many of wind turbines operates at high voltages to reduce resistive losses. (J.F. Manwell, 2009)

In terms of energy production, to maximize energy output the wind turbine should be installed in the area far from obstacles and vegetation; otherwise the energy output reduction should be calculated on a stage of a feasibility process.

Some areas could not be used for a wind turbine because of geological or environmental concerns. For example from ecological point of view, the potential location should not be in environmentally restricted areas such as living areas of rare animals or birds. For wind turbine locations close to urban areas or detached dwellings noise and visual impacts should be carefully investigated.

At the case study location at Killoch several buildings are situated the territory of the company. Additionally, at the north-west of the site a coal mine is situated with a few buildings that should be taken into account as well. Apart from that, there are few high trees that could reduce wind speed at the site.

Highway A70 which is going at the south-east is ideal for the equipment delivery. At the north-east corner there is a transformer which could be used for a grid connection. After overview of the territory, several potential locations were identified (Figure 20).

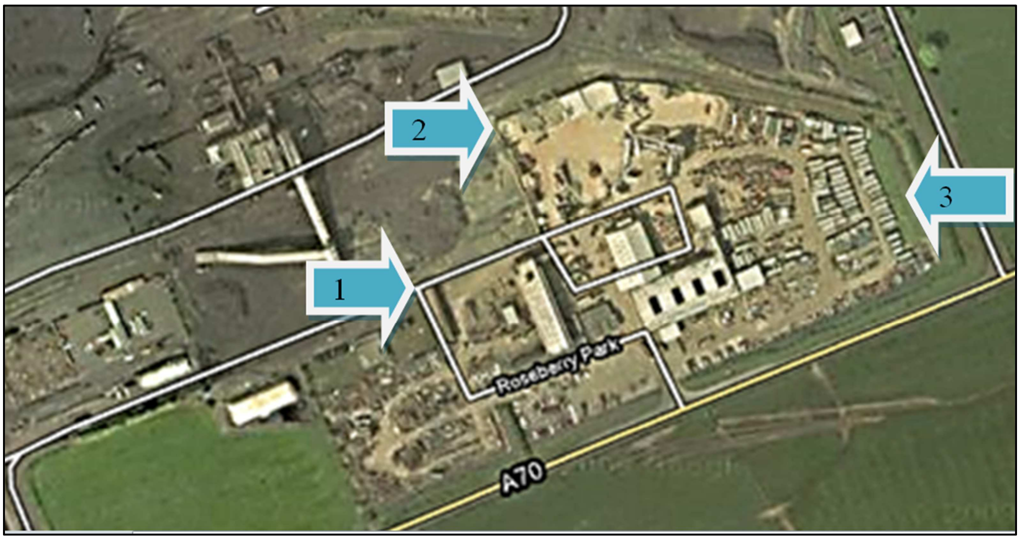


Figure 20 Wind turbine proposed locations.

The first location is situated at the corner of a wall about 4m high, which is at north-west side of the main office building and at west side to IT building. An advantage of this territory is area around which is free from any industrial objects or process. So if a turbine was located at site 1, no changes in manufacturing process would be required. However this site is closest among others to a few residential buildings. So noise and visual impacts should be investigated in details. Additionally this place is far from the nearest transformer, so the cost of electrical works would be slightly higher.

The second proposed site is situated at the territory of materials storages for the asphalt plant of the company. The advantage of this site is that it is more distanced from residential properties which are screened from a wind turbine with several buildings. On the other hand, some changes in asphalt manufacturing process would be required for a wind turbine installation.

The third place is the closest to the transformer and located on a small hill which enhances wind turbine performance. However this area is reserved for drivers training purposes and is not likely to be used. Additionally it is too close to roads. For wind turbines with rotor diameter more than 16m the distance to trunk roads should be no less than the height of the turbine plus 50m (Highway agency, 2007).

To sum up, after the site review two potential places reminds for a wind turbine installation (site 1 and 2, Figure 20). Both of them will be investigated further in terms of energy production, noise and visual aspects.

9. Results and analysis

The basis of information about methods of calculations, weather data and electricity load of the company was introduced in previous paragraphs. Using this data energy output from PV and wind turbines was calculated and analysed in this chapter. The particular attention was paid to demand/supply analysis and monthly profile of energy generation.

9.1. Solar PV energy production

Power output profile from 229 solar PV (218W, p.45) is created using modelling in “Merit” software. All parameters, as efficiency of PV and inverters, were applied to get more reliable data.

The peak of power generation is accounted for 49.7kW. Variations in power output through the year are associated with solar radiation fluctuations. Seasonally, energy from PV panels cahnges significantly. Thus, in January PV energy output is 9 times lower than in April and July (see Figure 21 Difference in power output from 50kW PV, January (Left) and July (right).Figure 21, Figure 22):

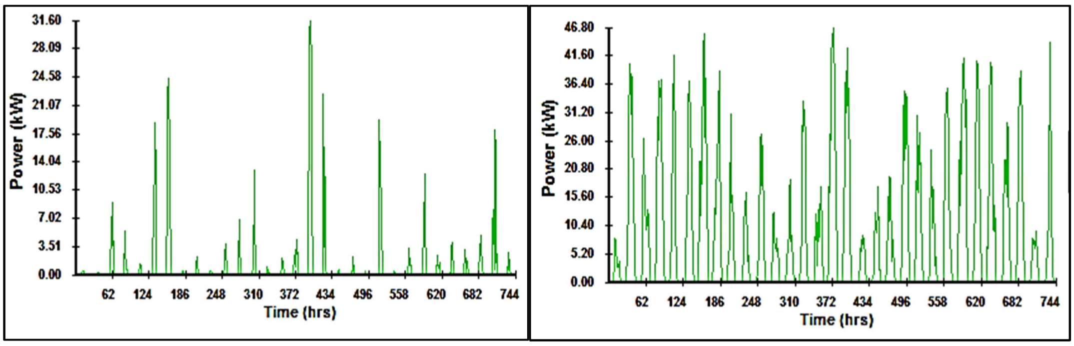


Figure 21 Difference in power output from 50kW PV, January (Left) and July (right).

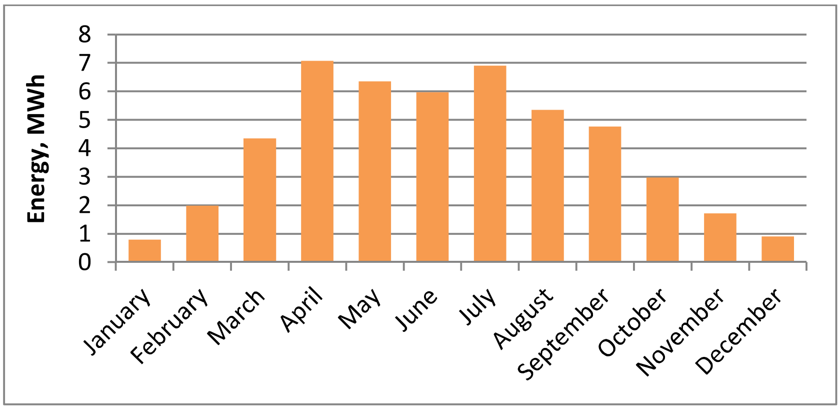


Figure 22 50kW solar PV energy generation, monthly distribution.

Figure 22 shows that during 5 months period from April to August energy gain from PV is the highest. The variance in energy output of 1MWh (14%) between April and June could be explained by different weather conditions as clouds cover and number of sun-shine hours during that year. The total annual energy production of solar PV energy reached 49.07MWh, and the annual demand of the company is accounts for 1,251MWh, consequently 229 PV panels would produce approximately 1/25th part of energy demand of the company per year.

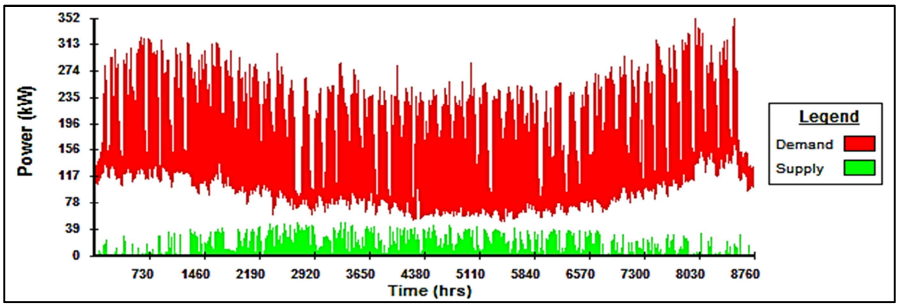


Figure 23 Annual 50kW PV Supply / Demand profile

Figure 23 shows that all produced energy would be consumed on site because the base load is higher than maximum power output from PV panels. This means that the company would save about 49MWh of energy with cost of 10p per each kWh (£4,900 in total).

Table 3 Annual supply/demand data of PV panels with 50kW peak power

Equipment	Generated electricity, MWh	Electricity surplus, MWh	Percentage of the total energy load, %	Percentage of energy consumed on site, %
50kW PV	49.7	0	4.0	100

The summary of energy produced by PV system and delivered to the company is shown at Table 3. The PV system covers only 4% of the total energy demand. However because of the high base load of the company, all produced electricity would be consumed without any export to the grid. The advantage of this will be discussed further in this project together with the variant of increasing the PV system to 100kW.

9.2. Wind energy production

Energy from wind was calculated hourly using detailed wind speed data (see p. 34) for each hub height / location and power curve of each turbine with respect to cut-in, rated and cut-out wind speeds. This data, together with half-hourly demand data, was uploaded to "merit" software for analysis of supply/demand profile.

Wind energy generation is different for each turbine (see annex, Figure 42, Figure 43 and Figure 44). For instance, wind turbine with 50kW of peak power (p.46) would produce about 117MWh of energy annually, which is twice more than PV panels with the same power capacity. Summary of energy output from wind turbines is presented at Figure 24:

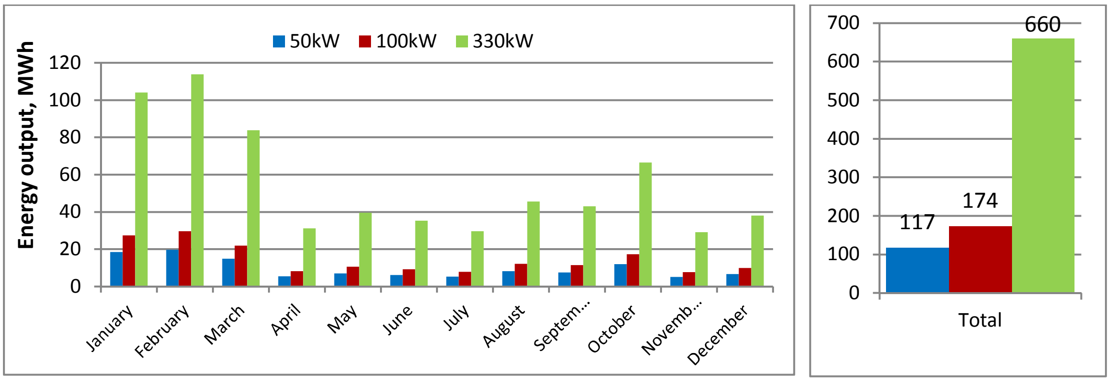


Figure 24 Energy generation by wind turbines 50kW, 100kW and 330kW of rated power

The annual deviation of wind energy during the year does not have a clear profile as solar energy. In January and February wind energy generation is the highest, however it does not indicate clearly that in winter there is more wind resource available at western Scotland territories. Thus, in November and December the power from wind is similar to summer period.

From Figure 24 it could be seen that the turbine with 100kW rated power generates only 50% more energy than 50kW wind turbine due to the difference in power curves (technical specifications of turbines are at p.46).

Wind turbine type	Wind power availability, %	Hours of full power, %
50kW	65.9	4.9
100kW	65.9	0.4
330kW	72.0	1.8

Table 4 Wind power availability

Table 4 shows that the wind power availability, based on cut-in and cut-out wind speed of turbines is the same for 50kW and 100kW turbines. However the percentage of hours of full power, based on rated and cut-out wind speed, for 50kW turbine is significantly higher. Consequently, the 50kW turbine captures more energy per each kW installed capacity from the same wind resource. The 330kW turbine has high percentage of power availability because of the low cut-in speed of 3m/s.

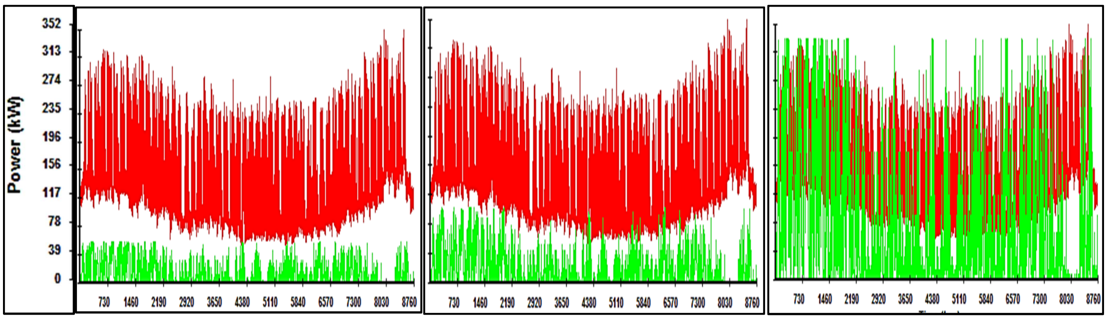


Figure 25 Energy supply (green) / demand (red) annual profile of 50kW(left), 100kW (middle), 330kW (right) wind turbines

Figure 25 indicates the difference between 3 sizes of turbines in energy supply of the company. Two types of turbines – 50kW and 100kW – work mostly in the base load, which gives minimal or zero surplus of energy. The power rate of the biggest 330kW turbine at peak power overlaps peaks in demand and generates surplus energy that could be sold to the grid.

