WIND POWERED THERMAL ENERGY SYSTEMS (WTES)

A TECHNO-ECONOMIC ASSESSMENT OF DIFFERENT CONFIGURATIONS

MASTER THESIS OF

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POSTGRADUATE PROGRAMME RENEWABLE ENERGY

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ABSTRACT

Within the framework of a world population growth that would reach 8.9 billon inhabitants by 2050 (UN, 2004), energy supply will face major challenges regarding a sustainable dispatch, and particularly, in mitigating climate change.

In 2013, 81% of the world primary energy demand was covered by fossil fuels and the carbon dioxide (CO_2) emissions were around 31.6 Gt (IEA, 2015). Concerning the final energy demand, during 2011 the global energy use for heat reached 172 EJ (one-third of the global primary energy supply). Moreover, three-quarters of the final energy use for heat (FEH) was provided by fossil fuels (IEA, 2014).

Projections for the upcoming years developed by the International Energy Agency (IEA, 2015) seem not to be very auspicious and, undoubtedly, the energy sector will go through a natural transformation, shifting from fossil fuels to renewable energy technologies, but this will only be feasible if the proper incentives are encouraged.

Despite the economic competitiveness of variable renewable energies, if only Levelized Cost of Energy (LCOE) is regarded, their weather-dependant generation characteristic is one of the first barriers to overcome when analysing its large scale integration into the system. Thus, the deployment of different storage systems rises up as the immediate solution. However, many of the currently commercially available large storage units can only be built at certain locations (i.e. pumped storage) and the transportable energy storage systems, such as lithium-ion or redox flow batteries, present relatively high investment costs (Battke, Schmidt, Grosspietsch, & Hoffmann, 2013).

Consequently, a new cost-effective concept of dispatchable, geographically and time independent wind power systems is needed. Ergo, the Wind powered Thermal Energy System (WTES) concept is conceived. This concept is based on the conversion of wind power into heat, followed by a cost-effective and efficient storage for on-demand electricity generation by heat engines, combining the systemic benefits of steam power plants with the use of wind power.

In this thesis different WTES concepts, which can be developed with commercially available devices, are techno-economically assessed focusing on the conversion of wind power into heat and the following thermal storage. No reconversion of heat into electricity is considered. Firstly, five different heat generation concepts for WTES are investigated based on literature research: electric boiler (EB), electrical driven HP (eHP), mechanical driven HP (mHP), retarder (RET) and

absorption HP (AHP). Three different system sizes, as far as final heat demand is concerned, are analysed: 23.6 MWh/yr – 11,800 MWh/yr – 118,000 MWh/yr.

Furthermore, the five WTES concepts are ranked based on the Levelized Cost of thermal Energy ($LCOE_{HEAT}$) taking into account their average Capital Expenditures (CAPEX) and Operational Expenditures (OPEX), also considering different capacity factors (CF) and a life span of 20 years. On top of that, in order to develop cost intervals for each concept and, therefore, analyse possible costs deviations, two different scenarios for each technology are assumed: Maximum scenario, which accounts for the maximum CAPEX and OPEX reviewed, and Minimum scenario, which accounts for the minimum CAPEX and OPEX reviewed.

Moreover, an additional analysis for large systems is performed regarding the $LCOE_{HEAT}$ variation as function of the distance between the WTES windfarm and the final heat demand and it aims to analyse the maximum distance cost-achievable.

Every analysis developed within this thesis is compared with traditional heat generation sources so as to estimate the economic feasibility of the WTES.

Finally, results show that small system presents remarkably higher LCOE when compared with medium/large systems, mainly drive by its more than 3 times higher capital expenditures (CAPEX) and, small system's most cost-convenient WTES technology is mHP which presents lower LCOE along the entire CF spectrum. As far as medium and large system is concerned, both system sizes present promising heat generation costs, as far as LCOE is concerned. They differ only in the fact that large system presents lower costs manly drive by the economies of scale considered. Furthermore, it is interesting to point out that in large systems when CFs lower than 0.25 are considered, RET technology presents LCEO which are slightly higher (15%) than those obtained by mHP. Moreover, all technologies can be considered as cost-effective alternatives, even when low CFs are analysed.

Further research is necessary to analyse if WTES are an efficient and cost-effective solution for large variable renewable energies. Detailed assessments concerning thermal energy storage and technologies cost breakdowns are needed in order to optimize the costs involved.

DECLARATION

I state and declare that this thesis was prepared by me in accordance with the best practice guidelines for scientific work of the University of Oldenburg and that no means or sources have been used, except those, which I cited and listed in the References section.

Stuttgart, 29th of February 2016

Alejandro Nicolás Nitto

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Acronyms

AC	Alternating current
AEP	Annual Energy Production
AHP	Absorption Heat Pump
BN€	Billion Euros
CAPEX	Capital Expenditures
CF	Capacity Factor
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CSP	Concentrating Solar Power
DFIG	Doubly Fed Induction Generator
EB	Electric Boiler
EHP	Electrical driven Heat Pump
EJ	Exajoule
FEH	Final Energy use for Heat
GDP	Gross Domestic Product
GHG	Greenhouse gases
GT	Gigatonne
HDR	Hydrodynamic Retarder
HP	Heat Pump
KWH	Kilowatt hour
LCOE	Levelized Cost of Energy
$LCOE_{ELECTRICITY}$	Levelized Cost of electrical Energy
$LCOE_{HEAT}$	Levelized Cost of thermal Energy
M^3	Cubic meters
MHP	Mechanical driven Heat Pump

MTOE	Million tonnes of oil equivalent
MW	Megawatt
O&M	Operation and Maintenance
OECD	Organization for Economic Cooperation and Development
OPEX	Operational Expenditures
PCM	Phase Change Material
PHES	Pumped Heat Energy Storage
PV	Photovoltaic
RE	Renewable Energy
RET	Retarder
TCM	Trillion cubic meters
TCS	Thermo-Chemical Storage
TES	Thermal Energy Storage
TW	Terawatt
TWH	Terawatt hour
USD	United State Dollars
WEC	Wind Energy Converter
WTES	Wind powered Thermal Energy Systems

INTRODUCTION

Within the framework of a world population growth that would reach 8.9 billon inhabitants by 2050, representing an increase of 47% compared to 2000 values (UN, 2004), and considering that “fossil fuels provided 85% of the total primary energy in 2004, which is the same value as in 2008” (IPCC, 2012), energy supply will face major challenges regarding a sustainable dispatch, and particularly, in mitigating climate change.

According to (IEA, 2015), in 2013 the world primary energy demand reached a peak of 13,560 million tonnes of oil equivalent (Mtoe), which represented an increase of 55% compared to 1990. Under the current policies scenario proposed by the author, a growth of a further 45% to 2040 is projected. Regarding the energy matrix, by 2013, 81% of the world primary energy demand was covered by fossil fuels and the carbon dioxide (CO_2) emissions were around 31.6 Gt. Under the current policies scenario, the author estimates that by 2020 CO_2 emissions will reach 34.2 Gt and by 2040 44.1 Gt. This increasing tendency will take place despite the fact that fossil-fuel shares of the world primary energy demand will be reduced to 79% by 2040. Considering this projections, the need of low carbon energy generation arises and, as oil and gas are becoming more and more expensive to extract (IEA, 2015), renewable energies emerge as a cost-efficient alternative powered by these costs trends.

Concerning the final energy demand, heat production in power generation has a significant impact on it. According to (IEA, 2014), during 2011 the global energy use for heat in industry, buildings and other sectors reached 172 EJ (one-third of the global primary energy supply). Moreover, three-quarters of the final energy use for heat (FEH) was provided by fossil fuels, which led to CO_2 emissions around 10 Gt per year (one-third of the global total in the energy sector for that year).

The use of energy for heating purposes is expected to continue growing in the upcoming future (IEA, 2014). Unfortunately, renewable energy (RE) plays, so far, a negligible role in the heat sector (with the exception of the traditional use of biomass for cooking and heating). However, some RE technologies, which are commercially available nowadays, can supply green, sustainable and cost-effective heat and, with the appropriate incentives, they can be even competitive with fossil fuel based heat generation sources (IEA, 2014).

In the report presented by (UNEP, 2015), the author analyses the levelized cost of heat production (equivalent to the Levelized Cost of Energy - LCOE[1]) for different traditional heating sources. As a result, the author concludes that the $LCOE_{HEAT}$ for a medium size woodchip Combined Heat and Power (CHP) plant ranges between 9-11 cUSD/kWh, while a woodchip boiler presents a $LCOE_{HEAT}$ ranging between 8-11 cUSD/kWh, a traditional gas boiler ranges between 6-7.5 cUSD/kWh and a Combined Cycle Gas Turbine (CCGT) - CHP plant has a $LCOE_{HEAT}$ between 4-7 cUSD/kWh.

Regarding the RE costs for electricity production, many studies have been developed i.e. (IRENA I. R., 2015). Renewable power generation is now competing head-to-head with fossil fuel-fired electricity generation options, which present a $LCOE_{ELECTRICITY}$ ranging between 4.5-14 cUSD/kWh. Currently, three renewable technologies compete directly with fossil fuel: hydropower (average $LCOE_{ELECTRICITY}$ around 5 cUSD/kWh), biomass-generated electricity ($LCOE_{ELECTRICITY}$ ranging between 3-6 USD/kWh) and geothermal power generation ($LCOE_{ELECTRICITY}$ ranging between 4-10 cUSD/kWh). However, onshore wind power is becoming a direct rival from these technologies since its $LCOE_{ELECTRICITY}$, in 2013 and 2014, ranged between 6-8 USD/kWh. Solar photovoltaics (PV), concentratin solar power (CSP) and Offshore wind power are fallen behind with average $LCOE_{ELECTRICITY}$ ranging between 11-30 cUSD/kWh, 17-35 cUSD/kWh and 10-21 cUSD/kWh respectively (IRENA I. R., 2015).

Despite its economic competitiveness if only LCOE is regarded, the weather-dependant generation characteristic of wind power is one of the first barriers to overcome when analysing its large scale integration into the system. Thus, the deployment of different storage systems rises up as the immediate solution. However, many of the currently commercially available large storage units can only be built at certain locations (i.e. pumped storage) and the transportable energy storage systems, such as lithium-ion or redox flow batteries, present relatively high investment costs (Battke, Schmidt, Grosspietsch, & Hoffmann, 2013). In this context, experts have already pointed out that "countries considering a transition to power systems based on renewables must look closely at electricity storage options. Storage should not be considered an end in itself. Rather, it is a mean to support a reliable, efficient, cost-effective and clean power sector by facilitating the deployment and integration of renewables" (IRENA I. R., 2015).

Consequently, a new cost-effective concept of dispatchable, geographically and time independent wind power systems is needed. Ergo, the Wind powered Thermal Energy System (WTES) concept is conceived. This concept is based on the direct conversion of wind power into

[1] Please refer to the Methodology section for a detailed explanation about how is estimated.

heat, followed by a cost-effective and efficient storage for on-demand electricity generation by heat engines, combining the systemic benefits of steam power plants with the use of wind power. This innovative and state-of-the-art system may represent a significant step forward concerning the wind power integration on the power system, providing an alternative firm and flexible power generation.

Since not any analyses concerning the renewable energy costs for heat production has yet been done, the present work is based on the LCOE assessment for RE heat production.

OBJECTIVE

The focus of this thesis is on the identification of potentials and feasibility for WTES concepts, which can be implemented with commercially available components already. This work intends to assess different WTES-concepts regarding their heat production and following thermal storage. The assessment for the reconversion of heat into electricity is out of the scope of the present work.

For this purpose, the following questions need to be addressed:

a. Which concepts of Wind powered Thermal Energy Systems are technically feasible taking into account the state of the art? Which are the substantially characteristics they differ in? What are the advantages and disadvantages of different WTES-configurations?
b. Which costs are involved in WTES-concepts that can already be implemented with commercially available components?

Background

This chapter gives an overview of the energy sector and also about the different components involved in WTES. Firstly, the dominant position of fossil fuels within the energy sector is explained and, then, heat and electricity production sectors are described. Afterwards, wind energy technology is presented, detailing different technologies, components, energy assessment and costs. The next section gives an overview of different heat generator technologies, investigating their different working principles, advantages/disadvantages and costs. The last section describes different thermal energy storage, regarding their working principles and costs.

At this point, a brief introduction of the proposed WTES concepts is required in order to understand why particular technologies are explained in the following background.

The present work assesses five WTES concepts, which present particular characteristics. The first concept proposed is a traditional wind energy converter, followed by an electric boiler for heat generation purposes. The second concept also consists of a traditional wind energy converter but the electric boiler is replaced with an electrical driven heat pump. Both concepts are framed as “indirect heat generation” concepts, since the wind energy is not directly transformed into thermal energy, but firstly converted into electricity.

The remaining WTES concepts are considered as “direct heat generators” and, in order to avoid the intermediate electrical energy conversion, some components are not going to be taken into account. Then, the third concept consists of a wind energy converter, without all the electrical generation devices, followed by a heat pump without the motor (mechanical driven heat pump). The fourth WTES concept replaces the mechanical driven heat pump with a retarder, which is a well-known technology for vehicles brakes. Finally, the last concept adds an absorption heat pump next to the retarder.

Energy Sector

The first milestone for understanding how this sector is structured is *the energy price* itself. The price is considered as one of the key drivers of energy trends and one of the most influential triggers for consumers when deciding which fuel they decide to consume.

Historically, the energy sector has been dominated by fossil fuels. In 2013 the world primary energy demand reached peak of 13,560 Mtoe, which represents an increase of 55% compared to 1990. From these 13,560 Mtoe around the 81% was covered by fossil fuels: Coal 3,929 Mtoe (28.97%), Oil 4,219 Mtoe (31.11%) and Gas 2,901 Mtoe (21.39%) (IEA, 2015).

Concerning the oil prices, it has been historically high and between 2010 and 2014 each barrel was traded at 115 USD, but during 2015 it collapsed more than 50% and it was settled in the range of 40-60 USD/barrel (IEA, 2015).

On the topic of the natural gas prices, there is no global pricing benchmark, as there is for oil and, therefore, the prices spread between regions. The three most important regional markets are: North America, Asia-Pacific and Europe. Each of these markets present different price mechanisms but a detailed explanation about them is out of the scope of the present work.

Regarding the coal prices, the also present geographical spread markets, classified by coal quality, infrastructure and, of course, location. During the last 4 or 5 years coal prices are under a decreasing tendency and one of the reasons is the displacement of coal by the cheap shale gas produced in North America. However, coal, which is the most carbon-intensive fossil fuel, has attained in 2013 its highest shares of the energy mix for at least 40 years (IEA, 2015).

Following Table 1 shows the import prices of fossil-fuels so as to have an idea of the relation between them.

Table 1 - 2014 fossil-fuel import price - Source (IEA, 2015)

IEA Crude Oil imports [USD/barrel]	97
Natural Gas [USD/MBtu]	
United States	4,4
Europa imports	9,3
Japan imports	16,2
OECD steam coal imports [USD/tonne]	78

The estimated global remaining oil resources by the end of 2014 were around 6,100 billion barrels. As Figure 1 depicts, the world's proven oil reserves by the end of 2014 were around 1.700 billion barrels; the proven coal reserves, by the end of 2013, they were estimated around 968 billion tonnes and the proven natural gas reserves, by the end of 2014, were estimated around 216 trillion cubic meters (tcm) (IEA, 2015).

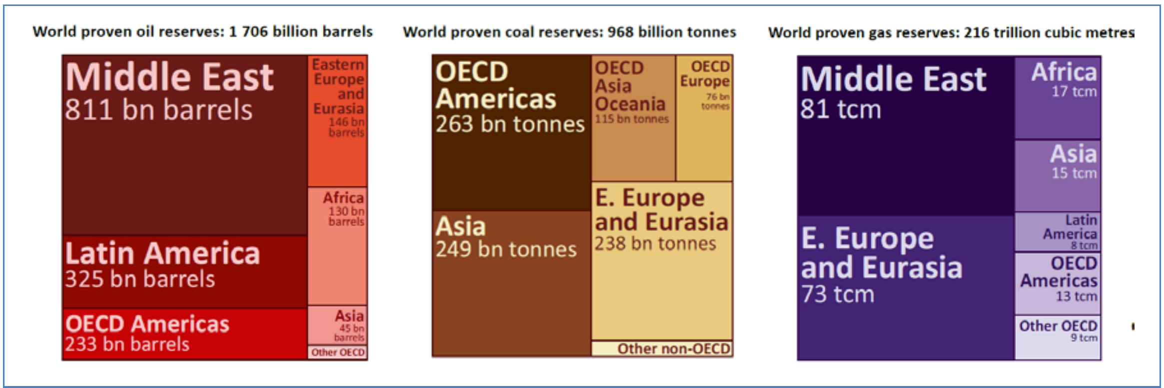


Figure 1 –World proven reserves for Oil, Coal and Gas - Source (IEA, 2015)

Considering the fact that the extraction of oil and gas is becoming more and more expensive and also the environmental impact of these fuels, the need of a low carbon energy generation arises and, as a result, renewable energies emerge as a potential alternative.

Heat Production Sector

Energy sources and end users are very assorted, heat can be produced and consumed at many scales, from very small domestic applications to large-scale use in industrial processes or district heating networks. It can be produced from different fuels and be provided at different temperature levels. Unfortunately, as Figure 2 schematically depicts, RE plays, so far, a negligible role in the heat sector (with the exception of the traditional use of biomass o cooking and heating, where out of the 54 EJ of primary bioenergy supply in 2011, more than 80% were used for heat production in buildings) (IEA, 2014).

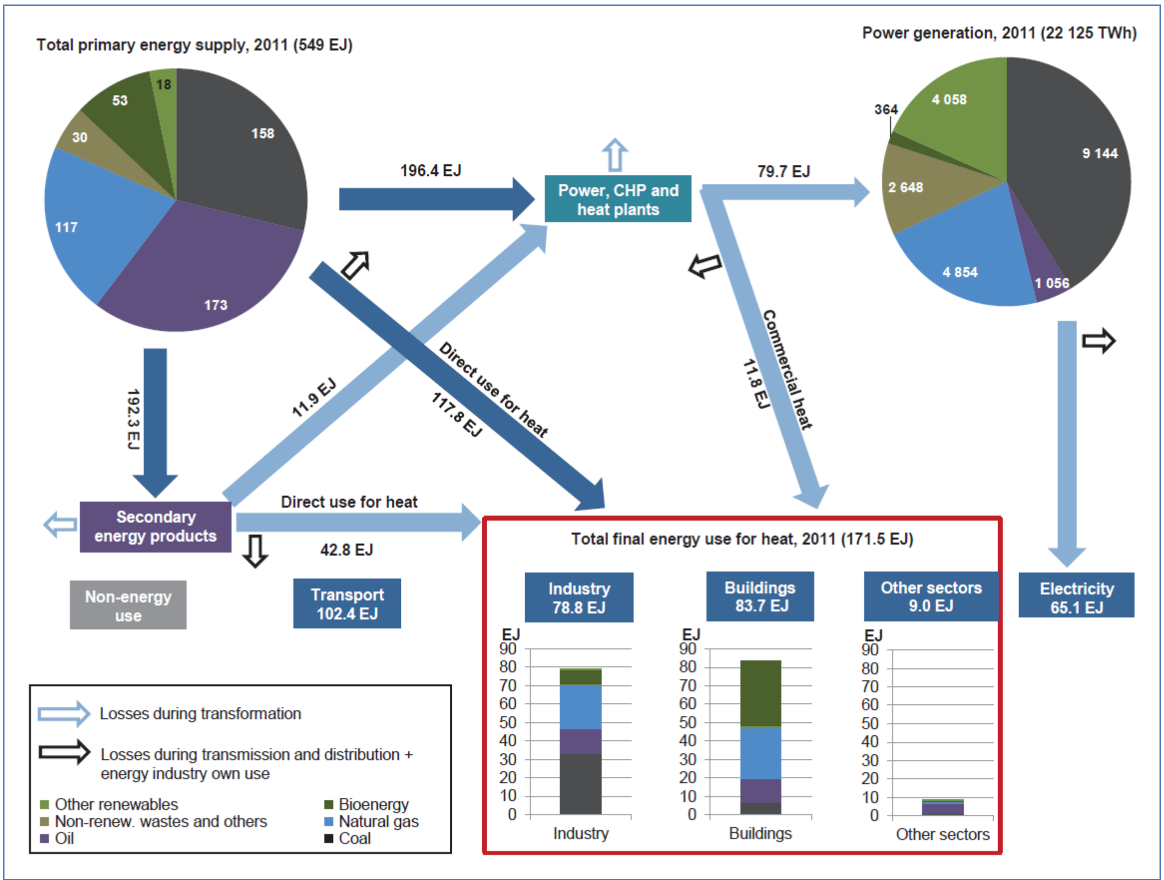


Figure 2 – Schematic overview of energy flows from total primary energy supply (TPES) to total FEH - Source (IEA, 2014)

When analysing the implication of different fuel sources for the total global FEH: "More than 40% of primary energy supply of natural gas is used for heat production in industry and buildings and around 20% each of world primary supply of coal and oil are used for the same purpose" (IEA, 2014).

As far as renewable energies for heat generation are concerned, some technologies, which are commercially available nowadays, can supply green, sustainable and cost-effective heat and, with the appropriate incentives, they can be even competitive with fossil fuel based heat generation sources. RE sources can produce and use heat by the direct use of it or through feeding the heat into district heating networks for heat in buildings or industry. Additionally, RE can be used to generate electricity, which can then be turned into heat. Figure 3 provides an overview of possible processes to convert RE into heat.

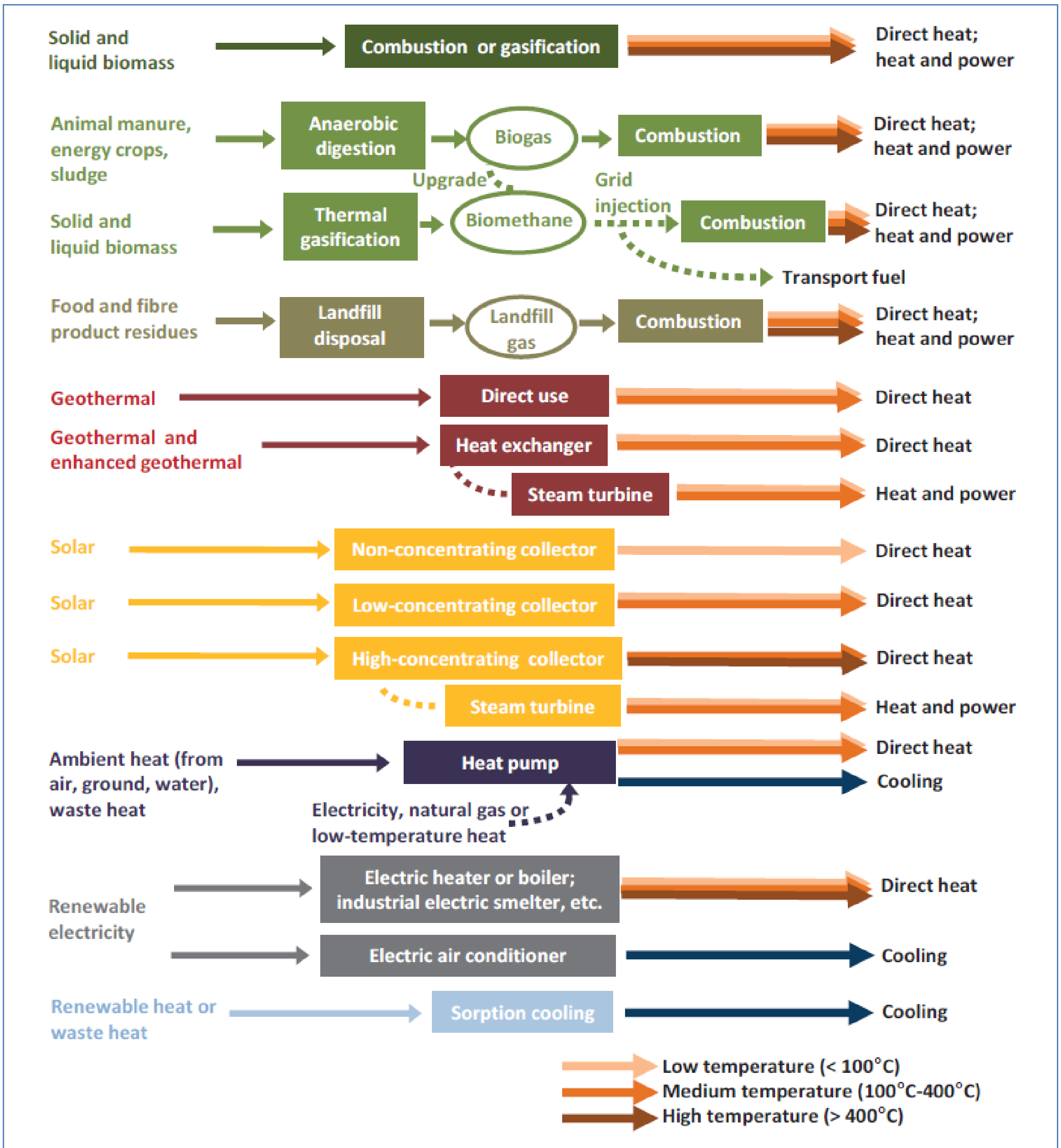


Figure 3 – RE sources and main technologies to convert them into direct heat and heat and power - Source (IEA, 2014)

Additionally, Figure 4 presents the commercially available RE technologies for heat production. Neither Figure 3 nor Figure 4, both developed by (IEA, 2014), consider the direct conversion from wind into heat, main characteristic of wind powered thermal energy systems, supporting the motivation of the present work.

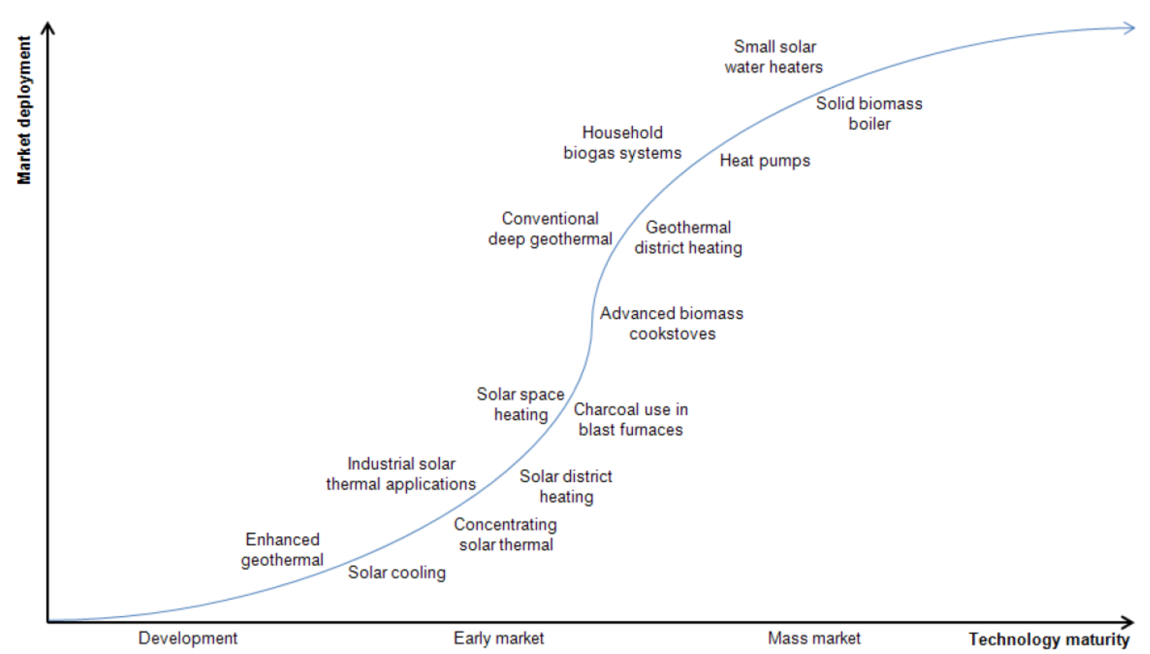


Figure 4 – The current state of market development of renewable energy heating and cooling technologies (IEA, 2014).

ELECTRICITY SECTOR

The trend in the electricity sector can be explained by the trends in the economic sector. From 1990-2013 the electricity demand roughly doubled and, if the global gross domestic product (GDP) evolution is analysed, it could be observed that it has also doubled its value. This relationship between GDP and electricity demand is, to some extent, dependent on the level of economic development of the country under analysis and the extent of access to electricity of that country among many other parameters.

By the end of 2013, global electricity demand reached around 20,144 TWh. Roughly 40% was used for industry purposes, 30% for residential, 25% for services and the remaining 5% is divided between transport, agriculture and other purposes. Concerning power generation, the global electricity matrix is still ruled by fossil fuels and the power sector accounts for more than 40% of total energy-related CO_2 emissions today. Fossil fuels provide two-thirds of global power generation, and renewable energy generation (hydropower excluded) holds only 6% of the total shares. Still, all renewables helped avoid an estimated 3.1 Gt of CO_2 emissions in 2013, equivalent to 25% of the total power sector CO_2 emissions (IEA, 2015).

In order to fulfil the forthcoming climate change challenges, renewable energies may be considered as one of the most promising alternatives. Then, as a result of a joint effort from policy makers, countries representatives and technology manufacturers, over the last decade 318 GW of hydropower were built, followed by wind power (318 GW) and solar PV (173 GW).

Furthermore, between 2000 and 2014, global investment in renewables for power generation totalled $2.5 trillion (around $165 billion per year) ((IEA, 2015) (IRENA I. R., 2015)).

The following technology overview is based on the report "World energy Outlook 2015" presented by the International Energy Agency (IEA, 2015) and on the report "Renewable power generation cost in 2014" presented by the International Renewable Energy Agency (IRENA I. R., 2015).

Wind: during 2014, 48 GW were added worldwide, led mostly by onshore developments, due to its declining LCOE. By the end of 2014, the total installed wind capacity reached 370 GW, mainly in China, US, Germany, Spain, India and UK. Offshore wind farms still depend critically on financial support from governments.

PV: During 2013, the cumulative installed capacity reached 40 GW, and by the end of 2014 a total installed PV capacity reached 180 GW. The European Union accounts for more than three quarters of solar PV capacity in 2010.

CSP: This technology is still in its infancy; at the end of 2014 the total installed capacity reached 5 GW worldwide.

Hydropower: due to its inherent relatively low LCOE it leads the RE technologies. Between 1971 and 2013 it helped avoid 64 Gt of CO_2 emissions globally. 36 GW were added during 2014, and the total installed capacity reached 1061 GW.

Bioenergy: it presents the advantage that when the feedstocks are plentiful and available at low cost, it results in a relatively low LCEO which can compete directly with fossil-fuelled power plants. Together with hydropower it is the most mature renewable energy technology. By the end of 2014, the total installed capacity was estimated around 89 GW.

Geothermal: Is a mature technology which can be considered as low-cost base load capacity when the resource is available (hot springs). However, when analysing hot dry rock systems this technology cannot be considered as low-cost base load capacity. 528 MW were added during 2014, and the total installed capacity reached 12.6 GW.

Concerning the cost of the renewable energy technologies, the LCOE is a commonly used parameter to compare different technologies. As Figure 5 shows, fossil fuel power costs range between 0.045 and 0.14 USD/kWh. From 2010 to 2014, hydropower, biomass and geothermal electricity production presented a steady average LCOE around 0.05 USD/kWh, 0.03-0.06 USD/kWh 0.04-0.10 USD/kWh respectively. These three technologies directly compete, cost concerning, with fossil-fuelled power plants. On the other hand, PV, CSP and Wind Offshore still present a LCOE not lower enough in order to be considered as a cost-effective alternative to traditional fossil fuel facilities. However, onshore wind power has gone through continuous technological improvements resulting in an increase of its capacity factors, which combined with a reduction in the installation cost, entailed to an average LCEO around 0.06 and 0.08 USD/kWh which directly competes with fossil-fuelled power plants.

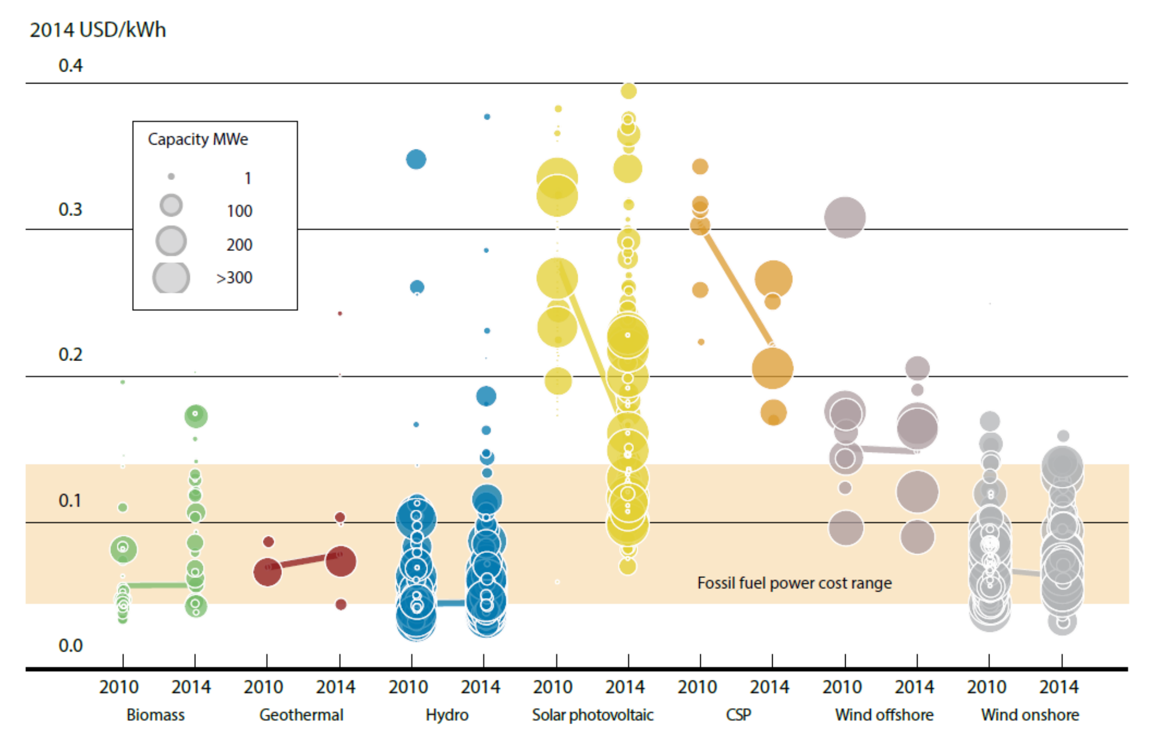
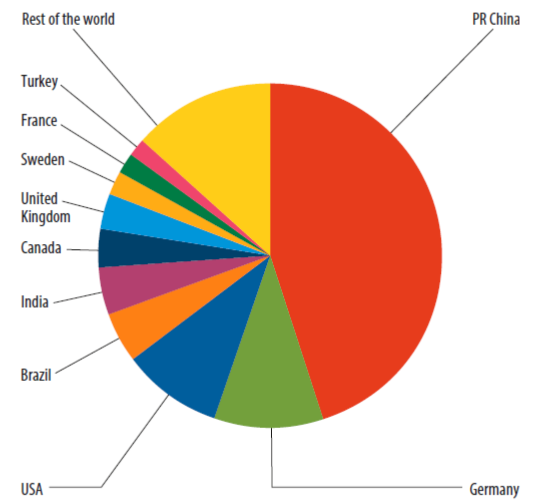


Figure 5 – The LCOE from utility-scale renewable technologies, 2010 and 2014 – Source (IRENA I. R., 2015)

<u>Wind Energy Perspectives</u>

By the end of 2014 twenty-four countries have more than 1 GW installed capacity and six of them (China, US, Germany, Spain, India and UK) have more than 10 GW, as Figure 6 depicts. Furthermore, during 2014 wind energy sector investments reached 88.9 bn€ (GWEC, 2014).