Table 5 Annual energy output from 3 types of wind turbines in undisturbed wind stream

Wind turbine	Annual energy production, MWh
50kW	117.07
100kW	173.74
330kW	659.89

Table 5 shows the energy output from undisturbed wind on site. However some obstacles reduce the energy from turbines. According to the Table 25 (annex), the height of the wake flow region that affects power from wind is 3H at the downwind distance of 20H, where "H" is the height of the obstacle/building. Consequently, two turbines 50kW (25m hub) and 100kW (37m hub) undergo power reduction from obstacles. Using the data of power reduction from wind and the site map with approximate building dimensions, the total power reduction was calculated for each turbine. Results are summarised in Table 6:

Table 6 Percentage of wind power reduction because of turbulence

Location (Figure 20)	Wind turbine (p.46)	Hub height, m	Wind direction, degrees (Figure 10)	Approximate power reduction, %
1	50kW	25	80…150 310…330	42.5 55.0
2	50kW	25	240…270 140…170 110…140	27.0 47.0 50.0
1	100kW	37	-	-
2	100kW	37	260…280	7.8
1/2	330kW	50	-	-

Accordingly, because of the obstacles at "location 1" the 50kW turbine loses 5.8% of energy. Similarly at "location 2" the same 50kW turbine loses 9.4% and 100kW – 0.8% of energy. The turbine with 330kW of rated power at 50m hub is not affected by turbulence significantly. The turbulence intensity "I" could be calculated using equation (11), p.29. For this calculation the average height of obstacles assumed as $\overline{H} = 8m$, and area occupied with buildings as $A_H = 20\%$. Consequently, the turbulence intensity for each height equals $I(z = 25m) = 0.194$, $I(z = 37m) = 0.176$, $I(z = 50m) = 0.165$. Calculated values could be compared with the maximum possible value $I_{max} = 0.77\ when\ z = z_{min}$ (Mertens, 2006, p. 23).

Energy output is a major factor that affects financial outcomes and carbon dioxide emissions reduction. However the choice of location depends from other factors, among them are noise, visual effect and social issues.

Table 7 Annual supply/demand energy data for wind turbines at different locations.

Wind turbine	Loca tion	Generated electricity, MWh	Electricity surplus, MWh	Percentage of the total energy need, %	Percentage of energy consumed on site, %
50kW	1	110.3	~0	8.8	100
50kW	2	106.1	0	8.5	100
100kW	1	173.7	0.40	13.9	99.8
100kW	2	172.3	0.39	13.7	99.8
330kW	1/2	659.9	164.8	39.6	74.3

Table 7 confirms that 50kW and 100kW wind turbines produce electricity mostly for the base load. The surplus electricity is minor and could be neglected. The 100kW turbine covers the total energy demand slightly more than 50kW turbine. The biggest turbine gives the highest contribution of about 40% to energy supply of the company. Additionally, 25% of generated by it electricity could be sold to the grid. However, the current price of exported electricity is only 3p/kWh, and the price of energy consumed by the company is 10p/kW. Consequently, this would affect economic outcomes of the 330kW turbine that would be considered at economic analysis.

9.3. Energy from wind-solar combinations

Because of the high variability of wind and solar energy, it could be more profitable to use both of them to produce electricity. Thus, a combination of PV and wind turbine would cover more energy of the base load. Two combinations were chosen to investigate energy generation – 50kW PV with 50kW and 100kW wind turbines sited at location 1.

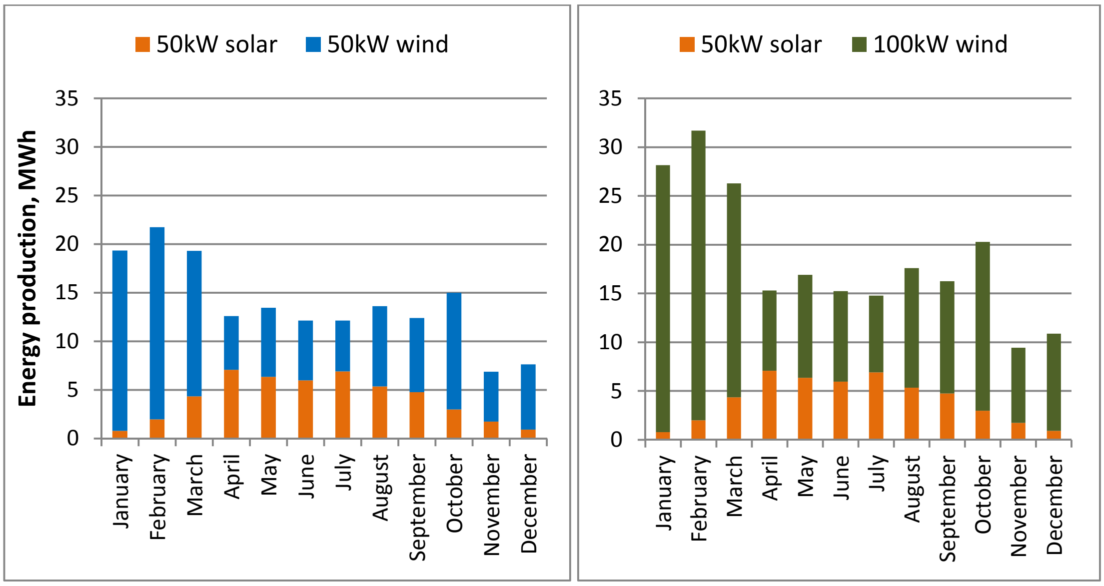


Figure 26 Energy production per month by two combinations of equipment

From Figure 26 it is clear that the lack of energy production by PV panels in winter is compensated by wind energy. Similarly, low energy from wind in summer is compensated by solar PV. Two combined sources give more even energy profile from renewables throughout a year. However in some periods, for example in November and December, energy output is low because of the lack of both - wind and solar energy.

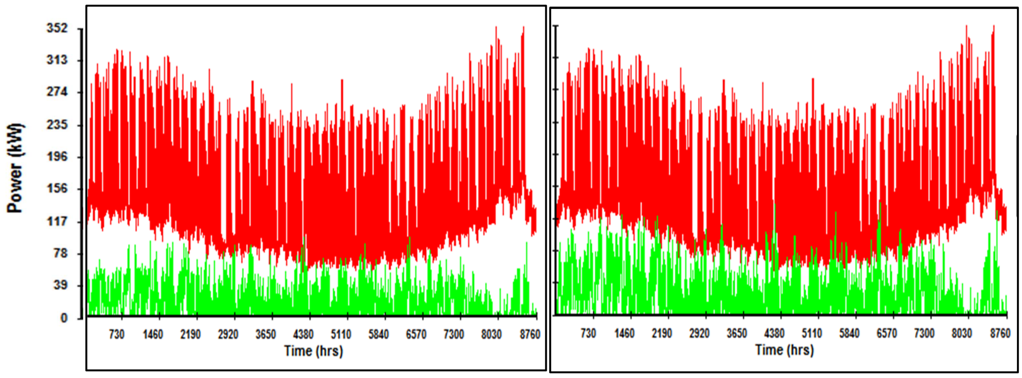


Figure 27 Power output profile for 50kW PV and 50kW wind turbine (left), and 50kW PV and 100kW wind turbine (right)

The power load from 50kW PV and 100kW wind turbine (Figure 27) covers the base load of the company more entire than 50kW PV and 50kW turbine. However both variants of equipment shown at Figure 27 could be considered as appropriate to install. The total amounts of supplied and surplus electricity are summarised in Table 8:

Table 8 Annual supply/demand energy data for two combinations of equipment

Set of equipment	Generated electricity, MWh	Electricity surplus, MWh	Percentage of the total energy load, %	Percentage of energy consumed on site, %
50kW PV / 50kW turbine	159.37	0.23	12.7	99.9
50kW PV / 100kW turbine	222.81	1.24	17.9	99.4

Finally, all discussed sets of renewable energy equipment technically suitable for installation. Combinations of PV and 50/100kW turbines are targeted at covering the base load of the company while the surplus of energy is minor. On the other hand, the 330kW turbine generates a significant surplus of electricity and could be advantageous because of exporting of energy to the grid. Further economic and environmental analysis would help to highlight benefits and drawbacks of all the renewable energy resources considered in this project.

9.4. Energy management & renewable energy generation

Energy management together with renewable energy generation gives the most constructive result for energy costs and carbon footprint reduction. The biggest challenge of energy management is to decrease energy use and cost as much as possible without reducing the quality of products or services of the company. Energy management involves 5 steps: Commitment, Understand, Plan and Organise, Act, Control, Monitor & Review (Harding, 2010). With application of renewable energy generation, stages of energy management remain the same; however the goal of the campaign shifts towards increasing the percentage of renewable energy usage in the total energy consumption of the company. That happens because every kWh of renewable energy that produced and consumed on site costs three times more than the same energy sold to the grid - approximately 10p/kWh against 3p/kWh. That means saved on renewables energy costs would be higher which decrease the payback period of systems and other positive economic outcomes.

It is clear that for renewables, that do not exceed the base demand level, all 100% of generated energy would be consumed on site. However, larger systems, for example 330kW wind turbine or a combination of 50kW PV and 100kW turbine would have a significant surplus of electricity. The total demand of the company is 1,250,861kWh p.a. and the system of 330kW turbine generates 659,890kWh p.a., from which 474,876kWh consumes on site (about 70%) that costs £47.5K with price of £0.1/kWh. The energy surplus of 185,014kWh could be sold to the grid for £0.03/kWh with the total cost of £5.5K p.a. If this electricity surplus was consumed on site, it would cost £18.5K. To sum up, for 330kW wind turbine system the company could save the additional £13K annually just because of energy management related to the renewable energy generation.

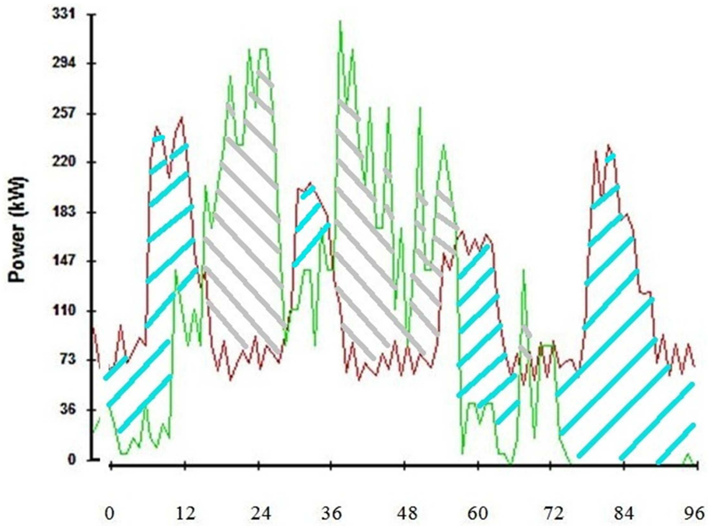


Figure 28 Example of demand (red) supply (green) profile, 16/07-19/07 based on 330kW wind turbine energy output

As an example, demand/supply profile for 4 days in July is shown at Figure 28, where blue-shaded areas are the excess of demand, and grey-shaded areas represent surplus of electricity generated by 330kW wind turbine. Generated energy surplus could be stored and released in time, when energy is required. There are several storages that could be used in renewable energy systems – batteries, flying wheel, hydro, hydrogen, compressed air. Among them batteries usually are designed for small amounts of energy, hydro-storage could be useful for large applications as grid balancing, others related with high expenditures or energy losses, so all of them could not work efficiently for medium-size industrial implementations.

The advantage of industrial companies is in different processes that require energy/electricity. Some of those appliances could be put into work when electricity from renewables is available. That would cause financial benefits and reduce embodied energy of the final manufactured product of the company. For instance, for Barr one of the ways to use energy excess is to shift high-energy load of bitumen tanks. In present time only one bitumen tank works from electricity – 23 tonnes of available capacity, the current maintaining temperature is 140 degrees. The temperature of bitumen should not go below 120 degrees. For the further calculations

130 degrees was taken as minimal temperature. Bitumen inside the tank could be heated between the range of 130-140 degrees when renewable energy is available. Specific heat of bitumen varies from 1.89 KJ/kg/^{o}C at 100^{o}C to 2.10 KJ/kg/^{o}C at 200^{o}C (Shell Bitumen, 1995, p. 387). Using interpolation the value of the specific heat for 135 degrees bitumen found as 1.96 KJ/kg/^{o}C. After that, energy which is necessary to have to increase temperature of bitumen by 10 degrees is could be calculated as:

$$Q_h = m * C_p * (T_2 - T_1) = 23000 * 1.96 * 10 = 450{,}800\ (KJ) = 125.22\ (kWh) \tag{11}$$

This Q_h is a value of energy that is necessary to increase the temperature of bitumen inside the tank. To this value an on-going heat loss should be added. It could be calculated as:

$$Q = U * A * \Delta T$$

A – is the surface area of the tank, m^2; ΔT – temperature difference between bitumen and outside air; U is U-value of the tank that was taken from "SpiraxSarco, Energy Consumption of Tanks and Vats" methodology for rough estimations (SpiraxSarco), according to which the U-value of the tank sides is:

$$U = U_o * I * X$$

Where U_o is typical U-value for tanks according to a temperature difference to air, in case of this work U_o=16W/m^{2o}C for the tank sides, I is a coefficient of insulation which was taken 0.1 using an assumption of 50mm insulation thickness; X is a coefficient of wind velocity, for this case study wind speed equals 4.2m/s and X=2.48. Based on those coefficients the sides of the tank U-value is 3.97W/m^{2o}C (SpiraxSarco).

It was assumed that the tank volume is 23 tonnes of liquid bitumen without a solid part of 7 tonnes. It was also assumed that the dimensions of the horizontal tank are 1.2m radius and 5m length which give the outside area of 46.72m^2.

The annual average temperature in Scotland is 9^{o}C and the temperature of bitumen is 140^{o}C so average energy loss Q is:

$$Q = 3.97 * 46.72 * (140 - 9) = 24.3(\mathrm{kW})$$

The Q value means that to keep the bitumen temperature of 140 degrees it is necessary to provide 24.3kW power (Note: this value was calculated roughly as an example).

After that, calculated value of $(Q_h/Q) = 125.22/24.3 = 5.15\ (hours)$ means the time for the tank to lose 10^{o}C of bitumen temperature. As a result, applying energy management, the base load could be reduced by 24.3kW when there is no available electricity from wind or solar PV. Intervals between heating of the tank should not last longer than 5.15 hours to avoid bitumen hardening. When renewables generate a high energy surplus it is possible to accommodate up to 125.22kWh for bitumen heating. This task could be realized by using software that works with attention to renewable energy generation and temperature of bitumen.

The overviewed example of energy shifts using bitumen tanks is only one of the possibilities to apply energy management. In other industrial companies it could be several processes that would allow applying the same smart energy schedule and loading more renewable electricity on site together with improving economics of renewables and reducing carbon footprint.

10. Renewable energy system economics

Primary economic estimations of renewable energy systems are based on financial expenditures and benefits. Total generating cost of electricity produced by a wind turbine or solar panels is determined by following factors (J.F. Manwell, 2009):

- Wind/solar regime
- Energy capture efficiency
- Availability of the system
- Life time
- Capital costs
- Financing costs
- Operation and maintenance costs.

First two factors – wind/solar regime and energy capture efficiency were discussed above. Briefly, wind and solar regime depends on energy resource available at the place of installation, and energy capture efficiency changes with design of a wind turbine, and material used for PV solar panels. The third factor – availability of the system – depends on time when the equipment is operational. Days for operation, maintenance and necessary repairs should be excluded from the total operational time. According to the statistics for current wind turbines, in total they require 6 days to repair any failures occurred (Figure 29) (Milborrow, 2010). Consequently the availability factor is 98%.

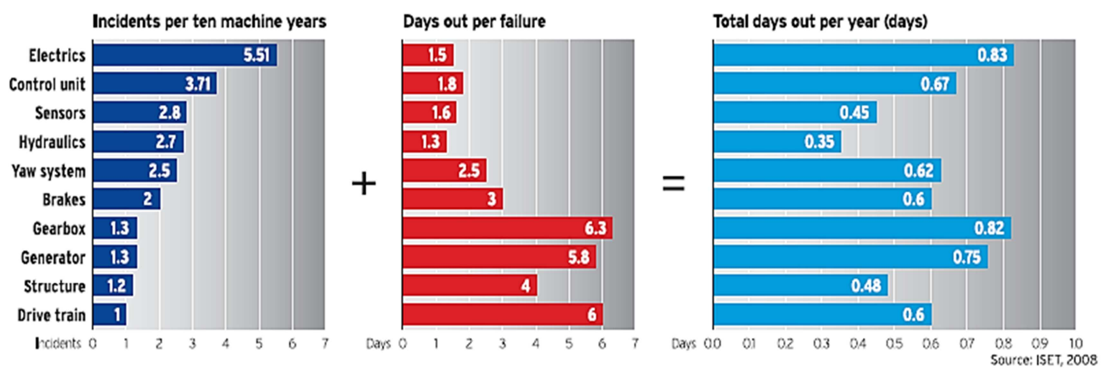


Figure 29 Failure rates and outage times of wind turbine components (ISET 2008 cited in (Milborrow, 2010))

According to the other resources the availability factor for modern turbines is between 97 and 99% (EWEA 2004 cited in (J.F. Manwell, 2009, p. 507)). The PV panels' availability factor is close to 100%. All operation and maintenance operations could be done during one day to avoid high energy losses. Considering the possibility of heavy snow and low temperatures in winter, the practical availability factor for Western-Scotland territories could be lower. In Scotland the number of days with snow cover (more than 50% of surface) at 9 a.m. is from 2 to 9 between November and March (Met Office, 1996-2005). For a wind turbine it could cause icing which decrease the availability factor. Despite that PV panels installed at a tilt angle, so the falling snow would slide down, in periods of heavy snow they could be covered entirely or partly and require cleaning. Taking into account these weather factors the number of days out of operation was increased by 5 a year for wind turbines and by 3 for PV panels (approximate values).

In Europe the lifetime period for economic analysis of wind turbines is assumed as 20 years which is the design life time (J.F. Manwell, 2009). However, because of the novelty of wind turbines with current design, this period was not checked in real-life operation. For solar PV panels the life-time period that declared by manufacturers is 25 years. During this time manufacturers guarantee the power output of at least 80% from the initial level. These life-time values are used for all financial estimations. However, if PV panels are connected to the grid, they need DC/AC inverters, which have a lifetime of 15 years and would require replacing once during the PV lifetime. This fact will be considered in further O&M costs calculations.

10.1. Capital costs

The total cost of the system includes capital cost of the equipment, costs of additional electrical equipment as inverters for PV or transformers for wind turbines, cost of the base, installation and connecting to the grid, infrastructure (as access roads for wind turbines), project management and financial costs.

For wind energy in different published resources the constituent part of each cost type is slightly varying. Two types of costs structures are introduced in Figure 30:

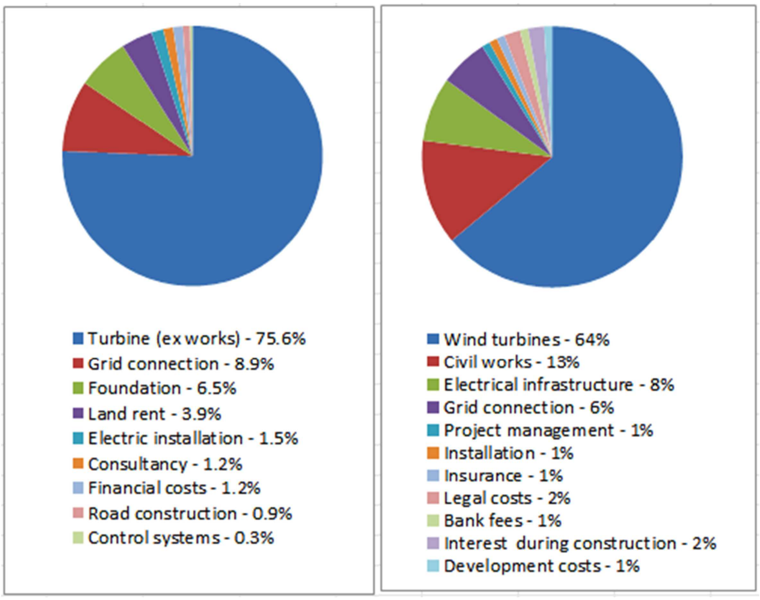


Figure 30 Cost structure of a wind turbine installation

left – typical 2MW wind turbine in Europe (Poul-Erik Morthorst, 2009),

right – typical 5MW onshore project (RenewableUK)

The cost of the turbine itself takes 65-75% of the total cost of the investment. Expenditures per kW power of a single wind turbine installation are generally higher. For this project, prices that received from one of the local companies are summarised in Table 9:

Table 9 Capital costs of wind turbines (TGC Glasgow, 2011)

Wind turbine type	50kW	100kW	330kW
Pre- Deployment Costs (Pre-con, Planning & Survey)	3,485	3,485	11,015
Turbine costs (Supply & Install)	226,215	335,260	865,197
Total	229,700	338,745	876 212

Considering the Barr company industrial profile, the cost of the wind turbine construction could be decreased by using its own concrete for the foundation of the turbine and technical machinery.

The capital cost of a medium size solar photovoltaic plant includes PV panels, necessary fittings for installation at tilt angle, investors and electrical connection to the grid, installation work, control and monitoring systems, financial and project management costs. The main difference from wind turbine costs distribution would be in absence of foundation and road construction expenditures. According to data received from local PV distributors, system of 229PV HiS-S218SF with inverters, all necessary fittings and installation work would cost £133,528 including 5%VAT (Solway Solar Systems, 2011).

In addition, the grid connection cost should be added to the values of the capital expenditures. For the turbines sites it would be necessary to make a grid connection overhead or underground lines of 200-250 m to the nearest transformer. The exact cost of the connection to the grid could be received after the investigation of the local grid capacity. For 50kW and 100kW wind turbines and 50kW PV panels the connection to the grid should be minor because of the zero or low electricity export. However for 100kW turbine power export to the grid could reach 50kW, and for 330kW turbine – 280kW (rated power minus base load of the company). Similar for the combinations of solar and wind energy the possible power export is accounted for 50kW and 100kW for 50kW PV/50kW wind and 50kW V/100kW wind respectively. As a result, the cost of the grid connection could vary significantly. In this project it is assumed as 6% and 1% of the capital cost of installations – solar PV and wind. Additionally, based on Figure 30, 1% of capital expenditure was added as a possible consultancy work payments.

10.2. Operation and maintenance

Operation and maintenance (O&M) costs include regular maintenance, repairs, spare parts, insurance and administration (Operation and Maintenance Costs of Wind Generated Power).

10.2.1. Wind turbines O&M costs

For wind turbines O&M cost usually represents per kWh energy generated. This approach allows easily take into account the size of the system and local wind power availability.

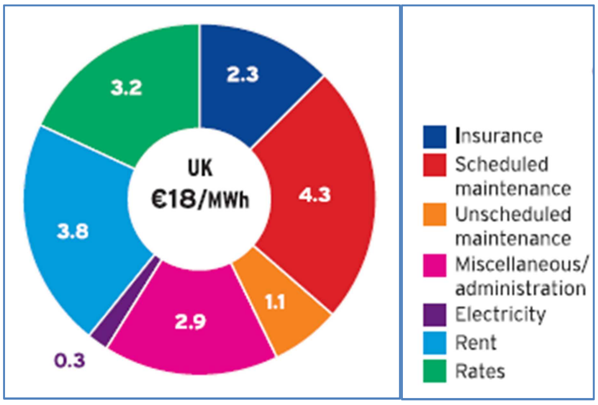


Figure 31 Total operation and maintenance costs per MWh of wind energy (Milborrow, 2010)

Figure 31 shows the O&M costs are included several parts. Thus, the cost of scheduled and unscheduled maintenance is only €5.4/MWh, which is 30% of the total O&M cost of €18/MWh. Another resource (Figure 32) indicates that for example 55kW wind turbines require approximately €3.5-4.5/kWh for O&M, which equals €35-45/MWh.

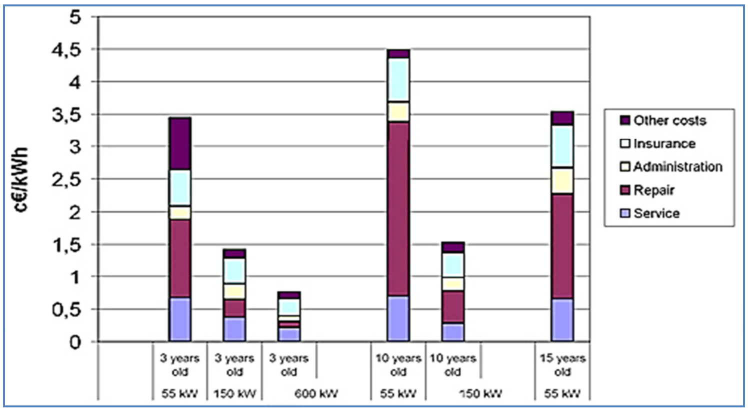


Figure 32 O&M Costs for selected types and ages of turbines (Jensen et al. (2002) cited in (Operation and Maintenance Costs of Wind Generated Power))

Figure 33 shows operational costs for turbines of different size using another approach. Concerning the turbines range used in this project, the O&M cost should be between 33 and 26 €/kW of the turbine size.