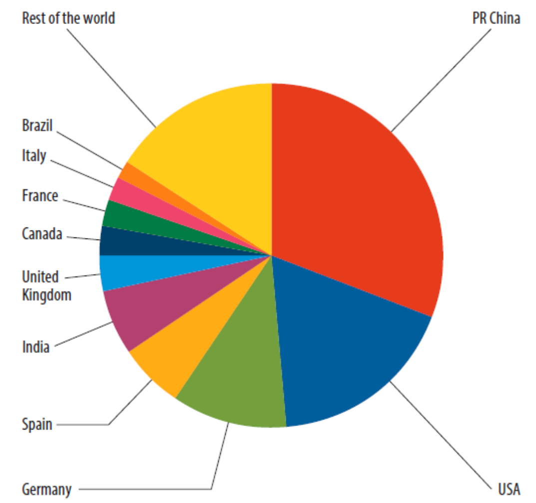
TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2014



Country	MW	% SHARE
PR China	23,196	45.1
Germany	5,279	10.2
USA	4,854	9.4
Brazil*	2,472	4.8
India	2,315	4.5
Canada	1,871	3.6
United Kingdom	1,736	3.4
Sweden	1,050	2.0
France	1,042	2.0
Turkey	804	1.6
Rest of the world	6,852	13.3
Total TOP 10	**44,620**	**87**
World Total	**51,473**	**100**

** Projects fully commissioned, grid connection pending in some cases* *Source: GWEC*

TOP 10 CUMULATIVE CAPACITY DEC 2014



Country	MW	% SHARE
PR China	114,609	31.0
USA	65,879	17.8
Germany	39,165	10.6
Spain	22,987	6.2
India	22,465	6.1
United Kingdom	12,440	3.4
Canada	9,694	2.6
France	9,285	2.5
Italy	8,663	2.3
Brazil*	5,939	1.6
Rest of the world	58,473	15.8
Total TOP 10	**311,124**	**84.2**
World Total	**369,597**	**100**

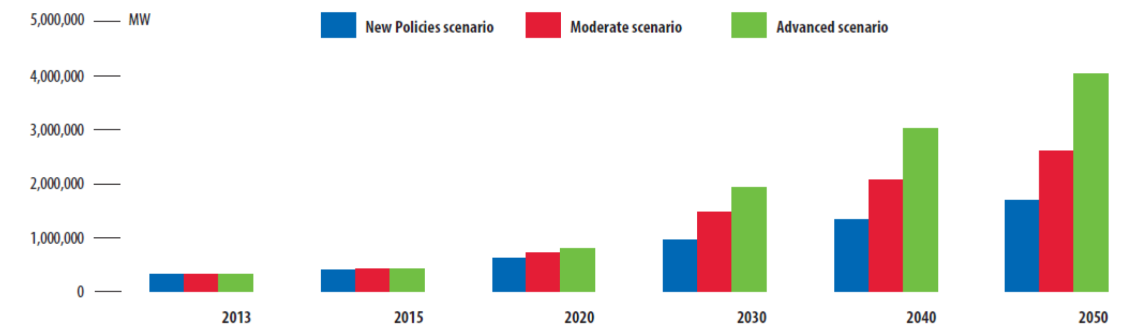
** Projects fully commissioned, grid connection pending in some cases* *Source: GWEC*

Figure 6 – New and cumulative wind power capacity by end 2014 – Source (GWEC, 2014)

The forthcoming of wind power generation seems to be promising. According to the "Global Wind Energy Outlook 2014" presented by the Global Wind Energy Council (GWEC, 2014), the total installed wind power capacity may reach 4 TW by 2050, as Figure 7 shows. In that report, the author used the International Energy Agency's New Policies scenario from the World Energy Outlook as a baseline and then developed two additional scenarios: Moderate and Advanced scenarios. Both scenarios were elaborated in collaboration with Greenpeace International and the German Aerospace Centre (Deutsches Zentrum fur Luft-und-Raumfahrt – DLR). These scenarios were described by GWEC as follows:

"The Moderate scenario reflects a world which carries on more or less the way it has for the past decade, with wind power continuing to gain ground but still struggling against heavily subsidized incumbents; without a comprehensive or cohesive carbon market, and with those that exist at very low prices. Policy instability decreases, but is still a factor, although the competition in the Organization for Economic Cooperation and Development (OECD) markets for a larger share of a stable or dwindling pie is intense."

"The Advanced scenario shows the potential of wind power to produce 25-30% of global electricity demand by the end of the scenario period, where there is a strong international political commitment towards meeting climate goals and national energy policy is driven by the need for enhanced energy security, price stability, job creation and the need to conserve our precious fresh water resources."



	2013	2015	2020	2030	2040	2050
New Policies scenario						
MW	318,128	396,311	610,979	964,465	1,324,814	1,684,074
TWh/a	620	972	1,499	2,535	3,482	4,426
Moderate scenario						
MW	318,128	413,039	712,081	1,479,767	2,089,261	2,672,231
TWh/a	620	1,013	1,747	3,889	5,491	7,023
Advanced scenario						
MW	318,128	420,363	800,615	1,933,989	3,024,473	4,042,475
TWh/a	620	1,031	1,964	5,083	7,948	10,624

Figure 7 – Global cumulative wind power capacity for each scenario – Source (GWEC, 2014)

Another prospect for wind energy is the one presented by the International Energy Agency in its "World energy Outlook 2015" (IEA, 2015). In that report, the author stated that the "global electricity generation from renewable energy sources increases by two-and-a-half times, from 5,105 TWh in 2013 to nearly 13,400 TWh in 2040".Of the 8,320 TWh increase, wind power will provide more than one-third, as Figure 8 depicts, and by 2040, wind and solar PV will account for 40% of renewables generation.

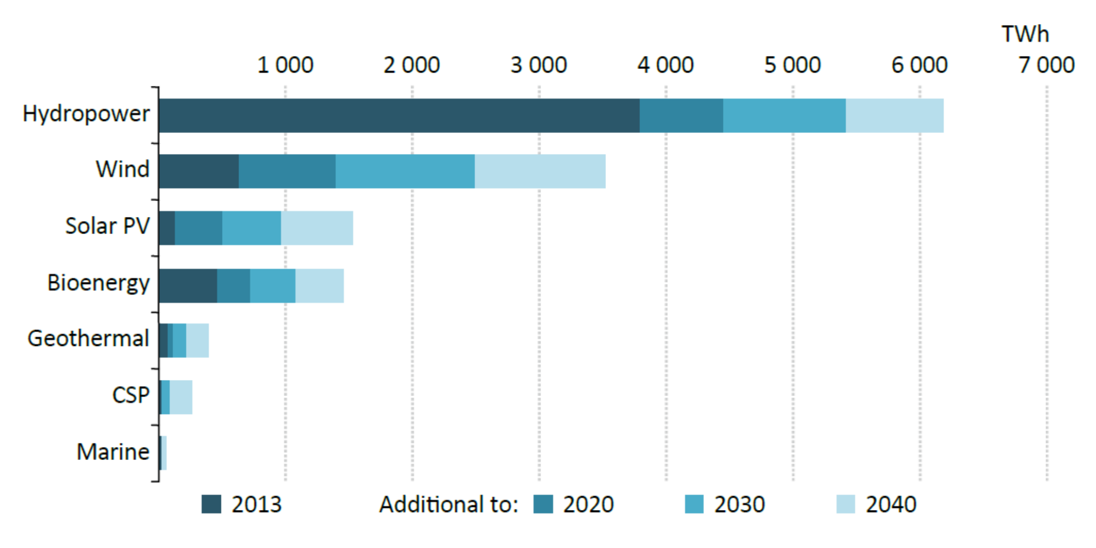


Figure 8 – Global renewables-based electricity generation by technology – Source (IEA, 2015)

The scenario was described by the IEA as follows:

"The central scenario in WEO-2015 takes into account the policies and implementing measures affecting energy markets that had been adopted as of mid-2015 (as well as the energy-related components of climate pledges in the run-up to COP21, submitted by 1 October), together with relevant declared policy intentions, even though specific measures needed to put them into effect may not have been adopted."

Since wind power deployment outlook seems to be very optimistic, it can be assumed that it will play an essential role regarding the energy supply. Furthermore, it can also be assumed that wind power might be able to face the upcoming challenges regarding a sustainable heat supply if WTES systems are developed. As a result, a combined portfolio of traditional wind power for electrical energy generation properly balanced with WTESs, may result in an even much more optimistic prognosis for wind power deployment.

Wind Energy Technology

Overview

Wind energy production involves a broad spectrum of mature technologies, which convert the kinetic energy of wind into electricity. However, the idea of making use of the inexhaustible and free-of-charge potential of the wind dates back to the year 1700 BC.

The first wind mills were constructed in Mesopotamia by Hammurabi for a wind powered irrigation project during the 17th century BC (Sathyajith, 2006). The earliest known instance of using a wind-driven wheel to power a machine dates back to Greece, on the 1st century AC, built by Heron of Alexandria (Lohrmann, 1995). The first electricity producing windmill was built in

1887 by John Blyth and it was a drag driven rotor (NE). From the first Blyth's wind turbine to the state-of-the-art converters developments in many areas of technology raised up contributing to the new generation of wind turbines. Areas like aerodynamics, power electronics, materials and computer science among many others went through considerable research processes which contributed to the currently more reliable, cost effective, and quieter wind turbines. Figure 9 depicts the evolution of modern wind turbines concerning their capacities, tower diameter and tower height.

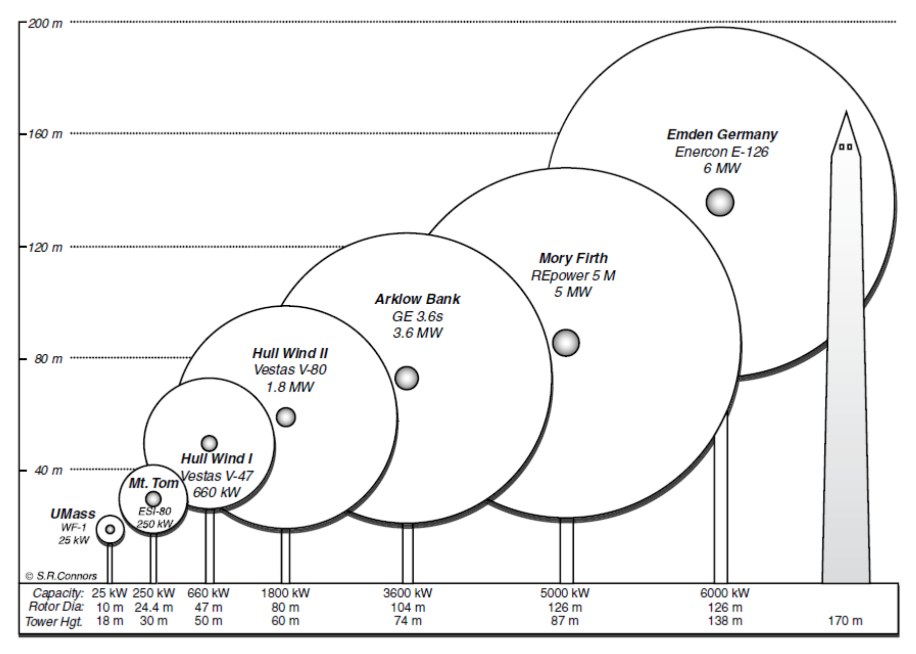


Figure 9 – Representative size, height, and diameter of wind turbines – Source (Manwell, McGowan, & Rogers, 2009)

The continuous evolution of wind energy converters is not over; reduction in the cost of energy should still be possible and offshore wind energy presents great opportunities (EWEA, 2009) (IRENA I. R., 2015). Nevertheless, only onshore wind energy converters are considered in this thesis since offshore windfarms present distances which result economically and technically unfavourable.

Wind Energy Converters

Modern wind energy converters (WEC) follow a simple operating principle. The kinetic energy from the wind is captured by the rotor blades, which convert it into mechanical power in its rotating shaft. This mechanical power is then transformed in electrical energy by the electric generator. Blades, rotor, gearbox and generator are installed at the nacelle, at the top of the tower, which stands on a foundation in the ground. Both blades and nacelle are controlled based on wind speed and direction measurements.

Even when the basic operating principle is easy to understand, developing a wind turbine requires a wide number of design decisions such as: axis orientation, number of blades or choice of material.

Over the years, a dominant design has emerged, which consists of horizontal axis three-bladed rotors, mostly up-wind, tubular steel tower and pitch-control for braking and an integrated gear box. However, a prevailing technology does not imply that it is the best solution for every site. The best turbine technology for a given project depends on the site's precise wind profile among other requirements.

Regarding the rotor axis direction, a wind energy converter could be designed either with a vertical or horizontal rotor axis. In the first case, the rotor axis is perpendicular to the wind direction and could be drag or lift driven. Vertical axis rotors present a low rotational speed; no gearbox is needed and they emit less noise compared to horizontal axis rotors. On horizontal rotor axis devices the rotor is parallel to the wind direction and lift rather than drag forces are used.

As far as the axis orientation and hub is concerned, up-wind devices face the wind avoiding the wind shade that the tower causes, resulting in fewer fluctuations in the power output. Conversely, down-wind converters have the rotor on the lee-side.

The control mechanisms of a wind energy converter is one of the most important design considerations since they optimize aerodynamic efficiency, keep the generator within its speed and torque limits and rotor and tower within its strength limits. Control strategies can be stalling, pitch or furling[2].

Concerning the generator and drive train, WEC technology could be direct or indirect drive. In the first case no gear box is needed but it requires a synchronous generator, which happens to be expensive. Indirect drive train requires a gear box, which is driven by the rotor shaft, directly connected to an asynchronous generator.

Wind Turbine Components

Rotor Blades:

Their purpose is to transfer the energy from the wind to the rotor hub. State-of-the-art wind turbines have rotor blades around eighty meters length and most modern blades on large wind turbine are made from "composites, primarily fiberglass or carbon fibre reinforced plastics, but sometimes wood/epoxy laminates are used" (Manwell, McGowan, & Rogers, 2009).

[2] Please refer to (Manwell, McGowan, & Rogers, 2009) for a detailed explanation about different control strategies

HUB:

This component connects the blades to the main shaft, which is connected to the gearbox (indirect drive train) or to the generator (direct drive train). They are generally made of steel, either welded or cast.

DRIVE TRAIN AND GEARBOX:

The drive train consists of all the other rotating parts downstream of the rotor as low-speed shaft, gearbox and a high-speed shaft. There are two different drive train concepts: Integrated drive train (Shaft, gearbox and generator in one unit) and Module drive train (Gearbox, shaft and generator separate).

The gearbox converts the high torque mechanical power of the low-speed rotating shaft in high speed low torque mechanical power in its high-speed shaft. A gearbox normally has a single gear ratio between the rotation of the rotor and the generator, typically one to fifty (Manwell, McGowan, & Rogers, 2009). The gearbox can be either parallel shaft or planetary.

ELECTRICAL GENERATOR:

This component converts the mechanical energy to electrical energy. The electrical generator could be either an asynchronous (induction) generator or a synchronous generator. When the generator is directly connected to the electrical grid constant or nearly constant rotational speed is entailed.

However, if the generator is indirectly connected to the electrical grid power electronic converters are needed in order to operate the wind turbine at variable speed. Hence, many modern wind turbines are equipped with a Doubly Fed Induction Generator (DFIG) with the stator directly connected to the grid and the rotor connected through a set of sliprings to a converter, being able to feed the rotor with variable frequency AC. Finally, the rotor's AC frequency is chosen in order to obtain on the stators the grid frequency despite variations in the rotational frequency.

INVERTERS:

They transform the generator's output frequency to the grid-required frequency such that the frequency of the AC in the stator of the generator may be varied. Then, it would be possible to run the turbine at variable rotational speed and the WEC will generate alternating current at exactly the variable frequency applied to the stator. The main advantage of indirect grid connection is that it is possible to run the wind turbine at variable speed, which may give a slight advantage in terms of annual production. However, its basic disadvantage is its higher cost.

NACELLE AND YAW SYSTEM:

The nacelle could be explained as the wind turbine housing, where every component between the hub and the electrical output cables are protected from the weather.

The yaw system purpose is to keep the nacelle (and the rotor) properly aligned with the wind. The wind vane measures the wind direction and the electronic controllers of the active yaw operate one or more yaw motors. If the yaw system turns in the same direction for a long time, the cables carrying the electricity could be damage and, therefore, the wind turbine is equipped with a cable twist counter, which tells the controller that it is time to untwist the cables by rotating the nacelle in the other direction.

ELECTRONIC CONTROLLERS:

All the wind energy converter's sensors are continuously controlled by a computer, collecting statistics on its operation. This device monitors the WEC status and also the yaw mechanisms, if any malfunction or unexpected behaviour occurs the computer calls the turbine operator's computer.

Modern turbines are able to monitor or set between 100 and 500 parameter values. Moreover, the controller also checks the power quality of the current generated by the wind turbine.

TOWER:

It supports the nacelle and the rotor. Normally its height is around 1 to 1.5 times the rotor diameter (Manwell, McGowan, & Rogers, 2009). Since the wind speed increases logarithmically with height, increasing tower heights can be observed over the years in order to take advantage of the strongest winds. The tower height selection is based on the economic trade off of increased energy capture versus increased cost.

Towers can be tubular steel, lattice, or concrete towers.

WIND ENERGY ASSESSMENT

The first step for a successfully wind assessment is the proper acquisition and treatment of wind data. Wind speed measurements are done by an anemometer, which converts the rotational speed into impulses. Anemometers are calibrated in certified wind tunnels at known wind speeds and then the calibration formula is obtained, which is the relationship between the frequency of the pulses and the wind speed.

On the other hand, even when is not of interest for the site selection, the distribution of the wind direction is important for the layout of a wind farm. This measurement is done by a wind vane, which positions itself according to the wind direction and a small sensor at the foot of it sense that position.

The wind behaviour for a particular site is characterized by its wind rose, Figure 10. This graphical output is developed by a polar representation of gridding, where the frequencies of winds speeds over a time period are plotted and sorted by wind directions (commonly between 12 to 16 sectors) and colour bands show wind speed ranges. Finally, the direction of the longest spoke shows the wind direction with the greatest frequency.