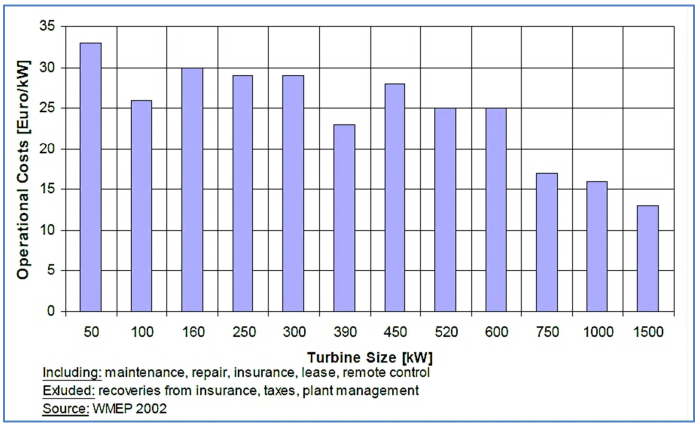


Figure 33 Operational costs as a function of the turbine size (WMEP, 2002 cited in (Wiggelinkhuizen, 2007))

According to other sources estimated O&M annual cost is 1.5-2% of the capital cost of the system (DWIA 2006 cited in (J.F. Manwell, 2009)). To compare results from mentioned four different resources and approaches see graph at Figure 35:

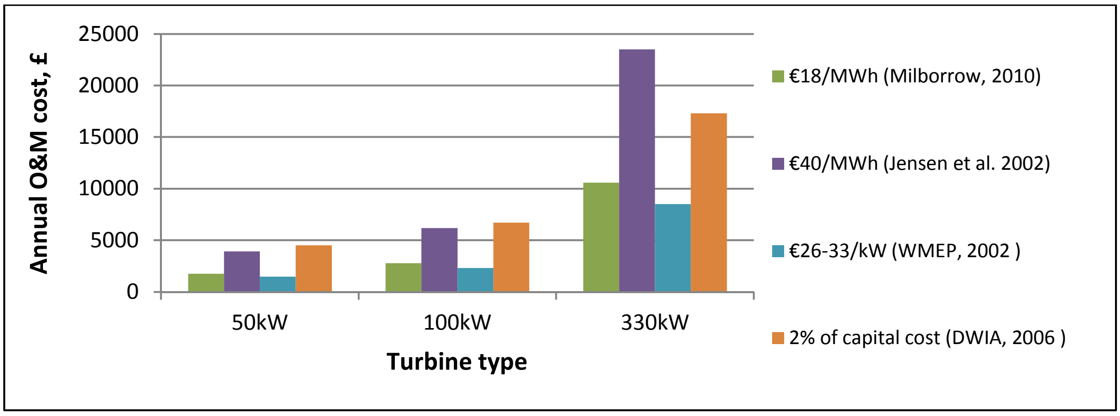


Figure 34 Annual O&M costs for wind turbines using different estimating methods.

At Figure 34 it could be seen that the second and third methods give similar results for smaller turbines (50kW and 100kW). For the 330kW turbine, the method described at Jensen et al. 2002 (cited in (Operation and Maintenance Costs of Wind Generated Power)) give the highest O&M cost.

On the planning stage it is challenging to predict O&M cost which in real life would depend on the turbine type, age, site of installation and local market trends. Additionally O&M costs are changes through the life-time of wind turbines. For example, at year 5 annual cost of corrective maintenance (repairs) accounts for 0.5-0.8% of investment cost, however at year 15 it increases to 4-6%. Totally, the average O&M cost through the life time period is 2-4% of investment costs per year (Wiggelinkhuizen, 2007).

Table 10 Annual average O&M costs for wind turbines

Wind turbine (p.46)	50kW	100kW	330kW
Annual O&M cost, £	2,922	4,497	14,971

In this project O&M costs of all 4 methods were averaged and assumed as equal through the life time period of wind turbines. The values were summarized in Table 10 and taken for further financial calculations.

10.2.2. Solar PV panels O&M costs

Similar to wind turbines, O&M cost for PV panels consists of regular maintenance, repairs, spare parts, insurance and administration. All those actions are targeted at PV efficiency and performance increasing. The regular maintenance of a PV system includes inspection and servicing of equipment to prevent any breakdowns and energy production losses. Major activities are shown in Table 11:

Table 11 Major elements of PV O&M (EPRI, 2010)

Preventive Maintenance	Typical Frequency, times/year
Panel Cleaning	1-2
Vegetation Management	1-3
Wildlife prevention	Variable
Water Drainage	Variable
Retro-Commissioning	1
Upkeep of Data Acquisition and Monitoring systems (e.g. Electronics, Sensors)	Undermined
Upkeep of Power Generation System (e.g. Inverter Servicing, BOS Inspection, Tracker Maintenance)	1-2

The frequency of O&M depends on the specifics of the PV system location. For instance, “on land” PV would require frequent vegetation management to prevent shadings. However for roof mounted PV this activity could not be necessary at all. Wildlife as birds nesting or other small animals could harm PV materials, cause dirtying of PV surface and problems with wiring. Regular checking of electronics and power generation system helps to prolong life time of PV and inverters.

Possibly, the main O&M activity is cleaning. Current PV panels have a special surface which decreases dirt settling on it. The tilt angle of PV arrays helps water to stream down and naturally wash the surface. However in dusty/desert regions or locations with high pollution PV panels could require cleaning every few months. Additionally it is impossible to prevent birds’ drops or leaves adhesion. According to the industry stakeholders, PV performance could drop between 1-5% annually because of dirt. And based on external factors, panel washing can improve efficiencies by as much as 10-15%, but usually by 3-5% for PV at tilted angles (EPRI, 2010, p. 12). Frequency of cleaning should be developed individually for the exact PV installation during operation according to the actual necessity. It is suggested to clean PV panels at least once in March/April before the period of high intensity of solar radiation.

Panel washing for large commercial ground of roof mounted PV systems costs approximately $2.5/kW (£1.5/kW), but for more complex systems it can reach $10/kW (£6.1/kW). Smaller arrays of 100 kW and less has more expensive panel washing costs on a basis of installed kW power. The total O&M cost of PV system (including cleaning) is varying between $6-27/kW (£3.7-16.5/kW) (EPRI, 2010).

The other method of presenting O&M costs of PV is in dependence from produced electricity. Using this method, O&M costs are varying from 0.02 to 0.1 c€/kWh (£0.0175-0.0874/kWh) (PVResources (c)).

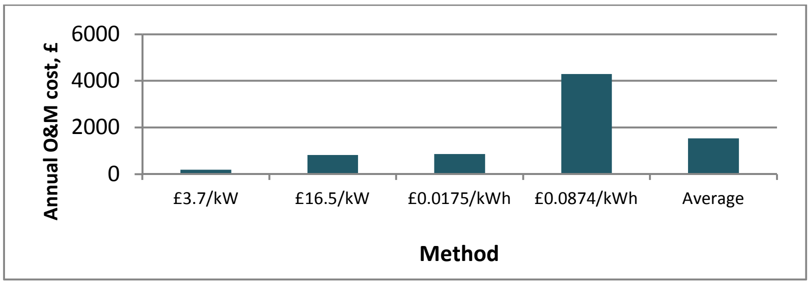


Figure 35 Annual O&M costs for PV panels using different estimating methods.

Similar to the wind turbine, annual O&M cost of PV panels was chosen as an average of two described values and accounted for £1,539 (Figure 35). This amount will be used in further economic calculations.

10.3. Financial benefits

To estimate economics of each system it is necessary to calculate the amount of annual income. For a renewable energy unit that connected to the grid there are three possible types of financial benefits. Firstly, energy from a wind turbine and PV could be consumed by the company itself. It would cause decreasing of electricity load from the grid, and, consequently, reducing annual payments for it. Currently the average the electricity price for the company is 10p/kWh. Therefore, total benefits from produced energy that consumed by the company equals to $E\,(kWh) * 10\,(^{p}/_{kWh})$ (Table 13). Because of the annual variability in solar energy and wind speed, energy output from renewables would be different from year to year (see p.89).

Secondly, if renewable energy system power capacity is higher than the base load of the company, it would produce energy surplus that could be exported to the grid for 3p/kWh. Most of the systems that are investigated in this project were selected to work generally at base load of energy demand. Consequently, the amount of exported energy is minimal for them. However, for example 330kW turbine produces significant surplus of energy.

The third income from renewable energy is FITs – Feed in tariffs scheme that was introduced 1/04/2010 in the UK. FIT scheme was founded to help the development process of renewable energy systems of different sizes. FITs are applicable different types of technologies – wind, solar, anaerobic digestion, micro-CHP and Hydro energy. According to the first year statistics of FITs, 72% of the installed capacity holds PV energy and 17% - wind energy in the UK. However, because of greater wind resource, in Scotland wind energy is a prevailing technology, it keeps 52% of all installed capacity, 32% - hydro and 12% - solar (Ofgem E-Serve, 2010). The amount of payments for each kWh generated by the system depends from the tariff rate. The FIT rate is fixed for the life time of the equipment (20 years for wind turbines and 25 years for PV panels). FIT rates changes according to the year of application. As an example, FITs for wind and solar technologies are shown in Table 12:

Table 12 FIT rates (an example for PV and wind technologies), (Ofgem, 2011)

Technology	Scale, kW	Tariff level for new installations (p/kWh)			Tariff lifetime
		Year 1	Year 2	**Year 3**	
Solar PV	>10-50	32.9	32.9	**30.1**	25
Wind	>15-100	25.3	25.3	**24.2**	20
Wind	>100-500	19.7	19.7	**19.7**	20

Note: Year 1 – 1/4/10-31/3/11, year 2 – 1/4/11-31/3/12, year 3 – 1/4/12-31/3/13

The project run time for medium-size systems could reach 2 years starting from planning process and finishing with commissioning (Global Energy Concepts, 2005), consequently FIT rates for “year 3” (commissioning till 31/3/13) will be used in further calculations. For many technologies FIT payments decrease each year. For example, solar PV FIT rates drops from 32.9p/kWh for the first year to 14.3p/kWh for year 11. So economically, it is more profitable to install PV during few coming years to get more financial benefits. Final results of financial calculations are shown at Table 13; they include costs of consumed and exported energy, and FIT payments.

Table 13 Cost of energy consumed on site and sold to the grid

Type of the system	Location (for wind turbines)	Cost of the energy consumed on site, £ p.a.	Cost of the energy exported to the grid, £ p.a.	FIT payment (year 2 rate), £ p.a.	Total income, £ p.a.	Income per installed kWp p.a.
50kW PV	-	4,853	0	14,608	19,461	389.2
50kW WT	1	10,692	0	25,876	36,568	731.4
50kW WT	2	10,285	0	24,890	35,176	703.5
100kW WT	1	16,802	12	40,758	57,573	575.7
100kW WT	2	16,665	12	40,425	57,102	571.0
330kW WT	1/2	47,488	4,945	126,020	178,452	540.8
50kW PV/50kW WT	1	15,914	7	40,484	56,405	564.0
50kW PV / 100kW WT	1	22,157	37	55,367	77,561	517.1

Note: Energy consumed on site calculated using wind turbines and PV panels availability factor. (WT – wind turbine, PV – photovoltaic panel)

It could be seen that the cost of energy export is minimal for all systems, thus even for 330kW wind turbine it reaches only 3% if the final annual income. So energy export is not a priority for renewable energy systems of medium size for industrial companies. The financial incomes of renewables from FIT tariffs is accounted for 2/3 parts (Figure 36Figure 36 Distribution of annual income from renewables between different payments) of the total values.

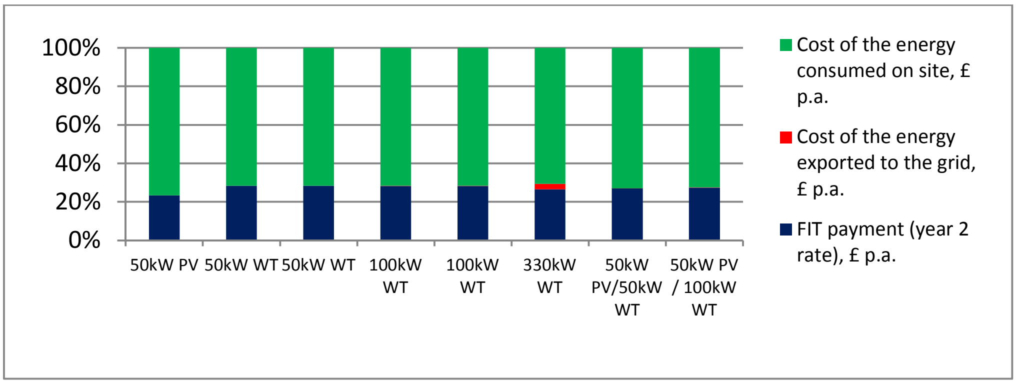


Figure 36 Distribution of annual income from renewables between different payments

Because of the high percentage of FITs in renewable energy finances, it is important to choose the site of the system correctly. For instance, with increasing of the PV system from 50kW to 100kW of capacity, the FIT rate (third year) would be 17.4p/kWh (Ofgem, 2011) instead of 30.1p/kWh. That would lead to decreasing of incomes in relation with the size of the system. Thus, for 50kW PV the annual income per installed 1kW is £389.2, and for 100kW it would be 30% less - only £266. Finally, that would cause increasing of payback period and other financial indicators.

To sum up, the size of the system should be chosen with reference to the current FIT value, because it is a major factor that determines total financial benefits. Calculated results of financial benefits are used further in pay-back period, NPV and IRR estimations for each system.

10.4. Payback period

Payback period is a standard economic parameter that allows to a company to calculate how long would it take for an investment to pay for itself. The classical way to calculate payback period is (Payback Period Definition):

$$P = \frac{Cost\ of\ project}{Annual\ cash\ flows} \tag{12}$$

The cost of the investment includes the equipment, work, infrastructure and other accompanying payments (see paragraph 10.1). Annual cash flows contain annual financial benefits (FIT tariffs, export of electricity and electricity consumed on site) minus annual O&M cost. Calculation of payback period for all discussed systems are summarised in Table 14:

Table 14 Payback period calculations

Type of the system	Location (for wind turbines)	Capital cost, £	O&M cost, £ p.a.	Benefits, £ p.a.	Payback, years
50kW PV	-	145,140	1,539	19,461	8.1
50kW WT	1	249,674	2,922	36,568	7.4
50kW WT	2	249,674	2,922	35,176	7.7
100kW WT	1	368,201	4,497	57,573	6.9
100kW WT	2	368,201	4,497	57,102	7.0
330kW WT	1/2	952,404	14,971	178,452	5.8
50kW PV/50kW WT	1	394,814	4,461	56,405	7.6
50kW PV/100kW WT	1	513,341	6,036	77,561	6.9

The difference in payback period of systems is only 2.3 years. The highest payback of 8.1 years has the system of 50kW PV. The smallest payback (5.8 years) has a 330kW wind turbine (Figure 37).

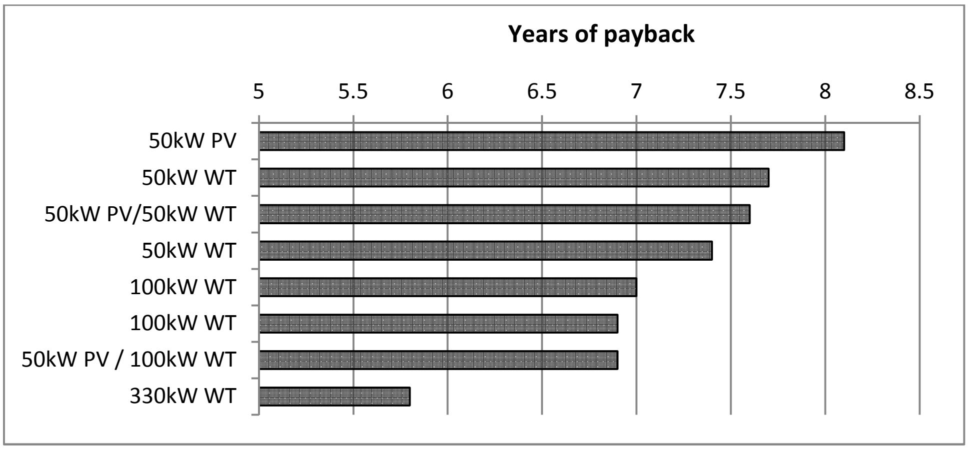


Figure 37 Payback period for different systems and combinations, years

Using the same example of 100kW PV system (see paragraph 10.3) and assuming doubling of capital expenditures and O&M cost in comparison with 50kW PV, decreasing of FIT tariff gives the payback of 12.3 years which is 50% higher than payback of 50kW PV.

Because payback period estimations ignore several financial parameters as profitability and value of money, other methods as NPV and IRR are used for calculation of financial benefits.

10.5. Net present value and internal rate of return

Net present value allows to a company compare different investment options in terms of financial benefits at the end of chosen period. Often the standard bank rate is used as a base for comparisons. In case of this work, the renewable energy investment will be compared with 4% of risk-free bank deposit rate of return. For all systems NPV will be calculated for the total life-time of the system – 25 years for PV panels and 20 years for wind turbines and combinations. Classical equation for NPV is:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (13)$$

where C_0 is a total capital expenditure, C_t – net profit from the investment for the t - time period, r – discount rate (4%) (Net Present Value - NPV). NPV was calculated with an assumption that energy generation and O&M cost of each system are constant throughout the life-time period. Additional parameter - internal rate of return (IRR) could be calculated with the same equation when NPV=0. Results of calculations are summarised in Table 15.

Table 15 NPV and IRR calculations for each system

Type of the system	Location (for wind turbines)	NPV, £ (r = 4%)	IRR, %
50kW PV	-	134,846	11.55
50kW WT	1	207,588	12.10
50kW WT	2	188,664	11.44
100kW WT	1	353,114	13.21
100kW WT	2	346,722	13.06
330kW WT	1/2	1,411,701	17.54
50kW PV/50kW WT	1	311,121	11.72
50kW PV/100kW WT	1	458,704	12.64

NPV results shows that investing in each system is significantly more profitable than a bank deposit. In fact, each system, after paying itself back, would give the rated profit of the capital investment size. According to the NPV and IRR coefficient, all of the systems give significant financial benefits. The most profitable system at the end of life-time is 330kW wind turbine.

For many business companies financial outcome is the most significant factor for making a decision. The result of all estimated economic parameters shows that in present time renewable energy is extremely profitable sector for investments as long as FIT rates are high. However, a company should be aware of all assumptions that were used in these calculations. During the planning process the financial part of the project estimates more accurately, but even this does not guarantee exact payback of IRR results because of uncertainties that renewable energy is accompanied with. Apart from economic benefits, other factors as environmental and social impacts should be taken into account while choosing a renewable energy system.

11. Environmental and social impact

This paragraph is targeted at review of environmental and social impact of a single medium-sized wind turbine and/or PV panels in western Scotland territories, based on a case study of at Barr Limited industrial site at Killoch. One of the positive environmental issues of renewable energy generation is reduction of CO_2 emissions. However renewable energy systems could impact negatively at the local environment, for example noise emissions or effect on wild life. Most of the environmental issues concerns the wind energy generation. On the other hand, photovoltaic technology has significantly lover impact on the local environment. Socially, a middle-size wind turbine or PV panels could affect the tourism industry or have an impact on education or employment rate at the local site.

11.1. Carbon dioxide emissions and savings

The most significant environmental benefit is reducing of greenhouse gas emissions, especially carbon dioxide. Many industrial companies are aware of environmental problems. According to the current Barr energy policy, they are aimed to reduce the energy consumption of the company from all resources at least by 5%. As a result, that would cause reduction of CO_2 emissions. This policy could be realised by efficiency improvement of energy consumption and investing in sustainable energy technologies as renewable energy.

In total, the population in the world produces about 16 million tonnes of carbon every day. Each energy generation system has estimated life-cycle carbon emissions. For example for a coal power plant it is about 800gCO2/kWh, and for on-shore wind – 4.64gCO2/kWh. Even biomass combustion the renewable energy technology with highest CO_2 emissions has a carbon footprint which is 10 times lower than a coal power plant (Values of CO_2 emissions from the other technologies could be found in annex Figure 47). Those values include all carbon that emitted during manufacturing, construction, power generation during life cycle and decommissioning (Parliamentary Office of Science and Technology, 2006).

Having expected values of annual energy generation by PV and wind turbines, carbon footprint and carbon savings could be calculated for each system (see Table 16).

Table 16 Wind and solar PV annual carbon footprints and savings

Type of the system	Location (for wind turbines)	Total energy generation, kWh p.a.	Carbon emissions, tonnes p.a.	Carbon savings, tonnes p.a.
50kW PV	-	49,070	2.85	18.25
50kW WT	1	110,300	0.51	46.92
50kW WT	2	106,100	0.49	45.13
100kW WT	1	173,740	0.80	73.91
100kW WT	2	172,320	0.79	73.30
330kW WT	1/2	659,890	3.04	280.72
50kW PV/50kW WT	1	159,370	3.35	65.18
50kW PV/100kW WT	1	222,810	3.65	92.16

In carbon emission calculations it was assumed that the energy mix in the UK has a carbon footprint of 430gCO2/kWh (Renewable UK (A)). Annual carbon savings were calculated by multiplying of energy generation and electricity mix carbon footprint value, minus carbon emissions by renewables.

Because of the significant difference in energy generation between PV and wind with the same power capacity and life-cycle emissions (58gCO2/kWh and 4.6gCO2/kWh respectfully), carbon saving from on-shore wind energy is more than 60% higher than CO_2 saving from solar PV technology.

To sum up, even renewable energy systems are not entirely "Green", however they cause CO2 emissions that are many times lower than from fossil fuels technologies. CO_2 emission savings from investigated wind and solar systems would be accounted for 3.4…52.2% from the total emissions of the company. It is perfectly corresponds with the energy policy. Additionally it would reduce embodied carbon of manufacturing products.

11.2. Wind energy environmental and social impact

Among the most known environmental issues of wind energy is noise, visual impact, effect on the birds' life and electromagnetic interference (J.F. Manwell, 2009). Many wind energy programmes were delayed or reversed because of the possible impact on the local environment.

11.2.1. Sound pressure level calculations

For the UK and even Scotland, where most of the territories are occupied with cities, villages and houses, many wind turbines and farms are installed close to people homes. Because of that, the noise problem is one of the most important among the other environmental impacts.

The technology of wind turbines improved dramatically in terms of noise emissions reduction, for example blades air foils and operating strategy (J.F. Manwell, 2009). However, still people who leave close to wind farms have complains about industrial noise generating during the whole life-cycle of wind turbines from construction and operation to decommissioning. The additional problem of generating noise is that people have different reaction on it. Some people could be very sensitive to the new sound resource especially in relatively calm rural lands as western part of Scotland.

Sources of noise emitted from a wind turbine could be divided into two groups: aerodynamic and mechanical. Aerodynamic noise is producing because of the airflow over blades and tower. Mechanical noise is connected with work of gearbox, generator, yaw drivers, cooling systems and other mechanical equipment. With increasing of speed and turbulence of wind flux the noise from a wind turbine increases as well (J.F. Manwell, 2009). UK standards require rising of noise pressure level because of wind turbines of no more than 5dB(A) above background for day and night time. According to the other European standards ISO 1996-1971, noise limits for a day, evening and night times were determined separatelly for different types of districts (see Table 17).

Table 17 ISO 1996-1971 Recommendations for community noise limits (Weed, 2006)

District type	Day time limit, dB(A)	Evening limit, dB(A)	Night limit, dB(A)
Rural	35	30	25
Suburban	40	35	30
Urban residential	45	40	35
Urban mixed	50	45	45

Note: Evening time – 7-11pm, Night time – 11pm-7am

The other different international organisations and countries issue their own guidelines of the noise level. For example, the World health Organisation suggested sound levels of 35 dB(A) for daytime and 30dBA at night inside residences with open windows to avoid critical effects as annoyance, speech intelligibility and sleep disturbance (Weed, 2006).

Each manufacturer of wind turbines announces the noise pressure level generating by their wind turbines. For the turbines that used in this project, noise levels are summarised in Table 18

Table 18 Wind turbines noise level

Turbine type	Noise level, dB(A)
50kW, Endurance E-3120	94.8 dB(A) at the turbine, wind speed 10m/s
100kW, Nothern Power	55 dB(A) at 40m distance
330kW, Enercon E-33	101 dB(A) at the turbine, wind speed 10m/s

If sound power level L_{WA} (dB(A)), of wind turbine is unknown, it could be calculated from rated power of the turbine P_{WT} (W), diameter D (m) or tip speed at the rotor blade V_{tip} (m/s) (J.F. Manwell, 2009):

$$L_{WA} = 10(log_{10}P_{WT}) + 50 \quad (14)$$

$$L_{WA} = 22(log_{10}D) + 72 \quad (15)$$

$$L_{WA} = 50\left(log_{10} V_{tip}\right) + 10(log_{10}D) - 4 \quad (16)$$

Given equations 14 and 15 could be a simple way for a rough estimation of noise levels; however, they were developed for old types of turbines. Equation 16 is more accurate because it shows the dependence of sound pressure from the tip speed of the rotor which represents aero dynamical nature of noise (J.F. Manwell, 2009, p. 489).

Using the given or calculated data, noise level from each turbine could be calculated for any distance from it. The territory of the company is situated in a rural site with a few houses and communities distributed in the area. The detailed map is presented in annex Figure 45. The noise emission from wind turbines at any distance could be calculated applying the following equation (Mertens, 2006):

$$\mathrm{L_p} = \mathrm{L_w} - 10\log_{10}(4\pi \mathrm{r}^2) \quad (17)$$

The other equation (J.F. Manwell, 2009) using frequency-dependent sound absorption coefficient α:

$$\mathrm{L_p} = \mathrm{L_w} - 10\log_{10}(2\pi \mathrm{r}^2) - (\alpha * \mathrm{r}) \quad (18)$$

Where L_p is a noise level dB(A) at a distance r (m), L_w – noise level at the resource. Using equation (17) and approximate distances from wind turbines locations (1 or 2) to each property, noise levels results were calculated and summarised in Table 19:

Table 19 Noise level from wind turbines at each location

Dwelling location (Figure 45)	distance, m (1)	distance, m (2)	Noise level from wind turbines at each location – 1 or 2, dB(A)					
			50kW, (1)	50kW, (2)	100kW, (1)	100kW, (2)	330kW, (1)	330kW, (2)
A	189	274	38	35	41	38	44	41
B	579	695	29	27	32	30	35	33
C	600	705	28	27	31	30	34	33
D	842	937	25	24	29	28	32	31
E	842	905	25	25	29	28	32	31
F	968	1021	24	24	27	27	30	30
G	779	726	26	27	29	30	32	33
H	705	611	27	28	30	31	33	34
I	600	579	28	29	31	32	34	35
J	705	674	27	27	30	30	33	33
K	747	695	26	27	30	30	33	33

It could be seen that among the dwellings, A, B, C and I are sited closer to the wind turbine locations and have the highest level of noise. Among the buildings on the territory of the company, the main office building have the highest requirements in terms of the noise, it should not exceed 50 dB(A) to have no any affect on efficiency of work (J.F. Manwell, 2009).