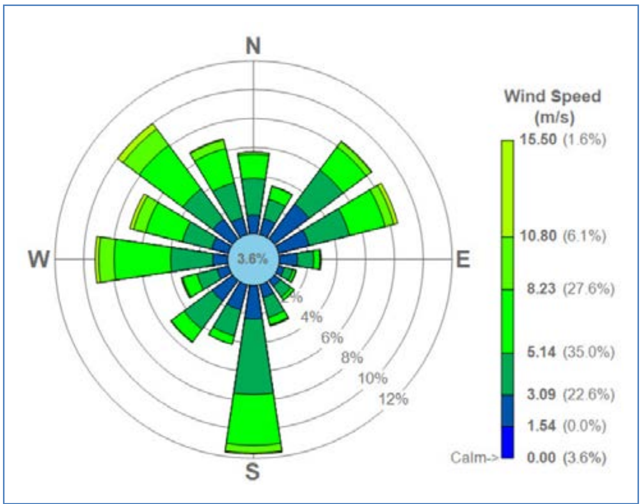


Figure 10 – Wind rose plot[3]

Both wind speeds and wind directions are stored in data loggers, data is recorded every 2-3 seconds and then averaged every 10-minute intervals. Then, the following step consists in analysing the measurements. Firstly an histogram and a frequency distribution for the mean wind speed are done, commonly 1 m/s bins are used. The frequency distribution of a measured wind regime can be approximated by a Weibull distribution, which is characterized by two parameters, as equation (1) depicts: the scaling parameter "A", which is proportional to the average wind speed, and the shape parameter "k". The following equation depicts the probability of occurrence "p" for a specific wind speed "u".

$$p(u) = \frac{k}{A} \cdot \left(\frac{u}{A}\right)^{k-1} \cdot e^{\left[-\left(\frac{u}{A}\right)^{k}\right]} \qquad (1)$$

Finally, for the calculation of the gross annually energy production (AEP), the approach of (Gasch & Twele, 2012) is considered. The AEP is estimated, as schematically shown in the following Figure 11 as follows: the total time period in hours is multiplied by the power curve of the

[3] Henceforward, when no source is indicated, the Figure/Table/Equation is developed by the author

selected wind turbine, which is an official document issued by the wind energy converter manufacturer where the whole spectrum of power as function of the wind speed is shown. And then, the result is multiplied by the Weibull approximation of the analysed wind regime.

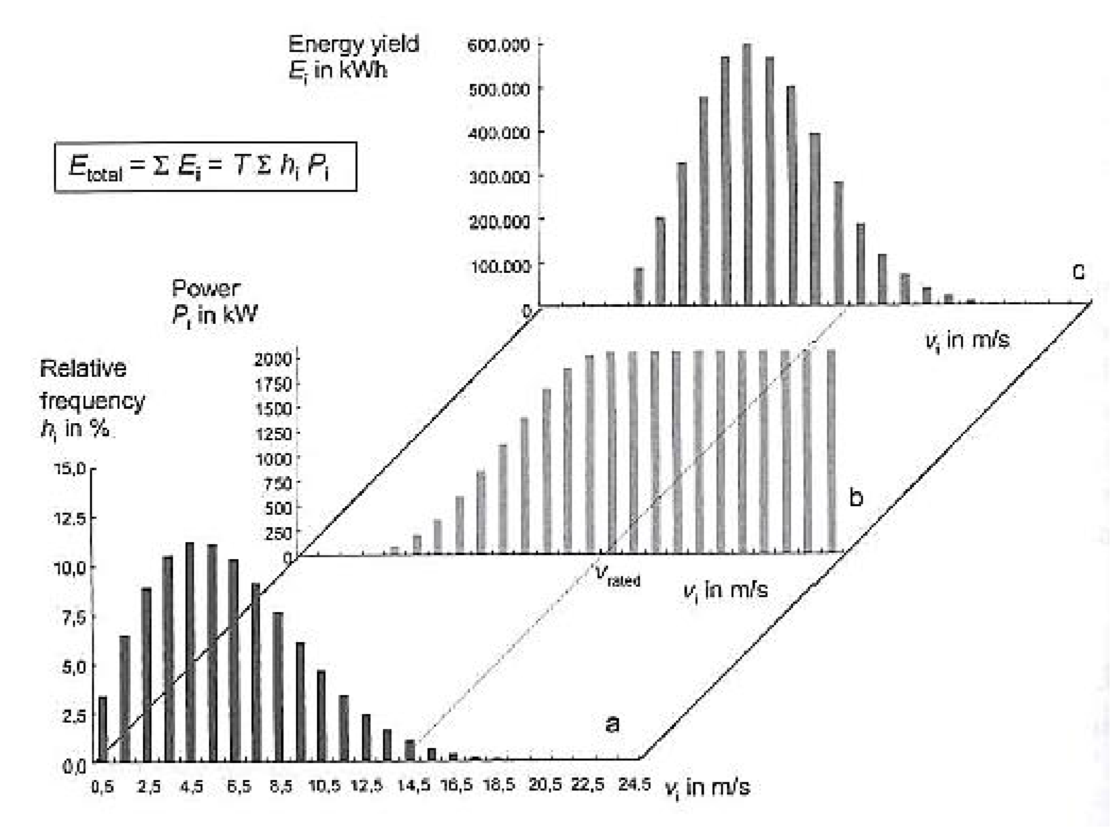


Figure 11 – Schematic energy yield estimation – Source (Gasch & Twele, 2012).

Since the power in the wind is a cubic function of the wind speed, the higher the wind speeds, the larger the amount of kinetic energy available, equation (2). The increase of wind speeds with heights respond to a logarithmic function, commonly known as “Logarithmic wind profile”. Another parameter influencing the maximum energy that can be harnessed by a wind turbine is the rotor swept area (rotor blade size).

$$E_{WIND} = \frac{1}{2} \cdot m \cdot v_1^2 = \frac{1}{2} \cdot \rho \cdot A \cdot L \cdot v_1^2 \Rightarrow by\ derivation$$

$$P_{WIND} = \frac{dE_{WIND}}{dt} = \frac{d\left(\frac{1}{2} \cdot \rho \cdot A \cdot L \cdot v_1^2\right)}{dt} \Rightarrow P_{WIND} = \frac{1}{2} \cdot \rho \cdot A \cdot L \cdot v_1^3 \qquad (2)$$

Then, the capacity factor (CF) concept needs to be clarified. The CF is defined as the real AEP divided by the theoretical maximum AEP, if the wind turbine were producing energy at its rated power during all of the 8760hs of the year, as equation (3) depicts.

$$CF = \frac{real\ AEP}{theoretical\ AEP} = \frac{real\ AEP}{8760hs \cdot P_{RATED}} \quad (3)$$

Additionally, capacity factors are also affected by the overall quality of the wind resource at the site, i.e. annual average wind speed, and also by inter-annual variability in the resource quality. Then, it can be concluded that, as Figure 12 shows, different places can be characterized with different capacity factors.

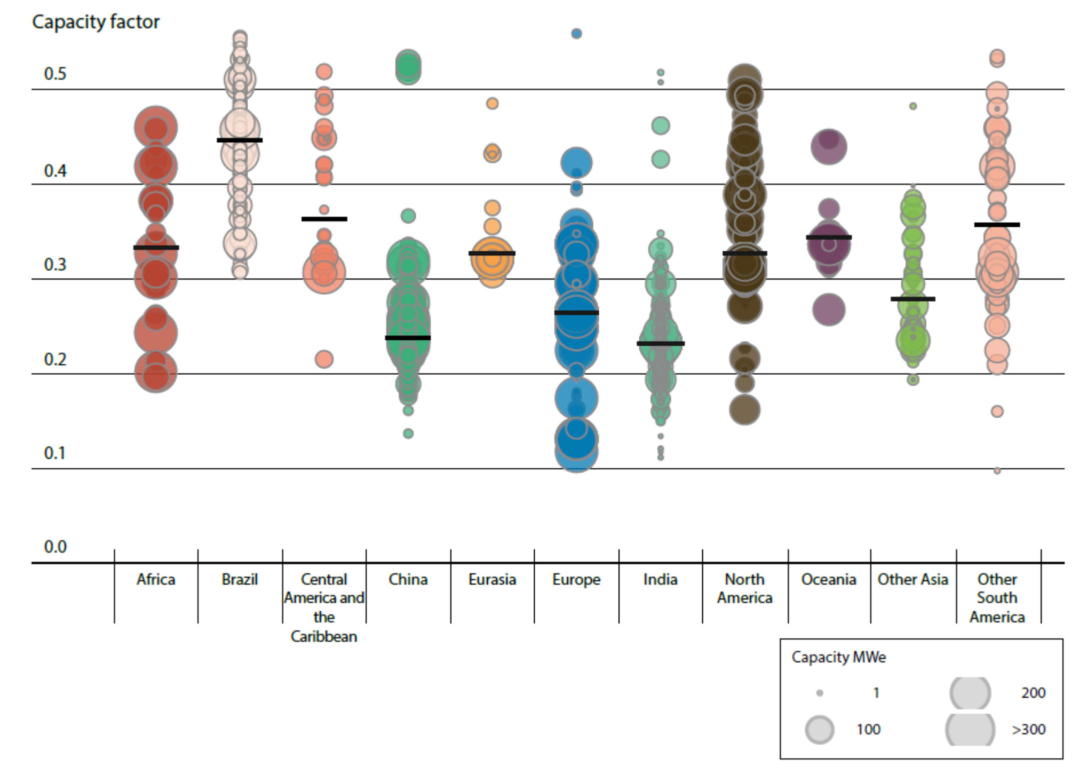


Figure 12 - Capacity factors by project and weighted averages for different sites – Source (IRENA I. R., 2015)

WEC Costs

In order to properly estimate all costs of a wind turbine, a careful assessment of all components over the lifespan of the complete power plant must be taken into consideration.

Within the framework of this work, two different wind energy converter's configurations are analysed in relation to both their capital expenditures (CAPEX) and operational expenditures (OPEX). Following Figure 13 depicts in a schematic and summarized way, the total cost of a wind project.

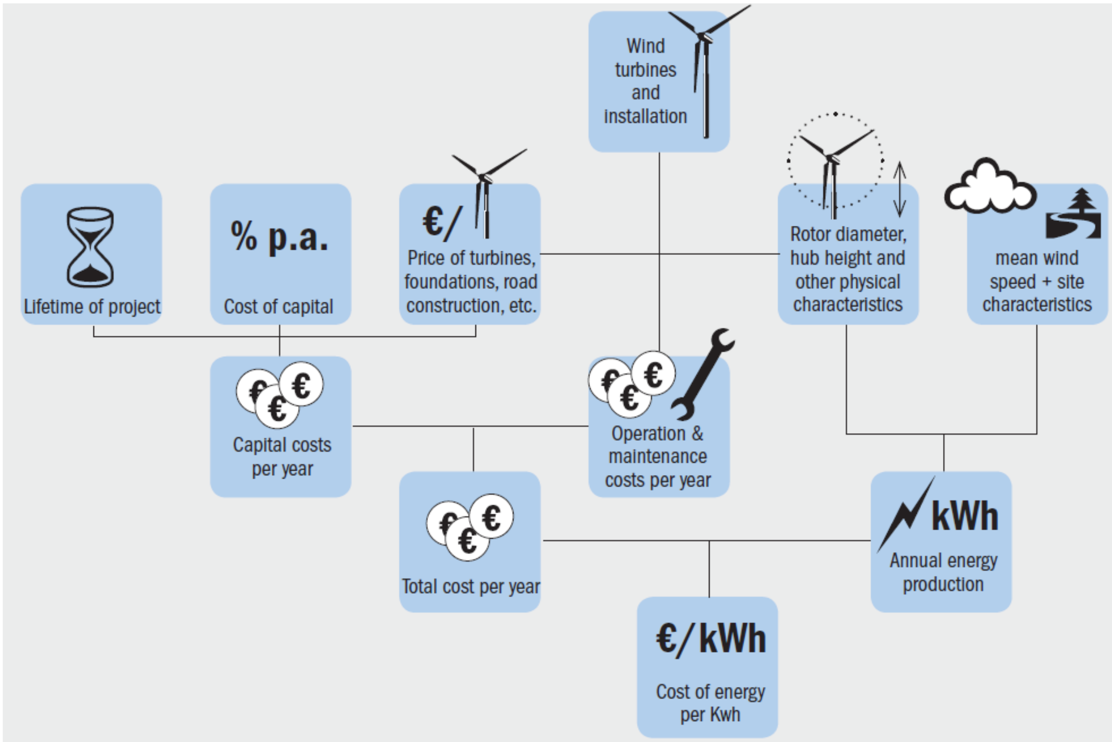


Figure 13 - The cost of wind energy - Source (EWEA, 2009)

The (EWEA, 2009) research, shows that cost of energy production per kWh (LCOE) is influenced by the capital cost, financing cost, O&M costs and expected annual energy production. Moreover, theses parameters (and the resulting LCOE) are influenced by the location of the wind farm, Figure 14, since different sites imply: different capacity factors and the consequent variation of the AEP, different capital expenditures due to different manufacturing processes, and different cost for raw materials, among many others influences. Hence, these parameters must be clearly studied in order to understand its influence in the LCEO of wind power projects.

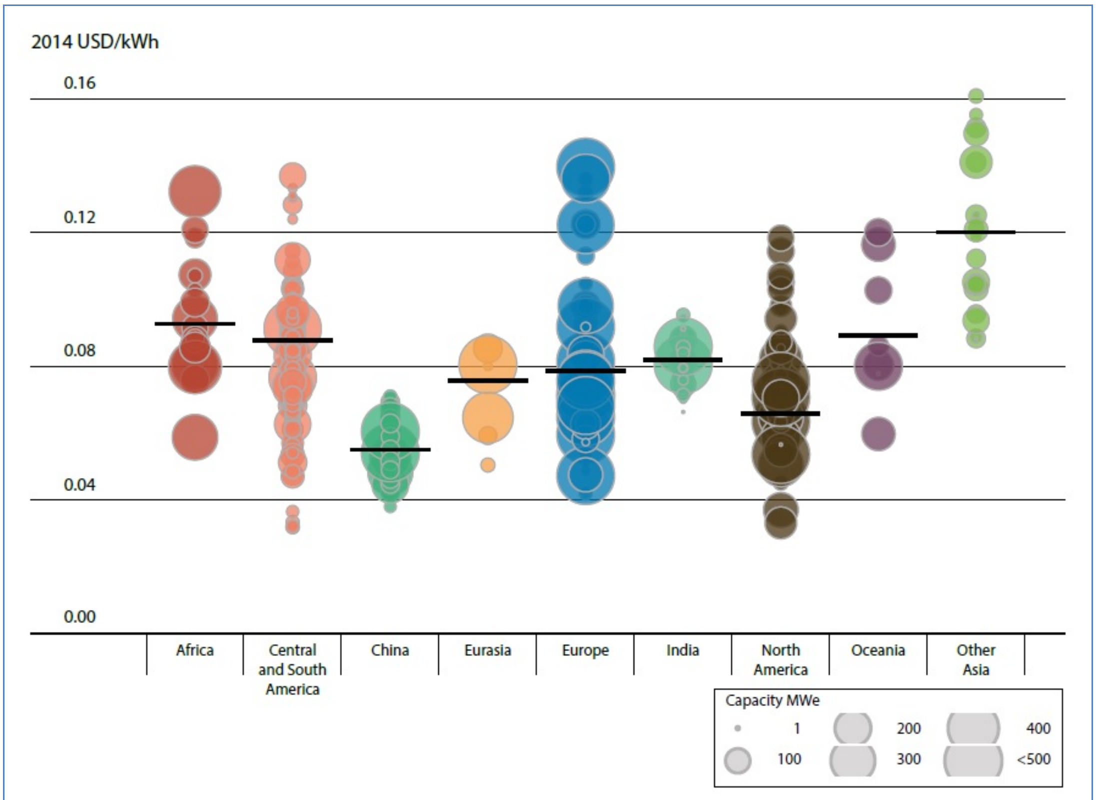


Figure 14 - The LCOE and weighted averages of wind projects by country and region - Source (IRENA I. R., 2015)

For the purpose of this work, CAPEX and OPEX are analysed for two different wind turbine configurations: a traditional WEC for electricity production and a traditional WEC for mechanical energy production in its main shaft, which implies the exclusion of some components from the CAPEX and OPEX estimation.

In the present work, three different system sizes are analysed and, therefore, three different wind turbines are considered: small power WEC, traditional WEC and a windfarm. Economies of scale for expected for windfarms when compared to a traditional WEC. Thus, a reduction of around 22% of the installed projected cost is assumed for wind farms between 20-50MW, according to the data of 2012-2013 from (U.S. DOE, 2013), for a detailed explanation about this estimation, please refer to the Assumptions section.

Traditional Medium/Large Power WEC

Capital Costs

Concerning the investment costs, it generally involves the cost of the wind turbine and the cost of the remaining installation. Wind CAPEX values presents variations from 1.00-1.35 M€/MW installed and its average is around 1.23 M€/MW (EWEA, 2009), where the wind turbine's cost itself has the biggest share of the total CAPEX. However, the total investment cost per MW of installed wind power capacity presents significant variations when analysing the same facility in different countries (Figure 15) and, therefore, when a particular project is analysed, a detailed economic assessment of the selected site is required.

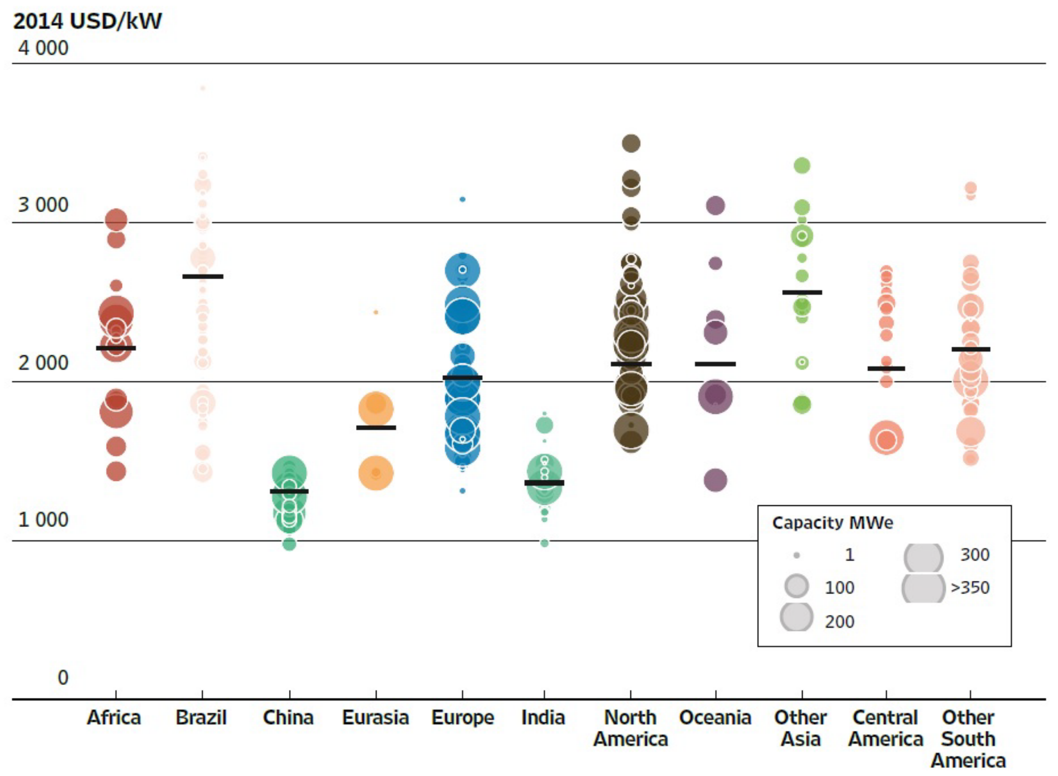


Figure 15 - Total CAPEX and weighted averages of wind farms by country and region - Source (IRENA I. R., 2015)

As shown in Table 2, the wind turbine's share in total cost (including the costs associated with blades, towers, transportation and installation) is around 76% and the corresponding shares for the grid connection is 9%, foundations 6.5%, land rent 4% and the remaining components account for less than the 6% of the total CAPEX (EWEA, 2009).