On industrial part of the company at the asphalt manufacturing, workers could wear noise protection as headphones if necessary. The IT server system is situated at the part of the main office which is closer to both locations 1 and 2. At this building windows are permanently closed and all cooling and ventilation is mechanical. So the outside noise would have less impact on the internal environment. The noise level at main office building is shown in Table 20:

Table 20 Noise levels at main office building

Location of the wind turbine	1	2
Distance to the main office, m	74	153
Noise from 50 kW wind turbine, dB(A)	46	40
Noise from 100 kW wind turbine, dB(A)	50	43
Noise from 330 kW wind turbine, dB(A)	53	46

The first location of wind turbines gives higher noise level for the office building because of the shorter distance between them. However a wind turbine at the second location would increase the noise level at industrial site of the company.

Calculated sound power levels given at Table 19 and Table 20 only introduce noise from wind turbines. The total noise coming to a particular place from several wind turbines or the other resources could be calculated as (Mertens, 2006, p. 9):

$$L_{total} = 10 * log_{10}\left(\sum_{i=1}^{N} 10^{L_i/10}\right) \qquad (19)$$

General guidelines says that two equal sound pressure levels generate cumulative noise that is 3dB(A) higher that one of them, and if one of the two resources give a noise 15dB(A) lower than the other it could be neglected.

For case study of this project the background noise is unknown and should be measured at critical sites (close dwellings, main office and manufacturing plant) to predict the final sound pressure level in case of a wind turbine installation.

11.2.2. Visual effects

The visual impact of a wind turbine or a wind farm depends on a landscape, number and design of the turbines, number of blades and colour. Visual impact could be assessed by making pictures of views of the local area without and with a single wind turbine or a farm. Open rural regions are the most sensitive to the visual impact. The US visual design strategies (NWCC 1998 cited in (J.F. Manwell, 2009)) recommend to use local land form to minimize visibility of access roads and protect land from erosion, use low profile and unobtrusive buildings design, uniform colour and structure design, minimise size, colour and number of label markings on turbines.

For the case study of Barr located at Killoch the approximate view of wind turbines of different size are shown in Annex, Table 26. Taking into consideration the industrial background of the local area (asphalt and coal plants), visual impacts of smaller turbines 50 and 100kW should not be significant. However, in larger view the rural area landscape would suffer from a new tall object on the site.

Visual impact of wind turbines usually causes a resistance from local householders and communities. On the other hand, a personal reaction on a view of a wind turbine varies for different people from positive and neutral to negative and could be hardly predicted. An explanation and promotional campaign among the local people could help to avoid or decrease number negative reactions.

11.2.3. Effect on birds' life

Wind turbines, as any other industrial object, have their own impact on wild life of surround areas. For example, major bird kills were reported at few wind farms in Europe and the US. Wind turbines with rotating blades of huge diameters, electrical lines and equipment could have a significant effect on birds' life (Colson, 1995 cited at (J.F. Manwell, 2009)):

- Bird electrocution and collision mortality
- Change to bird foraging habits
- Alteration to migration habits
- Reduction of available habitat
- Disturbance of breeding, nesting and foraging

Practically, the effect of wind turbines on birds' life can be assessed through the bird utilisation counts, utilization rate, mortality, to calculate bird risk (J.F. Manwell, 2009, p. 474):

$$Bird\ utilization\ rate = \frac{No.of\ birds\ observed}{Time * area} \quad (20)$$

$$Bird\ mortality = \frac{No.of\ dead\ birds}{Defined\ search\ area} \quad (21)$$

$$Bird\ risk = \frac{Bird\ mortality}{Bird\ utilization\ rate} \quad (22)$$

Bird risk could be calculated using different variable parameters, for example seasons, species, turbines type, and then compare risks from other types of facilities as highways or electricity transmission lines (J.F. Manwell, 2009). In Spain a bird's life study showed 0.13 bird deaths per turbine annually. In the US it was calculated that each 15,000 wind turbines cause 2.2 bird deaths per year (EWEA (A), p. 9).

Impact on birds' life is very site-specific. Observing the most popular birds nesting places in western Scotland, particularly Ayrshire identified that area around Killoch is not a popular natural habitat of birds. Additionally, Killoch site has industrial profile because of the coal mine for many years and it should be typically avoided by birds. The most common birds' nest places in east Ayrshire are situated at coastal sites near Largs, Irvin and Ayr, in mainland near Kilmarnock, Cumnock and Mouchline (Ayrshire Birding, 2010), (Kevin Waite, 2005).

11.2.4. Social impact

Social impact of wind turbines and farms includes effect on community cohesion, employment, education and tourism. Social resistance could cause difficulties for wind energy development in local areas. Public surveys are running in many countries to investigate public opinion about wind energy. For example a survey in 2002 in Germany showed that 86% are in favour about increasing of wind's contribution in energy mix (EWEA (A)). In the UK data from 50 surveys show that on average 77% of the public are in favour of wind energy, and 9% are against it (EWEA (B)) . Similar, surveys showed that public acceptance rising when a wind farm starts to operate (EWEA (A)).

Wind energy impact on tourism in Scotland was investigated on the basis of four case studies in 2008. According to the results, this impact is very small. However it is suggested to make a tourism impact investigation a part of a wind farm planning process. Wind farms reduce a value of scenery, so it is also suggested to install a small amount of large farms than scattered small farms throughout the territory (The economic impacts of wind farms on Scottish tourism, 2008).

In terms of impact on education and employment, wind turbines usually cause positive improvements, such as creating more local work places and improving energy awareness and education. Social resistance strongly depends on work with visual impact and noise emissions. A farm or a single turbine project that worked through those impacts has more opportunities to find social support of wind energy from society.

11.3. Environmental and social impact of solar PV energy

PV energy units do not cause so significant environmental impact as wind energy. For example, they do not have any noise generating because of the absence of moving parts. Similar, PV panels are generally located on flat surfaces, so the visual impact and impact for birds' life is not very significant. The major environmental issue of PV technology is land use. For example each kilowatt of power capacity takes about 7.5m^2 of surface. When PV panels are roof-mounted, they do not take any useful area, however for utility-scale ground-mounted PV plants, land use is a significant problem. Apart from PV arrays, it is also necessary to have roads and distance between modules for operation and maintenance works. For example, it was estimated that in the US to meet 100% of electricity demand of an average citizen by PV technology it is necessary to deploy 100m^2 of area, and with 1-axis tracking system this area doubles to 200m^2 (Paul Denholm, 2008).

Roof-mounted PV have a "zero" impact on land usage. It was calculated that about 18% of all residential and 65% of commercial roof-space is available and suitable for PV deployment (Chaudhari M., 2004 cited in (Paul Denholm, 2008)). However for large PV systems of hundreds of kW power capacity separated location of modules on many roof-tops would cause difficulties in operation and maintenance. Considering available roof-spaces in Barr at Killoch, 50kW PV system could be easily mounted without a land-use impact.

The social impact of PV small-middle scale energy is minor but mostly positive, because PV solar systems situated on roofs and less noticeable by people. On the other hand, PV systems demonstrate moving towards green energy and in general do not meet a social resistance.

11.4. Operational hazards

Renewable energy generation systems, as any other equipment, could cause different hazards that could occur in operation. Between two technologies, wind turbines more often become an object of extreme situations because of the rotating parts than PV. The first reason of hazards is related to weather conditions. For example, too strong winds and storms could cause breakdowns and fall of the construction or a part of it, lighting could cause fire, and icing could be a reason for ice drops in winter.

Analysis of 8 years of climate data from Prestwick Airport shown that during this time a wind speed over 18m/s occurred only twice. Additionally all manufacturers declare that cut-off speed of their turbines is 25m/s and the survival/extreme wind speed is at least 52m/s (see Figure 42 - Figure 44). So theoretically all of them should survive in high-speed wind gusts.

For Scotland locations temperature drops below “0” are frequent in winter, which could cause icing of wind turbines’ blades and tower. Ice drops are dangerous for people who work or live not far from the turbine. Investigations identified that for medium size turbines (25m radius and 40m hub height) the safety area is 200-250m far from the turbine, where there is no significant risk from ice fragments (Colin Morgan). For the same size of turbines it was calculated that in moderate climates (1-5 days of icing a year) the risk of ice throw at 50m distance is 0.01strikes/m^2/year. The graph at Figure 38 shows the risk of ice strikes in relation to distance from the turbine:

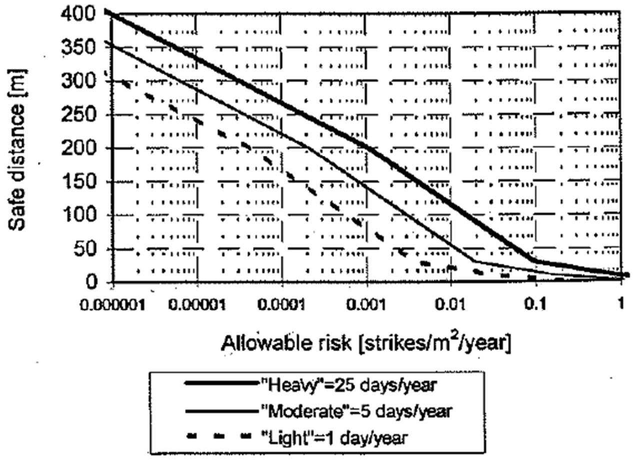


Figure 38 Safety distance for the chosen level of risk of ice strikes for 3-blades turbine with a 50m of diameter (Colin Morgan E. B.)

To reduce possible incidents, the access to the turbine could be limited by compulsory wearing of hard hats during icing periods. To avoid fire and damage of turbines because of lightning, all standard and necessary electric circuit protection should be installed.

The other operational hazards of wind turbines are connected with constructional errors. Defected parts are usually replacing by the manufacturer, however it could cost a lot of energy losses during the delivery and installation time.

Another hazard that concerns both – PV and wind energy – is work with electrical equipment and on height. To avoid accidents only professional personnel should be allowed to work at maintenance and operational tasks.

To sum up, most of hazards are connected to wind turbines technology which causes more risks to people who work close or provide O&M operations. As for PV panels, due to absence of rotating parts, they are more safe to work with.

12. Variability and uncertainty of wind and solar PV power

Uncertainty of wind and solar power predictions is connected to wind and solar radiation differences from year to year. Global horizontal solar radiation could change ±5% (p. 34), which depends on cloudy/clear year. Wind speed annual variations are more significant. Thus during the assessed period of 8 years annual average wind speed changes in diapason of +8…-12% (p. 35) from the average value. This difference in climate causes variability in economic performance of a renewable energy unit.

Additional decreasing of energy load from renewables could be caused by breakdowns. Repairs and replacing of parts of renewable energy system could take even a significant part of annual energy output. Mostly, those problems could occur with wind turbines because of the rotating mechanism of energy generating. As for PV technology, only an inverter replacement could be necessary during the life-time of the panels. However, for PV long interval between cleaning of panels would cause an energy gain drop from up to 15% (p. 70), it would be especially critical during summer months when the power output is the highest.

Another uncertainty is connected to economic factors. According to the annual benefits calculations, payments from Feed-in tariffs occupy 70-80% of the total income. Theoretically, a serious crisis could prevent the government from stable payments of the tariff during the whole life-time of the system. Without FIT the payback period increases from 5.8…8.1 years (see p. 74) to, for instance, 43.8y for the PV system, 30-32y for 50/100kW and 25y for 330kW wind turbine. All of those values are more than the life-time period of systems. So installation of renewable energy generation – PV and Wind – becomes unprofitable.

Conclusion

To conclude, many factors investigated in this project have an effect of energy generation, financial and environmental issues. Despite fast developing during past 20 years wind and solar PV technologies still have many unsolved problems that could prevent a business company from generating greed energy. On the other hand, good weather conditions and financial support from the UK government make renewable energy production highly profitable.

Western Scotland weather conditions – wind speed and solar insulation – are appropriate for generating substantial amount of electricity for an industrial company, cut electricity import from the grid and reduce carbon dioxide emissions. The size of PV units is limited by financial benefits because of the FIT different rates, and the size of wind turbines is limited by available land, probable aviation hazards and noise emissions and by other local parameters. Because of the limitations in sizes of the units it is possible to install both energy technologies – solar and wind. Those combinations would increase rated power of the system with saving of approximately the same rate of financial benefits as for single-type system.

The power output from PV and wind turbines is varying annually and seasonally because of the weather conditions. However it does not affect significantly the company manufacturing process if it does not work independently and has a connection to the grid which could cover all the whole demand if necessary. Management and shifts in energy consumption, which is possible to implement in industrial applications, could increase financial benefits from a renewable system with rated power which exceeds the demand profile.

Annual variability in energy production is more significant for wind energy than for PV systems. This fact could affect the decision about PV or/and wind system installation, because all business companies are anxious about hardly-predictable uncertainties, especially for long-term investments as renewable energy systems.

This investigation of the case study shows that financial benefits for all types of systems (50kW PV, 50/100/330kW wind turbine) are similar. Payback period is varying from 5.8y for 330kW wind turbine to 8.1y for 50kW PV panels. This difference between sizes and renewable energy technologies is not a major factor in decision making. The other financial indicator - net present value - shows that all systems at the end of the life time after the payback would bring the amount of finance that is comparable with capital expenditures of each system respectfully. The internal rate of return for all systems is in-between 11.5 and 17.5% which exceed standard bank rates several times.

Additionally a company, which plans to install a renewable energy system, should be aware of Feed-in tariff rates because they make up about 70% of total annual income. FITs rates are decreasing from year to year (see annex, Figure 48) which decrease economic outcomes from renewables.

Environmentally, all systems would reduce carbon footprint of a company according to the energy outcome rate. Consequently, systems with higher rated power would cut CO_2 emissions more significantly. As for negative environmental issues, they are higher for wind energy than for PV because of noise emissions, effect on birds' life and visual impact.

To sum up, western Scotland territories are highly potential for solar and especially wind energy generation. Business companies, that have available resources and appropriate territory for a renewable system installation, should overview this possibility and take actions while the financial support from the UK government is substantial.

Further work

Despite a huge number of published papers about renewable energy resources, many of them do not provide real and trustworthy information. Various points about renewables are still unclear.

In this project, stable parameters, as energy generation and demand or operation and maintenance costs, were used for all calculations. In real life they are not the same and changes because of the different factors. For example, the performance of the same case-study energy system would be different if the company would significantly decrease energy consumption due to energy savings or changes in manufacturing processes. In further work it would be interesting to investigate this situation in terms of energy management and economic parameters.

The other potential area to investigate is uncertainties and risks that accompany renewable energy generation. It is extremely important to know all issues that the system could potentially have during exploitation. For this work it would be helpful to overview several similar installations to understand the factors that affect risks occurrence at different sites.

Annex

Table 21 UK wind farms in operation and under construction, 2011 (RenewableUK, 2011)

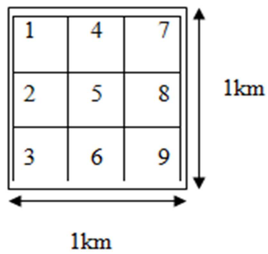
	Operational wind farms			Under construction		
Onshore	Country	Number	Power, MW	Country	Number	Power, MW
	England	109	848.49	England	10	144.33
	Northern Ireland	29	344.73	Northern Ireland	2	42.60
	Scotland	120	2,604.73	Scotland	19	1,178.57
	Wales	35	414.95	Wales	0	0.00
	Sum	293	4,212.90	Sum	31	1,365.50
Offshore	Country	Number	Power, MW	Country	Number	Power, MW
	England	11	1,364.80	England	6	2,054.40
	Northern Ireland	0	0.00	Northern Ireland	0	0.00
	Scotland	1	10.00	Scotland	0	0.00
	Wales	2	150.00	Wales	0	0.00
	Sum	14	1,524.80	Sum	6	2,054.40

Table 22 Values of roughness class and surface roughness length for various types of terrain (M.Ragheb, Wind Shear, Roughness Classes and Turbine Energy Production, 2011)

Roughness Class, RC	Roughness length z_o (m)	Landscape
0	0.0002	Water surface
0.5	0.0024	Completely open terrain with a smooth surface, such as concrete runways in airports, mowed grass.
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills.
1.5	0.055	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 1,250 meters.
2	0.1	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500 meters
2.5	0.2	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 250 meters.
3	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
3.5	0.8	Larger cities with tall buildings.
4	1.6	Very large cities with tall buildings and skyscrapers.

Table 23 Average wind speed at 10m height in Prestwick Airport and Killoch (Department of energy and climate change (A))

Height	Location	Prestwick Airport, m/s	Killoch, m/s	Difference, %
10m	1	5.4	6.0	11.1%
	2	5.5	6.2	12.7%
	3	5.6	5.7	1.8%
	4	5.2	6.0	15.4%
	5	5.3	6.1	15.1%
	6	5.4	5.8	7.4%
	7	5.2	5.5	5.8%
	8	5.2	5.8	11.5%
	9	5.4	5.7	5.6%
	Average	**5.4**	**5.9**	**9.6%**



Note: Location determines corners in a square kilometre with a centre (location 5) at each site.

Table 24 Example of wind speed calculations for 3rd of January

Day/time of measurement	Measured at Prestwick Airport, *H=10m, z_o=0.03m*, knots	Measured at Prestwick Airport, *H=10m, z_o=0.03m*, m/s	Added 9.6% difference, *H=10m, z_o=0.03m*, m/s	Calculated for Killoch, *H=10m, z_o=0.1m*, m/s	Calculated for Killoch, *H=25m, z_o=0.1m*, m/s
03/01/1989 00:00	9.00	4.64	5.08	4.03	4.66
03/01/1989 01:00	6.00	3.09	3.39	2.68	3.11
03/01/1989 02:00	6.00	3.09	3.39	2.68	3.11
03/01/1989 03:00	8.00	4.12	4.52	3.58	4.14
03/01/1989 04:00	7.00	3.61	3.95	3.13	3.63
03/01/1989 05:00	10.00	5.15	5.64	4.47	5.18
03/01/1989 06:00	8.00	4.12	4.52	3.58	4.14
03/01/1989 07:00	7.00	3.61	3.95	3.13	3.63
03/01/1989 08:00	9.00	4.64	5.08	4.03	4.66
03/01/1989 09:00	8.00	4.12	4.52	3.58	4.14
03/01/1989 10:00	14.00	7.21	7.90	6.26	7.25
03/01/1989 11:00	13.00	6.70	7.34	5.82	6.74
03/01/1989 12:00	12.00	6.18	6.77	5.37	6.22
03/01/1989 13:00	13.00	6.70	7.34	5.82	6.74
03/01/1989 14:00	12.00	6.18	6.77	5.37	6.22
03/01/1989 15:00	16.00	8.24	9.03	7.16	8.29
03/01/1989 16:00	15.00	7.73	8.47	6.71	7.77
03/01/1989 17:00	16.00	8.24	9.03	7.16	8.29
03/01/1989 18:00	17.00	8.76	9.60	7.61	8.81
03/01/1989 19:00	19.00	9.79	10.72	8.50	9.84
03/01/1989 20:00	17.00	8.76	9.60	7.61	8.81
03/01/1989 21:00	17.00	8.76	9.60	7.61	8.81
03/01/1989 22:00	20.00	10.30	11.29	8.95	10.36
03/01/1989 23:00	18.00	9.27	10.16	8.05	9.33
Average annual	**9.39**	**4.83**	**5.30**	**4.20**	**4.86**

Table 25 Wake behaviour of Variously Shaped Buildings (Meroney, 1977 cited in (Harry L. Wegley))

	Downwind distance (in terms of building heights, H)								
	5 H			10 H			20 H		
Building shape Width÷Height	Speed decrease , %	Power decrease, %	Turbulence increase, %	Speed decrease, %	Power decrease, %	Turbulence increase, %	Speed decrease, %	Power decrease, %	Turbulence increase, %
4	36	74	25	14	36	7	5	14	1
3	24	56	15	11	29	5	4	12	1
1	11	29	4	5	14	1	2	6	-
0.33	3	7	3	1	4	1	-	-	-
0.25	2	6	3	1	3	1	-	-	-
Height of the wake flow region (in building heights, H)	1.5 H			2.0 H			3.0 H		

Figure 39. Case-study location – Killoch, Scotland (Google maps)

Hyundai Solar Module HiS-S218SF

Mechanical Characteristics

Dimensions	983 mm (38.7") (W) × 1476 mm (58.11") (L) × 35 mm (1.38") (H)
Weight	Approx. 17.0 kg (37.5 lbs)
Solar cells	54 cells in series (6×9 matrix)
Output cables	4 mm² (12AWG) cables with polarized weatherproof connectors, IEC certified (UL listed), Length 1.0 m (39.4")
Junction box	IP65, weatherproof, IEC certified (UL listed)
Bypass diodes	3 bypass diodes to prevent power decrease by partial shade
Construction	Front : High transmission low-iron tempered glass, 3.2 mm (0.126") Encapsulant : EVA Back Sheet : Weatherproof film
Frame	Clear anodized aluminum alloy type 6063

Electrical Characteristics

| Mono-crystalline Type | | |

		218
Nominal output (Pmpp)	W	218
Voltage at Pmax (Vmpp)	V	27.2
Current at Pmax (Impp)	A	8.1
Open circuit voltage (Voc)	V	33.8
Short circuit current (Isc)	A	8.4
Output tolerance	%	+3/-0
No. of cells & connections	pcs	54 in series
Cell type	–	6" Mono
Module efficiency	%	15.0
Temperature coefficient of Pmpp	%/K	-0.44
Temperature coefficient of Voc	%/K	-0.34
Temperature coefficient of Isc	%/K	0.052

Figure 40 Hyundai Solar Module HiS-S218S, technical data (Hyundai Solar, 2010)

Model	STP 17000TL-10	STP 10000TL-10
Scope of applications		
MPP voltage range	400 - 800 V	320 - 800 V
Open circuit voltage	1000 V	1000 V
Max. input current (Input A / Input B)	33 A / 11 A	22 A / 11 A
MPP tracker	2 pc.	2 pc.
Nominal output	17000 W	10000 W
Output voltage	230 / 400 V, three-phased	230 / 400 V, three-phased
Power factor cos phi	1	1
Frequency	50 Hz ±5 Hz	50 Hz ±5 Hz
Harmonic distortion	< 4 %	< 4 %
Max. efficiency	98.2 %	98.1 %
Euro efficiency	97.7 %	97.7 %
Night-time consumption	< 1 W	< 1 W
Ambient temperature	-25 to +60 °C	-25 to +60 °C
Relative humidity	0 to 98 %, no condensation	0 to 98 %, no condensation
Heat dissipation	OptiCool fan	OptiCool fan
Protection mode	IP65	IP65
Circuit type	Transformerless, three-phased	Transformerless, three-phased
Grid monitoring	SMA Grid guard	SMA Grid guard
Fault current monitoring	Fault current monitoring according to VDE 0126	Fault current monitoring according to VDE 0126
Display	LCD graphics display	LCD graphics display
Casing	Aluminium	Aluminium
Dimensions (W / H / D)	665 mm / 690 mm / 265 mm	665 mm / 690 mm / 265 mm
Weight	65 kg (approx.)	65 kg (approx.)
Warranty *	5 years	5 years
Norms	CE mark, VDE 0126-1-1:2006-02, G83, G59/2	CE mark, VDE 0126-1-1:2006-02, G83, G59/2

Figure 41 Technical data, Sunny Tripower invertors, STP 17000/10000TL-10 (Sunny Tripower (A)), (Sunny Tripower (B))

Endurance wind power
we power the future

Turbine

Configuration	3 blades, horizontal axis, downwind
Rated power @ 9.5 m/s	50kW
Applications	Direct grid-tie
Rotor speed	42 rpm
Cut-in wind speed	3.5 m/s (7.8 mph)
Cut-out wind speed	**25 m/s (56 mph)**
Survival wind speed	**52 m/s (116 mph)**
Overall weight	**3 990 kg (8 800 lbs)**

Rotor

Rotor diameter	19.2 m (63.0 ft)
Swept area	290 m² (3120 ft²)
Blade length	9.00 m (29.5 ft)
Blade material	Fiberglass/Polyester
Power regulation	Stall control (constant speed)

Generator

Type	Induction generator
Configurations	3ϕ, 480 VAC or 600 VAC @ 60 Hz 1ϕ, 240VAC @ 60Hz

Brake & Safety Systems

Main brake system	Rapid fail-safe dual mechanical brakes
Secondary safety	Pitch control system (for over-speed regulation) using passive, spring-loaded mechanism
Automatic shut down triggered by :	- High wind speed - Grid failure - Over-speed - All other fault conditions

Controls

Control System	Programmable logic controller (PLC)
User interface	Wireless or wired network software interface for remote monitoring and control

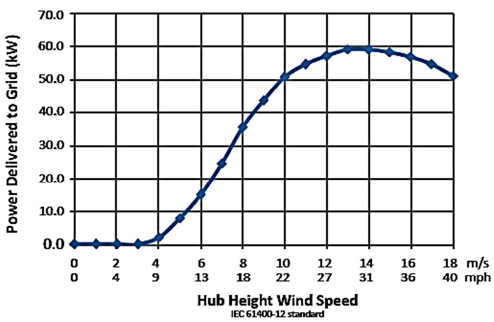
Warranty

Turbine & controls	5 years parts and labour

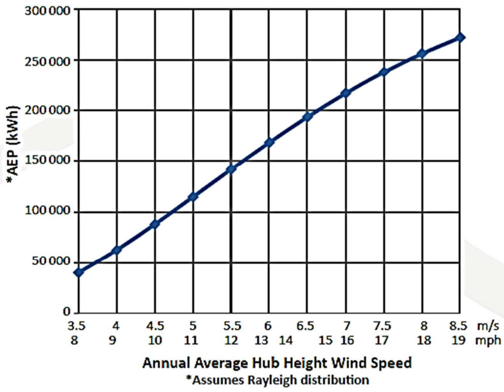
Towers

Free-standing monopole or lattice:	30.5m (100 ft), 36.5m (120 ft), 42.7m (140 ft)
Maintenance access	Safe climbing system Working space inside the nacelle Tower-top work platform

Power Curve



Annual Energy Production (AEP)



Annual Average Hub Height Wind Speed (m/s)	Annual Energy Production (kWh)
3.5	40 100
4.0	62 500
4.5	88 000
5.0	114 900
5.5	142 200
6.0	168 900
6.5	194 300
7.0	217 700
7.5	238 800
8.0	257 200
8.5	273 000