Table 2 - Cost structure of a typical 2 MW wind turbine installed in Europe - Source (EWEA, 2009)

	INVESTMENT (€1,000/MW)	SHARE OF TOTAL COST %
Turbine (ex works)	928	75.6
Grid connection	109	8.9
Foundation	80	6.5
Land rent	48	3.9
Electric installation	18	1.5
Consultancy	15	1.2
Financial costs	15	1.2
Road construction	11	0.9
Control systems	4	0.3
TOTAL	**1,227**	**100**

As the wind turbine cost has the biggest share of the CAPEX, it can account for as much as 84% for on-shore projects (EWEA, 2009), a cost breakdown concerning its components (Figure 16) leads to a better understanding of the total investment costs.

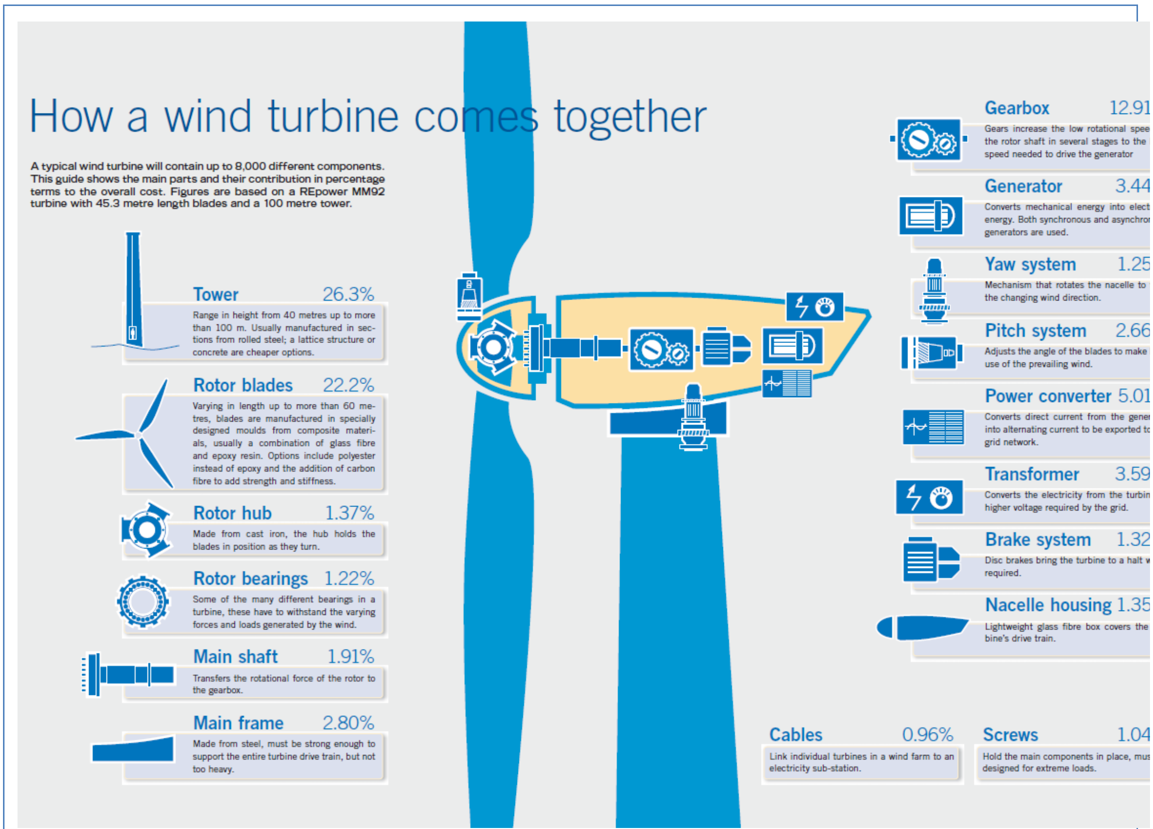


Figure 16 - Main components of a wind turbine and their share of the overall turbine cost for a 5 MW wind turbine - Source (EWEA, 2009)

Tower (26.3%), rotor blades (22.2%), gearbox (12.91%) and inverters (5.01%) have the biggest impact in the wind turbine investment costs (EWEA, 2009). However, these values may present variations depending on the model, nominal power, swept rotor area, among other considerations.

Operational Costs

Operation and maintenance (O&M) costs could be divided into fixed O&M costs, which are unrelated with the annual energy production from the wind farm, and variable O&M costs, which are directly related to the annual energy production from the wind farm. One of the best ways to estimate the O&M costs might be to develop a combined fixed and variable structure. However, many organization state annual O&M costs only as a percentage of the original turbine cost, i.e. they consider them as fixed, e.g. the Danish Wind Industry Association in 2009 estimated an O&M cost around 1.5% to 3% (Manwell, McGowan, & Rogers, 2009). On the other hand, many institutions prefer to use only a set cost per kWh produced and according to many authors, variable O&M cost presents variations from 8.7 to 15 €/MWh produced ((ENS, 2012), (Hedegaard & Münster, 2013) and (EWEA, 2009)).

Wind turbines, like any other industrial equipment, require service and maintenance processes which can be measured. O&M costs commonly consist of 6 elements:

- Insurance
- Regular maintenance
- Repair
- Spare parts
- Administration
- Miscellaneous

As far as the strictly operation costs, they may account the insurance on the wind turbine costs, taxes, and land rental costs, while the maintenance costs may account routine checks, periodic maintenance, electrical equipment maintenance, unscheduled maintenance costs among many others (Manwell, McGowan, & Rogers, 2009).

The estimation of the O&M costs is relatively easy for some elements like insurance or regular maintenance, however, for elements like repairs and related spare parts these costs are much more difficult to predict. The European Wind Energy Association developed a study concerning the weight of each of the previously mentioned O&M cost elements for German turbines and the shares of each of them can be seen in Figure 17.

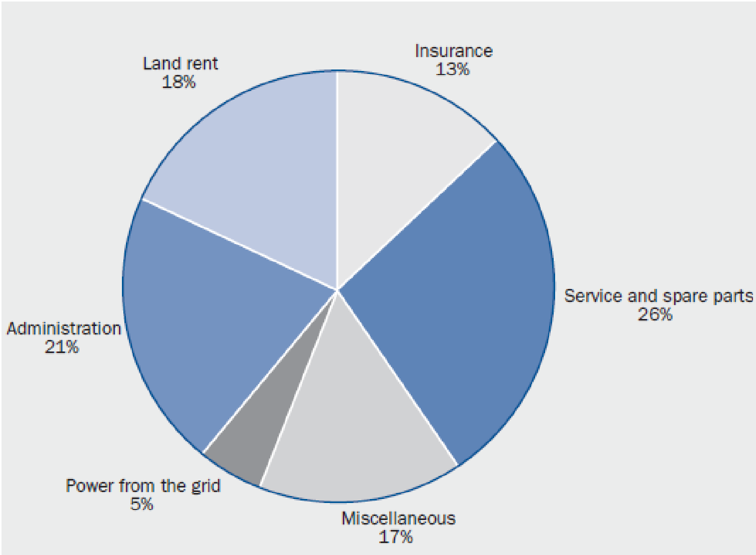


Figure 17 - Different categories of O&M costs – Source (EWEA, 2009)

Many authors agree that there is a close relationship between the increment of O&M costs with the wind turbine ageing (EWEA, 2009) (IRENA I. R., 2015), particularly the costs for repair and spare parts, which present low shares of costs during the first years and increase over time. Hence, during the first two or three years of operation, a low levels of O&M costs of around 2-3% of the total investment costs are expected, after six years O&M costs of around 5% are expected and for the last half of the WECs lifespan, considerable repairs and reinvestments might take place and these, actually, are the dominant O&M costs during the last ten years of the turbine's life (EWEA, 2009) (IRENA I. R., 2015).

Medium/Large Power WEC for Mechanical Energy Production

Capital Costs

As it is shown in Table 2, wind turbine external works represent around 75% of the total investment costs for a 2 MW wind turbine. Concerning a 5 MW wind turbine, its external works represent the 89.33% and the cost breakdown of its sub-components is shown in Figure 16 (EWEA, 2009).

For the purpose of the present work it is important to estimate the entire cost breakdown of a WEC. Table 2 and Figure 16 complement each other in the way they present each cost breakdown, however, both results are developed for two different WEC's nominal power and, therefore, either the 2 MW cost breakdown has to be up-scaled to the 5 MW values, or 5 MW results have to me downscaled to the 2 MW results. The present work is based on the second option and the downscaling factor (DSF) is estimated as the relation between the total wind turbine external works (2 MW turbine) and the sum of all the sub-components (5 MW turbine), as is shown in (4).

$$DSF = \frac{Total\ WEC\ external\ capital\ shares}{\sum subcomponents\ shares} = \frac{75\%}{89{,}33\%} = 0{,}8396 \quad (4)$$

Consequently, the downscaled sub-component shares are shown in the following Table 3. For the utilization of the wind energy converter for mechanical energy generation no Generator, Power converter and Transformer must be accounted and their shares must be subtracted from the total investment costs. Additionally, the need of gearbox is determined in the section "WTES-Concept" on page 45, and if no gearbox is needed for some systems, its cost share must be also subtracted.

Table 3 – Calculated sub-component share for a 2 MW wind turbine

Tower	22,08%
Rotor Blades	18,64%
Rotor Hub	1,15%
Rotor Bearings	1,02%
Main Shaft	1,60%
Main Frame	2,35%
Gearbox	10,84%
Generator	2,89%
Yaw System	1,05%
Pitch System	2,23%
Power Converter	4,21%
Transformer	3,01%
Break System	1,11%
Nacelle Housing	1,13%
Cables	0,81%
Screws	0,87%
	75,00%

Operational Costs

Variable costs are more difficult to estimate when no generator, power converter, transformer and gearbox are considered. All of the 6 elements of the O&M cost shown in Figure 17 (land rent, insurance, administration, power from grid and miscellaneous costs) are independent from the electric generation related components. Only the service and spare parts expenses, which hold a 26% of the total O&M shares (EWEA, 2009), are supposed to be reduced. Therefore, four different estimations in the reduction of the service and spare parts expenses are analysed (24%, 22%, 20% and 18%) and in the Assumptions section the chosen estimation is shown.

Traditional Small Power WEC

Capital Costs

Small WECs ranging from 1kW to 100kW present large investment cost ranges. The average turbine installed in USA, based on 96 units analysed, has a total investment cost of around 6 M€/MW (U.S. DOE, 2015). The actual wind turbine (e.g., the costs of the generator/alternator, blades, tower, and gearbox/mechanical system) has also the biggest share of the total CAPEX, as shown in Figure 18.

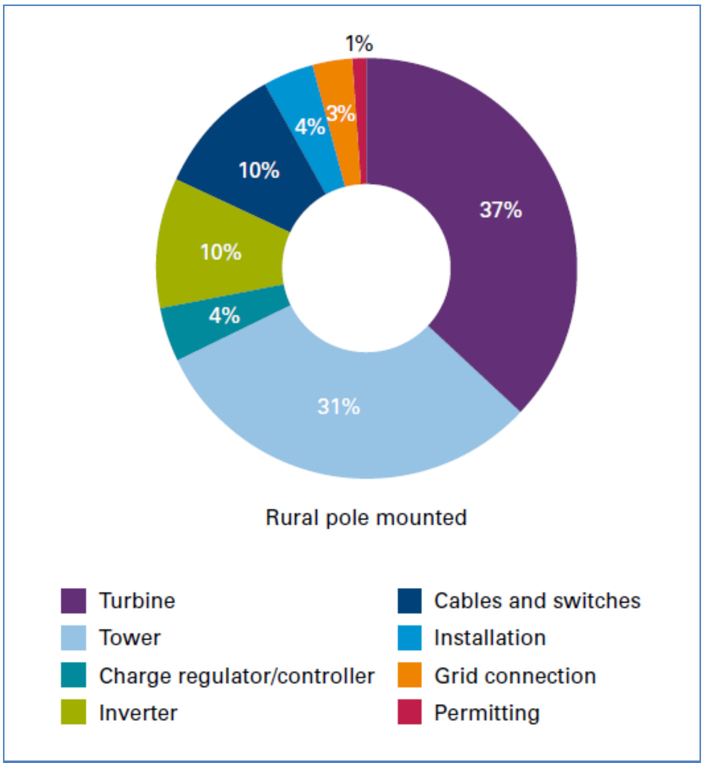


Figure 18 - Typical capital cost breakdowns for small WEC – Source (CT, 2008).

Operational Costs

O&M costs are divided into fixed O&M costs, which are unrelated with the annual energy production from the wind farm, and variable O&M costs, which are directly related to the annual energy production from the wind farm.

The estimation of the O&M cost is much more difficult than for medium/large WECs, since these data is scarce. However, according to (U.S. DOE, 2015), O&M costs estimation for small WECs between 11-49kW is around 25,000 €/MW annually.

Small Power WEC for Mechanical Energy Production

Capital Costs

As it is depicted in Figure 18, many components from small WEC are related with electricity generation purposes. In order to estimate the CAPEX for mechanical heat production, the following items must be discounted:

- Electrical Generator
- Charge Regulator
- Inverter
- Cables and Switches
- Grid connection

Since the CAPEX estimation requires some clarification regarding the assumptions performed, the selected considerations are shown in the Assumptions section.

Operational Costs

Hardly any reliable data is available for O&M costs for mechanical energy production in small wind turbines. This cost may be even negligible due to the economy of scale. However, a fixed reduction of 10% from the traditional O&M costs is assumed.

Heat Generators Technologies

Electric Boiler

An electric boiler (EB) is a type of boiler where the heat is generated by electricity, rather than through the combustion of a fuel source. Due to the large currents required they are normally three-phase devices and, according to (ENS, 2012), two types of technologies are available:

- Heating elements using electrical resistance. Typically, electrical resistance is used for smaller applications up to 1-2 MWs. These electric boilers are connected at 400 V.
- Heating elements using electrode boilers. Electrode systems are used for larger applications, i.e. in Denmark, larger electrode boilers are connected at 10 kV.

The working principle is simple, in the electrode boilers the system uses electricity flowing through streams of water to generate heat. It is formed with three-phase electrodes, a neutral electrode and a control screen. During the operation of the boiler, the current from the electrodes flows directly through the water which is heated in the process, thanks to its conductivity and resistivity properties. The current is a function of the active surface area of the electrodes and the water conductivity. The active area of the electrodes can be infinitely varied by operating the control screens, thus enabling output to be controlled between a minimum load of 10-20% (depending on size and voltage) and 100% (ENS, 2012).

The efficiency of an electric boiler is measured as how much electrical energy is required to produce thermal energy, and this type of boilers efficiency is around 1.

Its nominal power ranges from a few kW to more than 60 MW. It is considered a mature technology for household heating purposes and also for industrial developments. Its main advantage, compared with traditional fuel based boilers, is that Greenhouse gas (GHG) emissions can be avoided by suppling it with electricity from renewable energy resources. Furthermore, boiler's almost zero start-up time and its extremely dependable and easy to maintain characteristic make it a very attractive alternative for industrial heat production (Meibom, Kiviluoma, Barth, Brand, & Weber, 2006) .

Heat Pump

Overview:

The nominal power of heat pumps (HP) ranges from a few kW to more than 2 MW. HP have the unique characteristic of being able to provide either heating or cooling and, commonly, they can be classified into different types depending on which heat source and heat sink they are designed for.

Working principle of electric driven heat pumps

Basically, all heat pumps consist of a condenser, expansion device, evaporator and a compressor and make use of a vapour compression cycle to transport heat from the heat source to the heat sink as shown in Figure 19. When a heat pump is used in heating mode, the working cycle starts with the refrigerant in liquid phase exiting the condenser. Then, the refrigerant passes through an expansion valve where its pressure is reduced. Next, the low pressure refrigerant circulates through the evaporator, which works as a heat exchanger and where the heat (energy) from the low-temperature source is absorbed. As a result, the refrigerant evaporates into gas which is carried to the compressor. While passing through the compressor, the gasified refrigerant is pressurized and it raises its temperature. In order to upgrade the energy (low-temperature to high-temperature energy) an input power to the compressor is required, which is related to the temperature difference between the heat source and heat sink. Finally, the pressurized hot refrigerant circulates through the condenser, where the heat is removed to the heat sink, and as the refrigerant releases heat it changes phase back to liquid state and the process begins again.

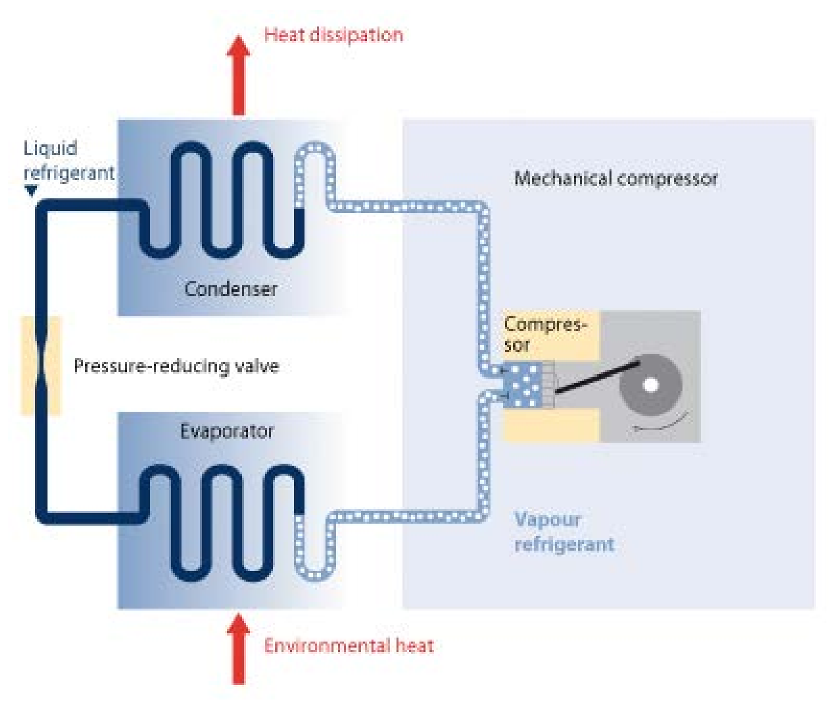


Figure 19 – Schematic vapour compression cycle – Source (Rheingas, 2015)

From the first law of thermodynamics, the total amount of heat delivered by the heat pump (Q_D) at the higher temperature T_D, can be estimated as the sum of the amount of heat extracted from the heat source (Q_S) at the low temperature T_S and the input energy required by the compressor (W_C), as is shown in equation (5).

$$Q_D = Q_S + W_C \quad (5)$$

The efficiency of a heat pump is commonly known as coefficient of performance (COP), which is always greater than 1. The maximum efficiency achievable by a heat pump is defined by the theoretical "Carnot-process" and is only dependent on the temperature level of both heat source and sink, as is shown in equation (6).

$$COP_{Carnot} = \frac{T_D}{T_D - T_S} \quad (6)$$

The COP of a heat pump can be defined as shown in equation (7). The practical COP will be always lower than the theoretical COP_{Carnot} because of losses in the system, typically around 50-65% of the theoretical COP. State-of-the-art large heat pumps present a Carnot efficiency set to 0.7 ((Meibom, Kiviluoma, Barth, Brand, & Weber, 2006), (dena, 2013)). For instance, a COP of 4 means that the heat pump converts 25 kWh electricity and 75 kWh of heat collected from the heat source (typically the ground or ambient air) into 100 kWh of heat output, as Figure 20 depicts. The COP deteriorates with increasing temperature differences between heat source and heat sink.

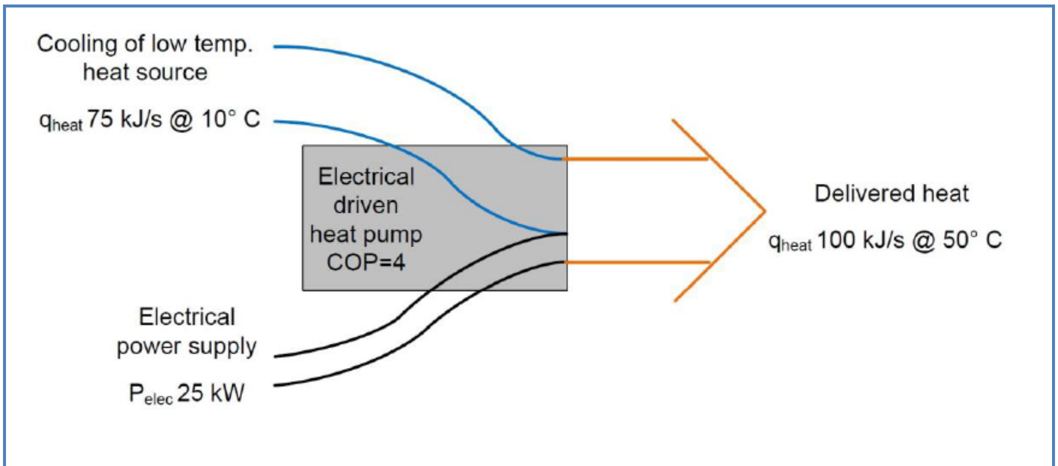


Figure 20 – Electric driven heat pump energy flow – Source (ENS, 2012)

$$COP = \frac{Q_D}{W_C} \quad (7)$$

Available heat sources

When assessing different heat sources for a HP, the most important aspects to consider are: temperature level, annual temperature, availability and investment cost attributed to the choice of heat source.

The available heat sources for electric driven heat pumps are:

Ambient air:

This heat source is the most common heat source worldwide, mainly due to the unlimited availability and to the inexhaustible characteristic of this resource. Since the COP is reduced by larger temperature differences, sites with significant ambient temperature differences might lead to unfavourable working conditions. Furthermore, when the temperature difference between heat source and heat sink is too large, the heat pump has to be stopped.

Air source heat pumps are designed for heat release directly to indoor air (air-air heat pump), or for connection to a hydronic heat distribution system (air-water heat pump).

Exhaust air

This heat source is restricted to buildings with mechanical ventilation systems and it presents higher operational costs. It presents favourable working conditions as the temperature of the exhaust air is in the range of +20°C. However, its limitation lies in the availability of the resource.

Ground soil

The ground soil is used as heat source since it can be considered as a “seasonal storage of solar energy”. For a detailed explanation of this technology, please refer to the reference (EHPA & SVEP, 2005).

Ground rock

This heat source is based on the utilization of the rock deep down on the earth as heat source, commonly up to the range of 200 meters. It is similar to the ground soil technology but it requires much less surface area and has, consequently, become the preferred choice in dense populated areas where space is limited.

Ground water

When the availability of the ground water is abundant and easy accessible, it can be used as heat source. The cold water is circulated through the evaporator, either directly or indirectly by use of an intermediate heat exchanger, and then re-injected to the soil by an injection well.

Surface water

When lakes are nearby, they can be used as heat sources, since during summertime the surface of the lake absorbs heat. A collector is lowered to the bottom of the lake and secured by anchors. The anchors compensate the lifting power of the ice produced around the pipe.

Further Characteristics

Some of the main advantages are that HPs are able to utilize energy at a low temperature level and that they have almost zero start-up time, typically less than 5 minutes. Additionally, when comparing its behaviour to electric boilers, heat pumps are more profitable since "they use 2-5 times less electricity to produce the same amount of heat" (Meibom, Kiviluoma, Barth, Brand, & Weber, 2006).

Absorption Heat Pump

This technology's main difference, compared with the compression heat pumps, lies in how the refrigerant is compressed. Traditional HP uses a compressor, whereas the absorption heat pump (AHP) uses thermal compression and the refrigerant is pumped in liquid state. Therefore, the energy required for pumping is considerably less in comparison to the required for compressing a gas. Additionally, heat at a high temperature level is used to regenerate the refrigerant, so that it can evaporate at a low temperature level and utilize low grade energy (ENS, 2012).

This technology, also known as Thermally Driven Heat Pumps, base its working principle in three temperature levels. As it can be seen in Figure 21, and according to (Kühn, 2013),[4] in the evaporator the refrigerant changes its phase and becomes vapour using a low temperature heat source (Environmental Heat - Q_0). Following, in order to "suck in" the vaporized refrigerant coming from the evaporator, a suitable liquid called "absorbent" is used. During the absorption process, which takes place in the absorber, heat is generated (Heat exiting the system - Q_1) and used for heating purposes, in the same way as the condensation heat is used. Therefore, the ratio of useful heat Q_1 to the low temperature heat from the absorber Q_0 is larger than the same relation for traditional compression heat pumps. In order to liquefy the vaporized refrigerant at the evaporation pressure, but at a higher temperature, the elevation of the boiling point is used by adding a second liquid to the refrigerant. During the absorption process, the absorbent is diluted and has to be regenerated so as to maintain its absorption capability. Therefore, the diluted solution is pumped to the higher pressure level into the Expeller, where the high temperature heat source supplies heat (Q_2) in order to boil off the refrigerant. The vaporized refrigerant is condensed in the condenser and throttled to the evaporator pressure, where the

[4] Since the scope of this thesis is not a detail assessment of thermal driven heat pumps, please refer to reference (Kühn, 2013) for a full description of this technology.

cycle starts again. The concentrated solution is also throttled and circulated back to the absorber where it can absorb the vapour refrigerant anew.

In order to elevate the boiling point, "the working fluid must be a mixture consisting of a volatile component and a non-volatile one. The most common mixtures for industrial applications are lithium bromide in water ($LiBr/H_2O$) and ammonia in water (NH_3/H_2O)" (IEA, 2014).

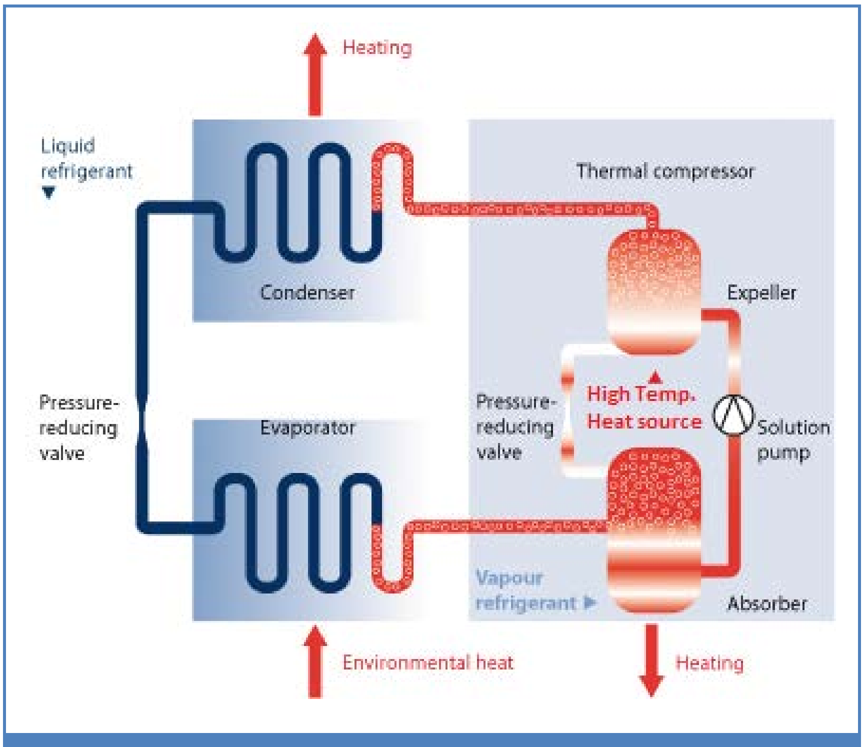


Figure 21 – Schematic absorption cycle – Source (Rheingas, 2015)

The efficiency of an AHP is also defined by its $COP_{HEATING}$, as shown in equation (8), as the relationship between the delivered heat and the high temperature heat source. Theoretically, in a AHPs 1 kJ of heat can regenerate 1 kJ of refrigerant, which means that it has a theoretical COP of 2. However, since internal losses take place, the practical COP is around 1.7 (ENS, 2012). Thus, the AHP converts 70 kWh heat at low temperature and 100 kWh of heat at high temperature (drive energy) into 170 kWh of heat output, as depicts in Figure 22. AHP's COP is not affected by temperature differences as the electrical driven heat pumps.

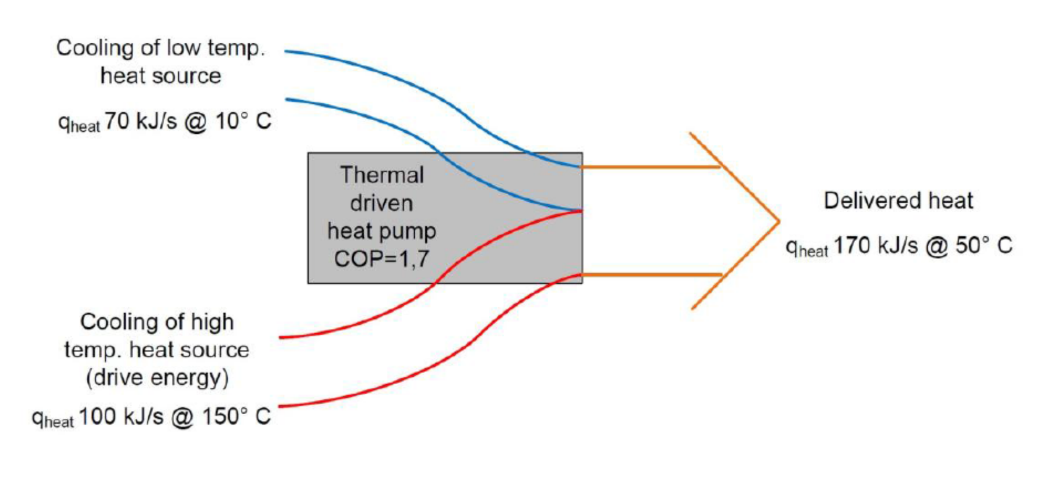


Figure 22 - Absorption heat pump energy flow – Source (ENS, 2012)

$$COP_{HEATING} = \frac{Q_1}{Q_2} \tag{8}$$

RETARDER

Compared with all the previous heat generation devices, retarders (RET) are considered as an undeveloped technology for heating purposes. However, this technology is well-known for vehicles brakes. Therefore, it is designed to stand intermittent loads, snow, heat and humidity. Consequently, retarders present enough robustness to cope with heat generation purposes.

Heat production by retarders working principle is based on the direct conversion from kinetic into thermal energy. Retarder manufacturers offer two different technologies: Hydrodynamic retarders (HDR), which present a remarkably lower cost and weight in comparison with regular electric generators, and induction retarders (IR), which offer the possibility of producing electricity as well as heat.

Hydrodynamic retarders achieve retardation by making use of the viscous drag forces between dynamic and static vanes in a fluid-filled chamber. A HDR comprises a rotor and a stator, which are equipped with vanes, and together form a toroidal working space. When retardation (heat production) is required, fluid is pumped into these chambers and the induced viscous drag slows the rotation and, consequently, the fluid heats up. The degree of retardation (heat production) is varied by adjusting the fill level of the chamber and, consequently, the output temperature from HDR is regulated. According to hydrodynamic retarder's manufacturer VOITH GmbH, state-of-the-art output temperatures range around 100°C and could be up-scaled to 120-150°C.

Additionally, HDR present an operational rotational speed in the range from 0-4000 rpm and the nominal power ranges around 200-500 kW, but for some industrial purposes higher power is achieved. Furthermore, HDR for heat production requires virtually no maintenance and have a long lifespan (Hoffel, Obser, & Schust, 2009). Moreover, they can operate with oil and water and can easily be scaled (VOITH, 2015).

Induction retarders make use of eddy currents induced in a conductor through electromagnetic induction to achieve retardation. There are two different technologies to produce a magnetic field: Permanent magnets or electromagnets.

The first technology consists of a ferromagnetic material (iron, nickel, cobalt, among many others) which is magnetized beforehand and, due to its physical characteristic and residual magnetism, remains magnetized and creates its own persistent magnetic field. On the other hand, electromagnets consist of a solenoid wrapped around a ferromagnetic material core. The magnetic field is produced when electric current flows through the coil and the strength of magnetic field is proportional to the current's intensity. When the current is called off, the magnetic field disappears.

IRs consist of a rotor attached to the shaft, with internal vanes to provide its own air cooling, and a stator either permanent or electromagnet. No contact between both components takes place. Retardation (heat production) is produced since the magnet of the stator produces a stationary magnetic field and, due to Faraday's law of induction, eddy currents are induced on the moving rotor. According to Lenz's law, these eddy currents create their own magnetic field, which opposes to the original field, and the interaction of both fields results in a decelerating drag force. Finally, the electrical energy of the eddy currents is dissipated as heat energy (heat production). IR's temperature reaches over 600 °C, even when the temperature from the permanent magnet stays under 100 °C (Okazaki, Shirai, & Nakamura, 2015).

HEAT GENERATORS COSTS

In this section an overview of the reviewed costs are shown. For the selected costs for the LCOE analysis, please refer to the Assumptions section.

ELECTRIC BOILERS

Regarding the costs, this technology presents the advantage of very low investment cost, when comparing with other heat production units, but as it uses electricity as fuel, the operating costs can be high compared to other boilers.

CAPITAL COSTS

The CAPEX estimations vary from 0.06 to 0.15 M€/MW for different authors (Gils, 2015) (ENS, 2012). The average capital expenditures is around 0.1 M€/MW.

Operational Costs

This technology presents both fixed and variable O&M costs. The average fixed OPEX is around 1,100 €/MW annually and the variable OPEX around 0.5 €/MWh (Gils, 2015).

Heat Pumps

The operational expenditures of HPs are very low compared to electric boilers. On the other hand, compared with traditional heating technologies, they are more complex and have a higher CAPEX but are counterbalanced with lower OPEX, which is only a fixed amount annually.

Electrical Driven (eHP)

Capital Costs

The CAPEX estimations varies from 0.68 to 1.004 M€/MW for different authors (Gils, 2015) (ENS, 2012). The average capital expenditures is around 0.7 M€/MW.

Operational Costs

This technology presents only fixed O&M costs and ranges from 3,700 to 7,300 €/MW (ENS, 2012). Its average OPEX is around 5,500 €/MW annually.

Mechanical Driven (mHP)

Capital Costs

For the CAPEX estimations of the mechanical driven HPs, only the cost of the motor is deduced from the total investment cost. The total cost to deduce depends on the nominal power of the system under analysis. Three different system sizes are analysed, their corresponding CAPEX estimations are shown in the Assumptions section.

Operational Costs

The estimation of the variable costs for mechanical driven HP is not straightforward due to the lack of data. This cost variation may be even negligible; however, since the only difference with a traditional electrical driven HP is the absence of its asynchronous motor. A fixed reduction of 10% from the traditional eHP's O&M costs is estimated.

Absorption Heat Pump

Capital Costs

The CAPEX estimations varies from 0.37 to 0.42 M€/MW for different authors (Gils, 2015) (ENS, 2012). The average capital expenditures is around 0.4 M€/MW.

OPERATIONAL COSTS

This technology presents only fixed O&M costs and ranges from 16,000 to 21,000 €/MW (ENS, 2012). Its average OPEX is around 18,500 €/MW annually.

RETARDER

CAPITAL COSTS

According to the retarder's manufacturer VOITH GmbH and to (Okazaki, 2015) the average capital expenditure for this technology is around 0.01 to 0.05 M€/MW.