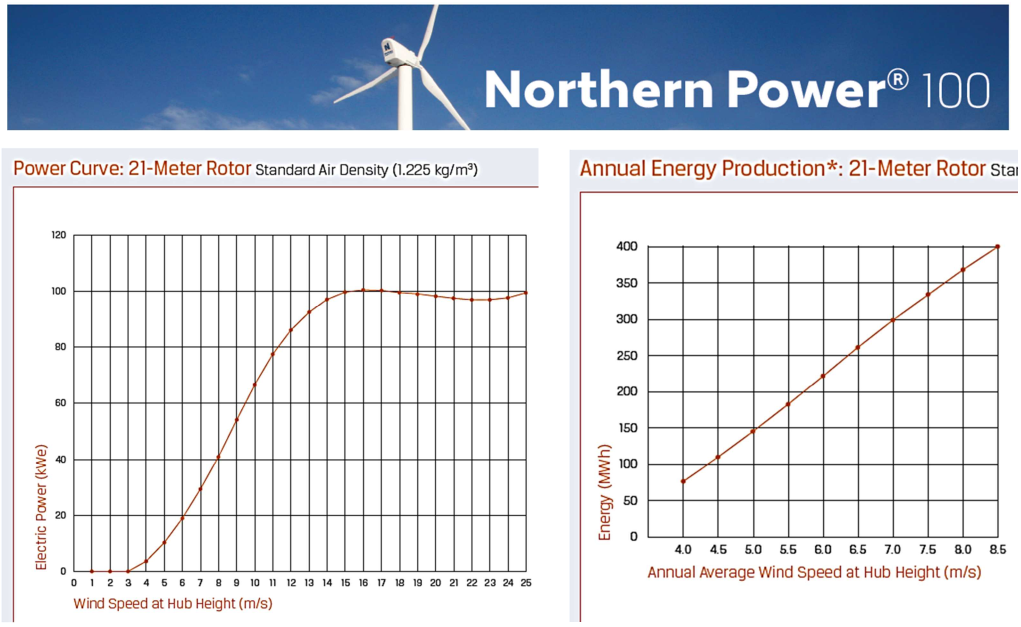
Wind Speed Conversion Table

m/s	4	5	6	7	8	9	10	11	12	14
km/h	14	18	22	25	29	32	36	40	43	50
mph	9	11	13	16	18	20	22	25	27	31

www.endurancewindpower.com
info@endurancewindpower.com

CE bullfrogpower
Endurance Wind Power uses 100% renewable energy at its head office and manufacturing plant

Figure 42, Endurance 50kWE-3120, technical data (Endurance)



GENERAL CONFIGURATION	DESCRIPTION
Model	Northern Power® 100
Design Class	IEC IIA (air density 1.225 kg/m³, average annual wind below 8.5 m/s, 50-yr peak gust below 59.5 m/s)
Design Life	20 years
Hub Height	37 m (121 ft) / 30 m (98 ft)
Tower Type	Tubular steel monopole
Orientation	Upwind
Rotor Diameter	21 m (69 ft)
Power Regulation	Variable speed, stall control
Certifications	UL1741, UL1004-4, CSA C22.2 No.107.1-01, CSA C22.2 No. 100.04, and CE compliant
PERFORMANCE	**DESCRIPTION** (standard conditions: air density of 1.225 kg/m³, equivalent to 15°C (59°F) at sea level)
Rated Electrical Power	100 kW, 3 Phase, 480 VAC, 60/50 Hz
Rated Wind Speed	14.5 m/s (32.4 mph)
Maximum Rotation Speed	59 rpm
Cut-In Wind Speed	3.5 m/s (7.8 mph)
Cut-Out Wind Speed	25 m/s (56 mph)
Extreme Wind Speed	59.5 m/s (133 mph)
WEIGHT	**DESCRIPTION**
Rotor (21-meter) & Nacelle (standard)	7,200 kg (16,100 lbs)
Tower (37-meter)	13,800 kg (30,000 lbs)
DRIVE TRAIN	**DESCRIPTION**
Gearbox Type	No gearbox (direct drive)
Generator Type	Permanent magnet, passively cooled
BRAKING SYSTEM	**DESCRIPTION**
Service Brake Type	Two motor-controlled calipers
Normal Shutdown Brake	Generator dynamic brake and two motor-controlled calipers
Emergency Shutdown Brake	Generator dynamic brake and two spring-applied calipers
YAW SYSTEM	**DESCRIPTION**
Controls	Active, electromechanically driven with wind direction/speed sensors and automatic cable unwind
CONTROL/ELECTRICAL SYSTEM	**DESCRIPTION**
Controller Type	DSP-based multiprocessor embedded platform
Converter Type	Pulse-width modulated IGBT frequency converter
Monitoring System	SmartView remote monitoring system, ModBus TCP over ethernet
Power Factor	Set point adjustable between 0.9 lagging and 0.9 leading
Reactive Power	+/- 45 kVAR
NOISE	**DESCRIPTION**
Apparent Noise Level	55 dBA at 30 meters (98 ft)
ENVIRONMENTAL SPECIFICATIONS	**DESCRIPTION**
Temperature Range: Operational	-20°C to 50°C (-4°F to 122°F)

Figure 43 Northern Power 100kW wind turbine technical specification (Northern wind)

Enercon E-33, 330kW

Technical specifications E-33

Rated power:	330 kW
Rotor diameter:	33.4 m
Hub height:	37 m / 44 m / 49 m / 50 m
Wind zone (DIBt):	WZ III
Wind class (IEC):	IEC/NVN IA and IEC/NVN IIA
WEC concept:	Gearless, variable speed Single blade adjustment
Rotor	
Type:	Upwind rotor with active pitch control
Rotational direction:	Clockwise
No. of blades:	3
Swept area:	876 m²
Blade material:	GRP (epoxy resin); Built-in lightning protection
Rotational speed:	Variable, 18 – 45 rpm
Pitch control:	ENERCON single blade pitch system; one independent pitch system per rotor blade with allocated emergency supply

Drive train with generator	
Hub:	Rigid
Main bearing:	Tapered roller bearing pair
Generator:	ENERCON direct-drive annular generator
Grid feed:	ENERCON inverter
Brake systems:	– 3 independent pitch control systems with emergency power supply – Rotor brake – Rotor lock
Yaw system:	Active via yaw gear, load-dependent damping
Cut-out wind speed:	28 – 34 m/s (with ENERCON storm control*)
Remote monitoring:	ENERCON SCADA

*For more information on the ENERCON storm control feature, please see the last page.

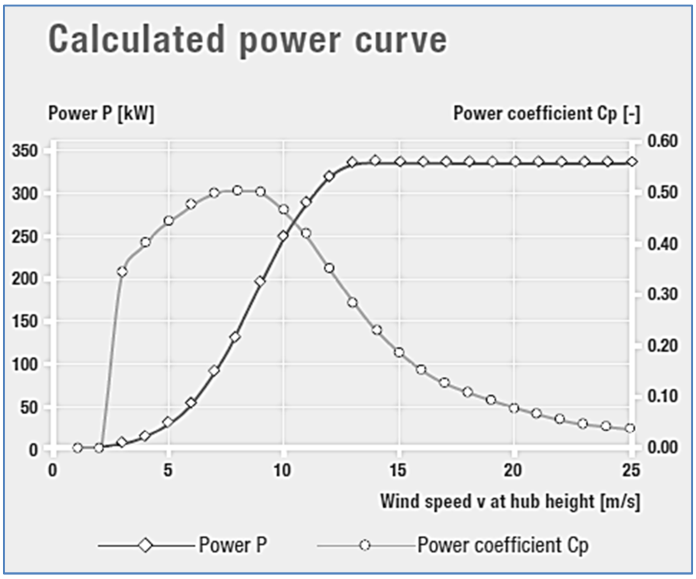


Figure 44 Enercon E-33/330kW wind turbine technical specification (Enercon, 2010)

Figure 45 Site of wind turbines locations (shown as white stars). Letters identify the nearest dwellings. Google maps

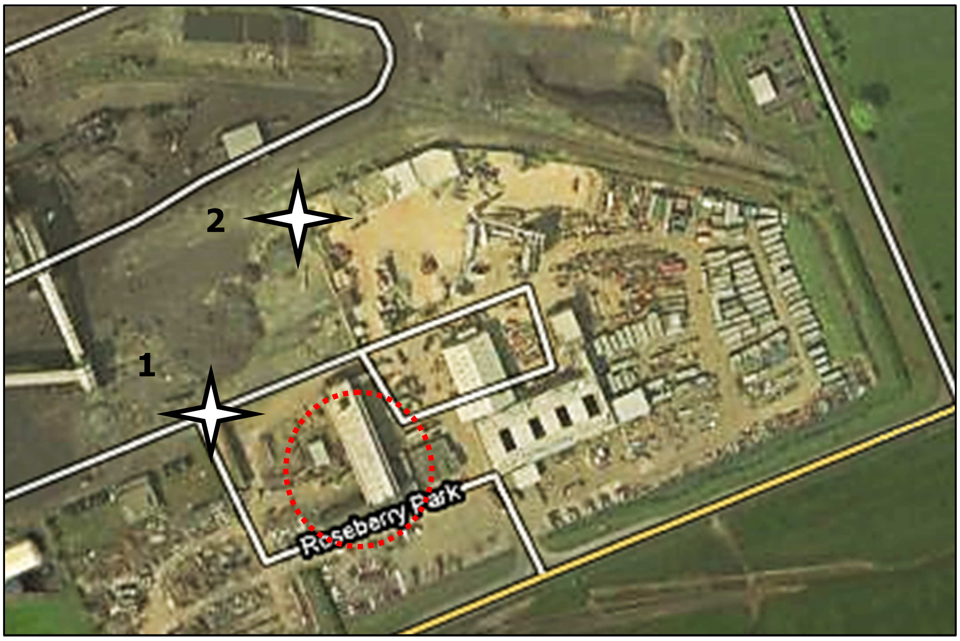


Figure 46 Main office building location (red line) relative to proposed wind turbine sites 1/2

Table 26 Visual impact of wind turbines at Killoch (turbines location 1)

View	Comments
	Normal view of the main office without a wind turbine
	50kW (25m hub, 9.6m blade length) wind turbine installed behind the main office

	100kW (37m hub, 10.5m blades length) wind turbine installed behind the main office
	330kW (50m hub, 16.7m blades length) wind turbine installed behind the main office

Google maps resource is used to generate views.

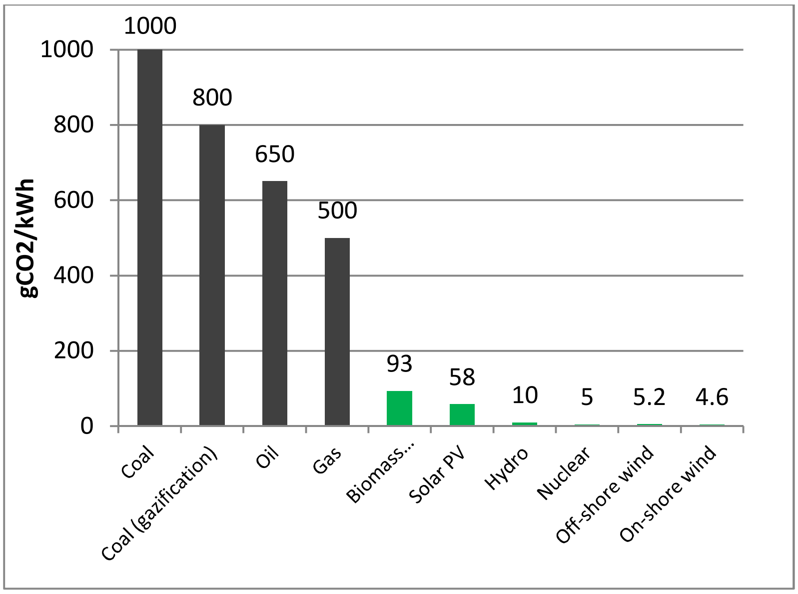
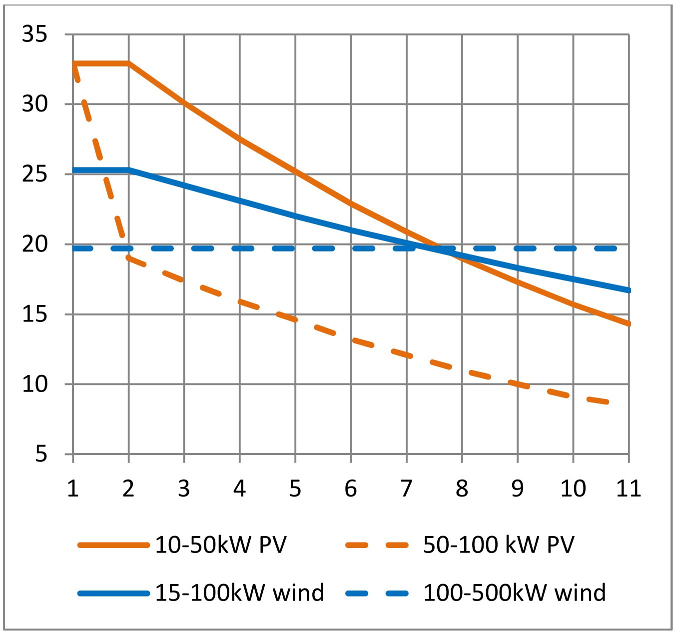


Figure 47 Life-cycle carbon footprint of different power generation technologies, grey – fossil fuels, green – low carbon technologies (Parliamentary Office of Science and Technology, 2006)



Note: year 1 is 2010/2011 starting from 1/04/10.

Figure 48 Examples of FIT rates changes for different years (Ofgem, 2011)

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