OPERATIONAL COSTS

Published data for operational costs for retarders are only rarely available. As retarders are supposed to be used as brakes, no experiences with the operation as heat generators are known yet. However, after consulting the retarder's manufacturer VOITH GmbH, it was advised to consider the OPEX as a fixed percentage from the total CAPEX. 2.5% and 5% for fixed O&M expenditures are estimated.

Thermal Storage Technologies

Thermal Energy Storage (TES) involves many different technologies and bases its working principle on the stocking of thermal energy either by cooling or heating a storage medium for its later utilization. The thermal energy itself can be stored at a temperature range between -40°C and 400°C.

Three different TES concepts are available: Sensible Heat Storage, Latent Heat Storage (phase changing material - PCM) and Thermo-Chemical Storage (TCS). They present different working principles. At present, sensible heat storage is commercially available and is in a much more mature stage of development, while TCS and PCM systems are mostly under development and demonstration stages.

TES systems can be designed as centralised (district heating systems, large industrial facilities, CHP, CSP) or distributed systems (domestic/commercial buildings for space heating). Since TES systems are used particularly in buildings and industrial processes, where roughly half of the energy consumed is in the form of thermal energy, TES systems can help balance energy demand, reduce peak demand, energy consumption, CO_2 emissions and costs, while increasing overall efficiency of energy systems (IRENA & IEA-ETSAP, 2013).

Moreover, TES systems are mature in CSP plants and, therefore, TES can help to exploit variable renewable energy sources.

According to (IRENA & IEA-ETSAP, 2013), TES can be described in terms of the following properties:

- Capacity: it is function of the system size, storage process and medium. Defines the energy stored in the system
- Power: it is a parameter related to the speed of the energy discharge (and charge) processes
- Efficiency: It is a parameter which accounts for the energy loss during the storage period and the charging/discharging cycle. It can be estimated as the ratio between the energy provided to the user and the energy needed to charge the system
- Storage Period: This parameter defines how long the energy is stored (i.e. hours, days, etc).
- Charge and Discharge time: needed time to charge/discharge the TES
- Cost: it can be defined in terms either of capacity (€/kWh) or power (€/kW) of the storage system. It depends on its CAPEX, OPEX and lifetime

Sensible Heat Storage

This TES system stores thermal energy by cooling or heating a liquid or solid storage medium (e.g. water, sand, molten salts, etc.), which is then kept in storage tanks with high thermal insulation. For large–scale application also underground storage systems are developed, both with solid and liquid storage medium.

Naturally, sensible heat storage has advantages and disadvantages. One of its advantages is its costs, which compared to PCM and TCS, is relatively low. Additionally, it can be applied to domestic systems, district heating and industrial needs.

However, sensible heat storage systems present a storage capacity which is limited by the specific heat of the storage medium and thermal insulation technologies, ranging from 10-50 kWh/m^3, and storage efficiencies between 50-90%. Besides, these systems require large volumes because of their low energy density (i.e. 3 and 5 times lower than that of PCM and TCS systems, respectively) (IRENA & IEA-ETSAP, 2013).

Latent Heat Storage

When larger energy densities are required, and also more constant discharging temperatures, sensible heat storage is no longer a cost-effective solution and, therefore, PCM-based thermal energy storage arises.

This TES system stores thermal energy by using phase change materials or PCMs (e.g. from a solid into a liquid state), offering a higher storage capacity. For example, when considering the melting process of ice, energy densities around 100 kWh/m^3 can be achieved, remarkably higher than the typical 25 kWh/m^3 for sensible heat storage options. Moreover, PCM thermal energy storages present higher efficiencies (ranging from 75-90%), which is associated with the latent heat of the phase change (IRENA & IEA-ETSAP, 2013). As a result, this system can be considered as "target-oriented", since it can be set by the constant temperature of the phase change.

Additionally, PCMs systems can be designed for both short-term (daily) and long-term (seasonal) energy storage.

Thermo-Chemical Storage

This TES system stores thermal energy by using thermo-chemical reactions (e.g. adsorption or the adhesion of a substance to the surface of another solid or liquid) and offers higher storage capacities than PCMs, being able to reach capacities of up to 250 kWh/m^3 with operation temperatures of more than 300°C and efficiencies from 75% to nearly 100% (IRENA & IEA-ETSAP, 2013).

TES Costs

Different parameters have direct influence in the TES cost estimation. Items like technical equipment, storage materials and operational expenditures must be included in the costs estimation. These estimations depend on its specific application and operational needs. PCM and TCS systems present higher costs than latent heat systems and result in a cost-effective solution only when a high number of cycles is ensured.

The costs are divided in CAPEX and OPEX. According to (Gils, 2015), the annual OPEX for all storage systems independently of the technology is 0.7% of the total CAPEX. On the other hand, the investment costs are highly dependent on the storage technology considered and they are function of two parameters: Energy density in kWh/m^3 and cost in €/m^3.

Latent Heat Storage

Sensible heat storage costs depend mainly on the system size, application and thermal insulation technology. They basically consist of a simple tank (which may require an efficient and, therefore, costly thermal insulation), the storage medium (usually cheap) and the equipment to charge/discharge.

Typical values of costs are between 50-300 €/m^3 (Gils, 2015). As a result, a complete system's cost for sensible heat storage ranges between 0.1-10 €/kWh, depending on the size, application and thermal insulation technology (IRENA & IEA-ETSAP, 2013).

PCM

The increment in the investment costs for PCM systems is directly related with the heat transfer technology to be installed in order to achieve the required charging/discharging power. Consequently, PCM storage systems investment costs range between 10-50 €/kWh (Gils, 2015) (IRENA & IEA-ETSAP, 2013).

TCS

As it is mentioned for PCM systems, TCS based TES also present higher investment costs than latent heat storage since TCS's materials must be pelletised or layered over supporting structures. Additionally, expensive containers and auxiliary equipment for both heat and mass transfer are needed.

TCS system can be operated as either open systems (often the cheapest option) or closed systems and its cost ranges between 8-100 €/kWh (Gils, 2015) (IRENA & IEA-ETSAP, 2013).

WIND POWERED THERMAL ENERGY SYSTEMS

WTES have not yet been studied in depth and their technical and economic feasibility are unknown. They are subject of this study and, therefore, this chapter gives, firstly, an overview of the wind powered thermal energy systems explaining the concept and the different methods for the heat production. Afterwards, the five proposed WTES-concepts are described, analysing their different working principles, as well as their strengths and weaknesses. The last section presents a literature overview concerning Wind&Heat production.

WTES-CONCEPT

WTES is based on the conversion of wind into heat which can be stored cost-effectively and nearly independently of the location. This technology has the potential to transform wind energy from an intermittent into a dispatchable source of renewable energy that is available upon demand. Consequently, WTES could result in a secured capacity which has the potential to fulfil energy policy objectives concerning security of supply and environmental sustainability.

Different WTES alternatives can be achieved by the combination of different technologies that are currently available on the market, but still, they have never been never analysed together as a whole system: wind turbines, high-temperature heat generator, high-temperature heat storage and heat engines. As a result, it links the systemic benefits of steam power plants with the use of wind power and, thus, it might reduce the need for investing in dispatchable power capacity.

Since there is no research about economic benefits of different WTES configurations, the first step is to study the feasibility, potential and probable costs of different WTES, providing useful heat at 100°C.

In order to develop a cost-effective system for the conversion of wind into heat, currently available high-temperature heat generators like electric boilers, heat pumps and retarders can be used. For the high-temperature heat storage units, according to (Thess, 2015) three different concepts arise: latent heat storage, thermochemical storage and sensible heat storage. Hence, commercial technologies being used for CSP could be the solution to this issue e.g. storing high temperature heat in beds made from natural materials such as granite or basalt with air as the heat transport and heat transfer medium. Additionally, another important consideration for the optimal heat storage is the proper technology selection, taking into account all the components involved as well as the energy source and energy demand (e.g. storage temperature, nominal power, working medium, among others)

Finally, for the reconversion from heat to electricity, traditional heat engines like the ones used in conventional steam power plants could be used.

The heat can be generated either directly or indirectly. The direct production refers to the direct transformation of wind energy into thermal energy without intermediate electric generators. Contrary to the direct, the indirect production requires an electric generator to convert the wind power into electric power and, then, utilizes the electric power to produce heat.

Indirect Heat Production

This heat production concept is based on the conversion of rotational energy into electricity using a conventional electric generator and the subsequent conversion of the electricity into heat, e.g. by an electric boiler or a heat pump. Indirect heat production presents the advantage that the heat generator does not have to be located in the vicinity of a centralized heat storage facility to which the electrical energy can be transported.

In order to achieve the most efficient power-heat-electricity conversion, Pumped Heat Energy Storage (PHES) can be used and the high temperature heat can be generated by electrical heat pumps. This configuration may result in an overall efficiency for the reconversion of about 54% (Thess, 2013).

Direct Heat Production

This heat production concept, contrarily to the indirect method, is based on the direct conversion of rotational energy into heat. Moreover, the heat production takes place directly in the WEC's nacelle and the heat storage facility must be as close as possible to the site, in order to reduce heat losses.

The heat generation could be developed by hydrodynamic/induction retarders or mechanical powered heat pumps.

Analysed WTES-Configurations

As mentioned before, the aim of this work is to assess different WTES-configurations regarding the heat production and storage. Hence, the following Figure 23 depicts five concepts which are analysed in this thesis, where both indirect and direct heat production are considered.

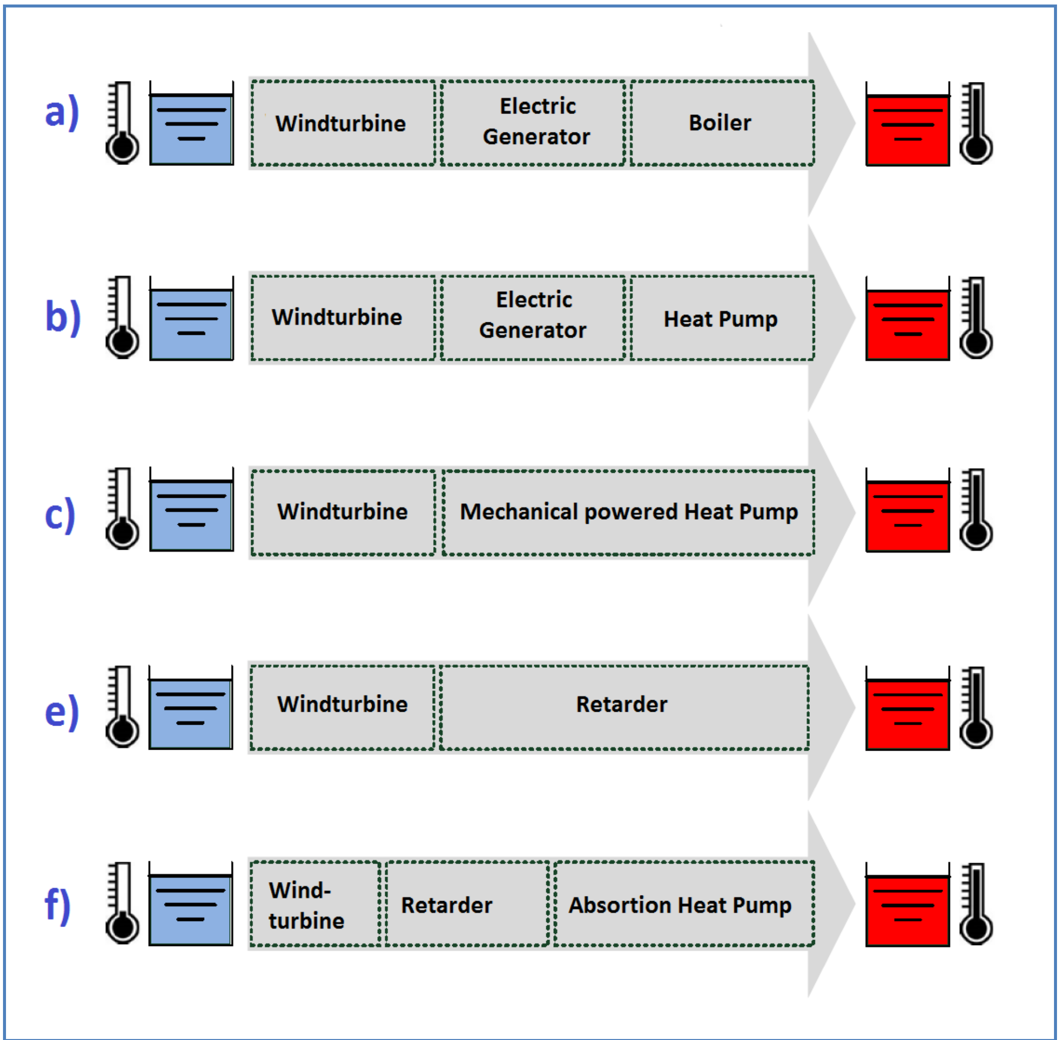


Figure 23 –WTES Configuration analysed

a) ELECTRIC BOILER– BASE CASE

This indirect heat production concept bases its working principle on a traditional WEC and an EB.

It is considered the base case of the analysis due to its simplicity. The wind physics behind a traditional WEC have been studied in depth over the years and, therefore, it is a mature technology that presents no inconvenience when analysing its operation. Moreover, there is a strong knowledge in every step of this technology i.e. CAPEX, OPEX and O&M procedures.

Concerning the electric boiler, it has a remarkably low investment costs and therefore relatively few operation hours are needed to cover the investments cost. Moreover, it presents a start-up time that almost equals to zero, which is an ideal characteristic when used in combination with an alternative power source. Additionally, CAPEX, OPEX and O&M procedures present no significant uncertainties since it has been on the market for many years.

As a result, this option is a highly dispatchable system, since both components present a relatively low start-up time, and the uncertainties of this system's costs and operation are low.

b) Electric driven Heat Pump (EHP)

This WTES-Concept, compared with the base case, replaces only the electric boiler with a heat pump, which is still powered by the electricity provided by the WEC. Therefore, all the previously mentioned advantages regarding WEC's technology occur again in this system.

The distinctive feature of this concept is the utilization of the HP. Like electric boilers, heat pumps can be regulated between standstill and full load almost instantly, which is an advantageous characteristic for WTES. The system benefit of HPs, when comparing them with EB, rely on their relatively higher efficiency; they use 2-5 times less electricity to produce the same amount of heat. Moreover, well-designed HP systems can be a more cost-effective solution than electric boilers.

Nonetheless, the mentioned increase in the efficiency comes with a higher investment cost, compared to EB. Thus, these higher initial costs might be a barrier in many cases, in spite of the fact that the overall lifetime cost of HPs are very satisfactory. Therefore, as heat pumps are capital-intensive, investments in large HP call for a relatively high number of full load hours.

Due to the weather-dependant behaviour of the wind, it might be assumed that the HP may present on/off working regimes. According to (Uhlmann & Bertsch, 2010), a performance reduction between 5-30% of heating capacity might be expected due to on/off cycling. Moreover, (SHERHPA, 2005) suggest that "transient losses due to the thermal mass of the compressor and refrigerant migration during the off cycle, are responsible for an 11% reduction in COP". The author also mentions that "compressor cycling causes efficiency losses of between 4 and 11% in air-to-air HP".

However, (Karlsson, 2007), concludes that the losses due to the on/off cycling are negligible when the duration of the start-up is very short compared to the total cycle time. Additionally, the author also mentions that the use of electronic expansion valve (EEV) gives the possibility not only to reduce the migration of refrigerant, which also contributes to a better efficiency in on/off working behaviours, but also gives the possibility of developing a superheat control over the evaporator, which impacts on the energy efficiency and provides a more stable control. As a result, this work considers neither losses nor COP reduction due to on/off cycling.

c) MECHANICAL DRIVEN HEAT PUMP (MHP)

This is a direct WTES-Concept, which means a direct conversion of wind into thermal energy without intermediate electric generator. The energy from the wind is extracted at the wind turbine blades and transformed intro rotational energy on the WEC's shaft, which is directly connected to the heat pump's compressor shaft. Then, the heat pump converts the rotational energy of its compressor into thermal energy.

Additionally to the HP's low start-up time, its higher efficiency and cost-effective characteristic, this directly connected concept it is assumed to present a more efficient characteristic, compared to the electrical powered HP, since one less energy conversion takes place.

Three different system sizes are analysed and, consequently, in order to fulfil the proposed heat demands, multi-compressor HPs are needed. Please refer to the Assumptions section for a detailed description of the proposed system sizes.

All the compressor's shafts are connected in series to the WEC's shaft. Additionally, as no electric generator is being considered on this concept, its efficiency is not considered for the energy production estimation.

Regarding the HP efficiency, as no electric motor is considered, its efficiency is not taken into account, which results in a higher COP.

In order to operate this system around the HP's optimal working condition, a gearbox is needed since the average rotational speed of a typical WEC is between 5-22 rpm (Rosenbloom, 2006).

d) RETARDER (RET)

In this concept, all the characteristics mentioned in concept c) regarding the WEC assumptions are identical. In this case, the WEC's rotational energy is directly converted into thermal energy by using a retarder, which is directly connected to the WEC's shaft. In order to analyse different nominal powers, it is assumed that all the required retarders are connected in series.

In order to operate this system around the retarder's optimal working condition, a gearbox is needed since it provides nominal power between 700-1,500 rpm. Therefore, a gearbox is considered for the economic estimations.

e) RETARDER AND AHP (RET+AHP)

Since the only difference between this concept and the previous one is the utilization of an absorption heat pump after the retarder, all the system characteristics mentioned for concept d) are still valid for this system. The addition of the AHP uses the output thermal energy from the retarder as the high temperature heat source, in order to deliver a higher thermal energy output.

LITERATURE RESEARCH

Despite its inherent potential for wind power integration, there are not many studies on the technology assessment of WTES. An investigation concerning the direct conversion of wind energy into heat using a Joule Machine was developed since a heat generator driven by a wind turbine can reduce the cost of energy for heating systems (Chakirov & Vagapov, 2011). Furthermore, (Meibom, Kiviluoma, Barth, Brand, & Weber, 2006) analysed the economic value of using electrical heat boilers and heat pumps as wind power integration measures relieving the link between heat and power production in combined heat and power plants (the electricity production from CHP plants is to some extent driven by the heat demand in the district heating grids that the CHP plants deliver heat to). Moreover, (Hedegaard & Münster, 2013) presented a case study of the Danish energy system in 2020 with 50% wind power and showed that individual heat pumps and heat storage units can contribute to the integration of wind power. Additionally, the authors concluded that in terms of reducing fuel consumption of the energy system, the installation of heat pumps is the most important step.

Concerning WTES prototypes as whole, only two patents were found. Firstly, (Hoffeld, Obser, & Schust, 2007) patented a WTES system sponsored by the German retarders manufacturer Voith Gmbh. The WTES concept is compound of a WEC and a hydrodynamic retarder, which stands in drive connection with the turbine rotor, in order to produce heat.

Secondly, (Lee, 2011) patented a WTES system sponsored by Apple Inc., where a WEC converts the kinetic energy from the wind into rotational energy in its shaft, which is connected to rotating blades. These blades rotate immersed in a low-heat-capacity fluid in order to convert that rotational energy into heat. Then, the system selectively transfers the heat from the low-heat-capacity fluid to a working fluid and, finally, the WTES uses the transferred heat to generate electricity.

When analysing the involved costs for WTES, (Okazaki, Shirai, & Nakamura, 2015) concludes that the power generation costs of WTES plants can be competitive with conventional electricity generation from wind power, if for this the additional provision of gas turbines is required as a back-up generation capacity. Additionally, the author also compares WTES with wind-battery storage systems, where significant cost-benefits can arise.

METHODOLOGY

The assessment of the WTES-concepts can be divided in two different work packages: a) Technologies assessment for WTES and b) economic assessment of the five different WTES-concepts. The technologies assessment for WTES is already fulfilled in the Backgrund and Wind powered Thermal Energy Systems sections. The current chapter describes which economical parameters and/or estimators are used in order to fulfil the economic assessment of the five WTES-concepts. Firstly, the background for the selected criterion is explained and, then, the chosen parameter is explained. Finally, all the assumptions which are made for the assessment are detailed.

"The choice of which measure is used to evaluate an investment is determined by several factors. These factors include the investor's perspective, regulation, risk, financing, cash flow, comparison of mutually exclusive alternatives, and so forth. Most of the economic measures are valid for most investments; however, certain measures are clearly inappropriate for some investments" (Short, Packey, & Holt, 1995).

The methodology proposed to be used in order to assess the different WTES-technologies is the Levelized Cost of Energy (LCOE). This method allows alternative technologies to be compared when different scales of operation, different investment and operating time periods, or both exist. LCOE is recommended for use when ranking alternatives given a limited budget simply because the measure will provide a proper ordering of the alternatives, which may then be selected until the budget is expended. Additionally, LCOE is also commonly accepted as an indicator either for accept or reject an investment. As mentioned before, although many different approaches are useful for assess/evaluate renewable energy technologies, the LCOE is a widely used measure for modelling or policy development.

In order to determine the most cost-effective WTES, LCOE will be applied so as to analyse the two following concepts:

a. Accept/Reject: Normally used when a single investment is under consideration, where it can either be accepted or rejected
b. Ranking: Used to select one or more investments from a set of non-mutually exclusive investment alternatives. The objective of the analysis is to select the set of investments that will maximize the value to the investor from his or her available investment funds

Levelized Cost Of Energy

The LCOE method used in this thesis follows the method presented by (IRENA I. R., 2015), based on a discounted cash flow (DCF) analysis, which discounts financial flows (annual, quarterly or monthly) to a common basis, taking into consideration the time value of money. The main advantage of this approach is its simplicity and transparency, which results in an easy-going method.

The formula used for calculating the LCOE is depicted by the following equation (9):

$$LCOE = \frac{\sum_{i=1}^{n} \left(\frac{I_i + M_i + F_i}{(1+r)^i} \right)}{\sum_{i=1}^{n} \left(\frac{E_i}{(1+r)^i} \right)} \tag{9}$$

Where:

LCOE = the average lifetime levelized cost of energy

I_i = investment expenditures in the year i

M_i = operations and maintenance expenditures in the year i

F_i = fuel expenditures in the year i

E_i = electricity (or heat) generation in the year i

r = discount rate

n = life of the system

Assumptions

In order to estimate the LCOE of the different WTES concepts, some assumptions are made. This section intends to clarify them.

WEC nominal power based vs. Fixed Thermal Output based

For the LCOE estimation, the generated energy (electrical or thermal) is a decisive parameter. In the systems proposed in this work, two different approaches are available. On the one hand, when considering the system as WEC nominal power based (WEC_$P_{N\text{-}FIX}$), different commercially available WECs are analysed and, therefore, their nominal powers correspond to the manufacturer datasheet. Then, after considering all the efficiencies involved, and their implications in the energy transformation chain, the resulting AEP is estimated.

On the other hand, when the system is analysed as fixed thermal output based ($OUTPUT_{THERM-FIX}$), the desired AEP are considered fix and the parameters which are analysed, taking into account the efficiencies involved, are the different WEC's nominal powers.

The first approach presents the advantage that the WEC's nominal powers are commercially available and, consequently, this approach offers a more realistic cost estimation. However, its main drawback is the limitation in the resulting AEP. Hence, the output thermal energy is limited by the WEC's nominal power and, therefore, different system sizes cannot be freely chosen.

The second approach, in contrast to the first, presents the advantage of choosing the output thermal energy without any restraints. Nonetheless, this approach may result in WEC's nominal powers which neither are commercially available nor provided by any manufacturer.

In the lights of these issues, since the present work intends to analyse particular system sizes, which are described in the following section, the second approach (Thermal output based estimations) is chosen.

SYSTEM SIZE DETERMINATION

As mentioned before, three different system sizes are analysed. The aim of these sizes is to dimension WTES to different market needs. Firstly, a small size system is proposed, ideally for a single off-grid house with four inhabitants. According to (Gils, 2015), an annual average heating demand of 5.9 MWh/Inhabitant is assumed. As a result, the total annual heat demand for a small WTES is **23.6 MWh/yr**.

From the annual average heating demand of 5.9 MWh/Inhabitant, medium and large systems are developed. The medium system is considered to be supplied by a single wind turbine and deliver heat to a village of 2000 inhabitants and, as a result, the total annual heat demand for a medium WTES is **11,800 MWh/yr**. Moreover, the large system is considered to be supplied by a windfarm and deliver heat to a village of 20000 inhabitants and, as a result, the total annual heat demand for a large WTES is **118,000 MWh/yr**. The following Table 4 sums up the consideration for the proposed system sizes.

Table 4 – System size parameters

Size	Avg. Heating Demand [MWh/Inh.yr]	Inhabitants [n]	Total Annual Heating Demand [MWh/yr]
Small	5.9	4	23.6
Medium	5.9	2000	11800
Large	5.9	20000	118000

WEC cost breakdown, Economy of scale and Efficiencies

Concerning the CAPEX and OPEX estimations for traditional WECs, no further explanations have to be done since both concepts are properly explained in the WEC Costs section. However, when WECs are used for mechanical energy production, some clarification regarding CAPEX and OPEX must be done.

Firstly, as it can be seen in Table 3 on page 29, some traditional medium/large WEC's sub-components have to be subtracted from the original CAPEX estimation, since they are needed only for electrical generation purposes. Thus, generator, power converters and transformer must be excluded. Hence, their corresponding CAPEX shares are deduced from the original CAPEX for electricity generation.

Additionally, the CFs analysed in the present work range from 0.10-0.55 in order to cover the wide spectrum shown Figure 12 on page 22.

Regarding the gearbox, due to the fact that the WEC's rotation speed is not high enough to match the nominal rotational speeds from mHP and RET, this item is needed and, consequently, remains in the CAPEX estimations for mechanical energy generation.

As far as OPEX is concerned, as can be seen in Figure 17 on page 28, only the "Service and Spare parts" shares are influenced by the deduction of the previously mentioned items for electricity generation. Unfortunately, data for the proper reduction estimation of this share is really scarce and, after analysing four different scenarios, a reduction of 2% of the original share is used. As a result, "Service and Spare parts" OPEX shares are reduced from 26% to 24%. Moreover, equally distribute annually fixed O&M expenditures are considered.

Secondly, the same problem occurs in small power WECs. Then, the sub-components, depicted in Figure 18 on page 30, which are no going to be considered in the CAPEX estimation and which are thus deduced from the original CAPEX for electricity generation are: Charge regulator, inverter, cables, switches and grid connection. Additionally, the total small WEC's share is 37%, but no cost breakdown is developed for this small power WEC itself. Therefore, in order to deduce the cost of the electrical generator itself, a fixed cost of 3000€[5] is deduced from the final CAPEX.

Another clarification that must be done concerns the economies of scale assumed in this study. Wind power projects costs exhibit economies of scale and, according to (U.S. DOE, 2013),

[5] This estimation is the result of a market research for asynchronous motors between 70-100kW

windfarms with installed capacities ranging between 20-50 MW experience a reduction around 22% of their CAPEX when compared to single wind turbines installations. Thus, large WTES, either for electrical or mechanical energy production, are considered to experience a 22% reduction in its CAPEX when compared to WTES medium systems. Regarding the OPEX estimations, no economies of scale are considered.

Finally, the last clarification refers to the WEC's efficiencies. Since electrical generators are not considered for mechanical energy production, their efficiencies must not be taken into account when estimating the AEP. Due to the fact that this work is thermal output based, not considering these efficiencies results in different WEC's nominal powers instead of affecting the thermal output ($AEP_{THERMAL}$). Efficiencies of 86% are considered for small power WECs and of 98% for medium/large power WECs.

MHP COST BREAKDOWN AND IMPLICATIONS

Cost breakdown data for mechanically driven HPs is carce. For converting a traditional eHP to a mHP, this work assumes that only the motor, which is used for powering the compressor, is deduced.

Regarding small HPs, which are considered for small WTES, they only have one compressor and, therefore, only one motor is deduced. Medium/large HPs, larger than 2MW, which are considered for medium/large WTES, have up to 16 compressors.

For small mHP's CAPEX, a fixed amount of 3,000 € is deduced from the total CAPEX. For medium/large HPs the estimation is done as follows:

a) The total power of the system is estimated
b) 2 MW (16 compressors) HPs are used. As a result, each compressor uses a 125kW motor
c) From the total power of the system, the total amount of 125kW motors are estimated
d) Each 125kW motor costs 15,000€ and then, the total cost for motors is calculated
e) All motors costs are deduced from the total CAPEX of the system

Concerning the OPEX for mHP a reduction of 10% from the eHP's OPEX is assumed.

Last but not least, when not considering the motors for mHPs, their COP changes. Small mHPs are assumed to use a motor with an efficiency around 86% and medium/large mHPs are assumed to use motors with efficiencies around 96%. Then, the new COP is estimated as equation (10) depicts.

$$COP_{mHP} = \frac{COP_{eHP}}{\eta_{MOT}} \tag{10}$$

TES DIMENSIONING AND CAPEX ESTIMATION

For the TES dimensioning, this work does not analyse which TES fits better each WTES technology, but it only considers its costs. For the TES sizing, firstly, the peak demand has to be estimated and then the total amount of hours to constantly supply that peak load. The first parameter is calculated by multiplying the total annual demand times 0.000319, which accounts for the maximum percentage of considered peak load. Then, the total amount of hours assumed to constantly supply the estimated peak loads are 2 hs for small systems, 5 hs for medium systems and 10 hs for large systems. Finally, the TES sizes, in kWh, are estimated by multiplying the peak loads by the total amount of hours to constantly supply that peak load. Al the calculations performed are according to the procedure presented in (Gils, 2015).

As a result, the estimated TES sizes are:

- Small TES: 15.1 kWh
- Medium TES: 18,821 kWh
- Large TES: 376,420 kWh

CAPEX is calculated by dividing the costs [€/m^3], which present typical values ranging between 200-1500 €/m^3, by the energy density [kWh/m^3] of the chosen TES technology, which presents typical values ranging between 30-70 kWh/m^3 (Gils, 2015) (IRENA & IEA-ETSAP, 2013).

The chosen costs in [€/kWh] are in accordance with (Gils, 2015):

- Small TES costs: 23.81 €/kWh
- Medium TES costs: 11.22 €/kWh
- Large TES costs: 9.62 €/kWh

SUMMARIZED ECONOMICAL PARAMETERS

The CAPEX and OPEX values used in this thesis are shown in the following Table 5.

Table 5 – Sum up of used economical parameters

Description		CAPEX [M€/MW]	$OPEX_{FIXED}$ [€/MW/yr]	$OPEX_{VARIABLE}$ [€/MWh]	η / COP [-]	Ref. -
WECs for electricity generation						
Small System	AVERAGE	6.00	25000	-	0.86	(U.S. DOE, 2015)
	MAX	8.20	35000	-		(U.S. DOE, 2015)
	MIN	6.00	20000	-		(U.S. DOE, 2015)
Medium System	AVERAGE	1.97	-	20.00	0.93	(IRENA I. R., 2015) (EWEA, 2009)
	MAX	2.39	-	20.00		(IRENA I. R., 2015) (EWEA, 2009)
	MIN	1.18	-	20.00		(IRENA I. R., 2015) (EWEA, 2009)
Large System	AVERAGE	1.53	-	20.00	0.93	(IRENA I. R., 2015) (EWEA, 2009)
	MAX	1.86	-	20.00		(IRENA I. R., 2015) (EWEA, 2009)
	MIN	0.92	-	20.00		(IRENA I. R., 2015) (EWEA, 2009)
WECs for mechanical energy generation						
Small System	AVERAGE	4.38	22500	-	0.86	(U.S. DOE, 2015)
	MAX	5.99	31500	-		(U.S. DOE, 2015)
	MIN	4.38	18000	-		(U.S. DOE, 2015)
Medium System	AVERAGE	1.77	-	19.60	0.95	(IRENA I. R., 2015) (EWEA, 2009)
	MAX	2.14	-	19.60		(IRENA I. R., 2015) (EWEA, 2009)
	MIN	1.06	-	19.60		(IRENA I. R., 2015) (EWEA, 2009)
Large System	AVERAGE	1.38	-	19.60	0.95	(IRENA I. R., 2015) (EWEA, 2009)
	MAX	1.67	-	19.60		(IRENA I. R., 2015) (EWEA, 2009)
	MIN	0.82	-	19.60		(IRENA I. R., 2015) (EWEA, 2009)
Heat Generators Technologies						
Electric Boiler	AVERAGE	0.10	1100	0.50	1	(Gils, 2015) (ENS, 2012)
	MAX	0.15	1100	0.50		(Gils, 2015) (ENS, 2012)
	MIN	0.06	1100	0.50		(Gils, 2015) (ENS, 2012)
Electrical driven HP	AVERAGE	0.70	5500	-	2.8	(Gils, 2015) (ENS, 2012)
	MAX	1.004	7300	-		(Gils, 2015) (ENS, 2012)
	MIN	0.68	3700	-		(Gils, 2015) (ENS, 2012)
Mechanical driven HP	AVERAGE	0.70	4950	-	2.92 - 3.26	(Gils, 2015) (ENS, 2012)
	MAX	1.004	7300	-		(Gils, 2015) (ENS, 2012)
	MIN	0.68	3300	-		(Gils, 2015) (ENS, 2012)
Retarder	AVERAGE	0.01	250	-	1	VOITH GmbH
	MAX	0.05	1250	-		VOITH GmbH
	MIN	0.01	250	-		VOITH GmbH
Absorption HP	AVERAGE	0.40	18500	-	1.7	(ENS, 2012)
	MAX	0.42	21000	-		(ENS, 2012)
	MIN	0.37	16000	-		(ENS, 2012)

Fundaments for maximum and minimum LCOE estimation

For the purpose of the assessment, it is interesting to analyse how each WTES LCOE scatters when considering upper and lower costs boundaries. This analysis may result in a WTES with a reduced LCOE but highly scattered or a really condensed LCOE but expensive.

The cost considerations for this analysis are shown in Table 5. However, a particular clarification for eHP and mHP is needed. Both technologies present the same CAPEX, but for the minimum and maximum analysis the mHP technology is studied differently.

- Maximum scenario for mHP: is exactly the same scenario which is used for eHP (pessimistic assumption). Then: $\mathbf{mHP_{MAX} = eHP_{MAX}}$
- Minimum scenario for mHP: the same scenario which is used for eHP is used but the deduction of the motors costs is considered. Then: $\mathbf{mHP_{min} = eHP_{min}}$ **– motors costs**

Fundaments for LCOE as function of distance

An additional analysis is performed where the LCOE (only for large WTES) are varied as function of the distance. The aim is to estimate how far away a WTES windfarm can be from the final demand. For this analysis, three parameters must be established for the heat transportation:

- CAPEX: after consulting some experts of the district heating field, they agreed that an acceptable estimation for the investment costs of would be 0.2 M€/km
- OPEX: according to the (VDI, 2012), operational expenditures for heat transportation nets are 1% of the total CAPEX
- Losses: No losses over 20% along the entire distance are allowed. According to the datasheet from ISOPLUS's, which is a tubes manufacturer, a losses coefficient of 18.737 W/m is assumed.

Results and Discussion

The current chapter presents the results of the economic assessment of the WTES. It is composed of three sections: firstly, the LCEO results for the system sizes with average cost considerations are presented, including heat generation and TES costs. Afterwards, the variation of LCOE as function of different costs scenarios (maximum & minimum) is developed, also including heat generation and TES costs. Finally, the LCOE variation as function of the distance is analysed and presented for both a general scenario and a particular case.

General Results – LCOE estimations

In order to develop the economical assessment of different WTES concepts, the average cost trends are considered. Additionally, traditional heating sources are presented in the results not only to compare WTES with each other, but also with commonly used heat generator units.

Figure 24 depicts how small system LCOEs are ranked when analysing different WTES concepts. This graphical representation shows in its y-axis the corresponding LCOE and in its x-axis the CFs which are considered for the analysis. As a result, the LCOE as function of the CFs is obtained.

Additionally, this graph shows the gas boiler heat production cost range, which is the most commonly used heat generator device on off-grid houses with a $LCOE_{HEAT}$ ranging between 10-15 c€/kWh (FICHTNER, 2014). As it is expected and, according to the literature reviewed in the Literature Research section, the base case proposed presents the most expensive LCOE for heat generation purposes. Hence, EB cannot be considered a cost-effective WTES solution, since its LCOE only breaks into the traditional gas boilers cost range when really high capacity factors over 0.40 are considered. In contrast, mHP presents competitive LCOEs along the entire CF spectrum and, based on this analysis, results to be the least-cost concept for a small WTES system.

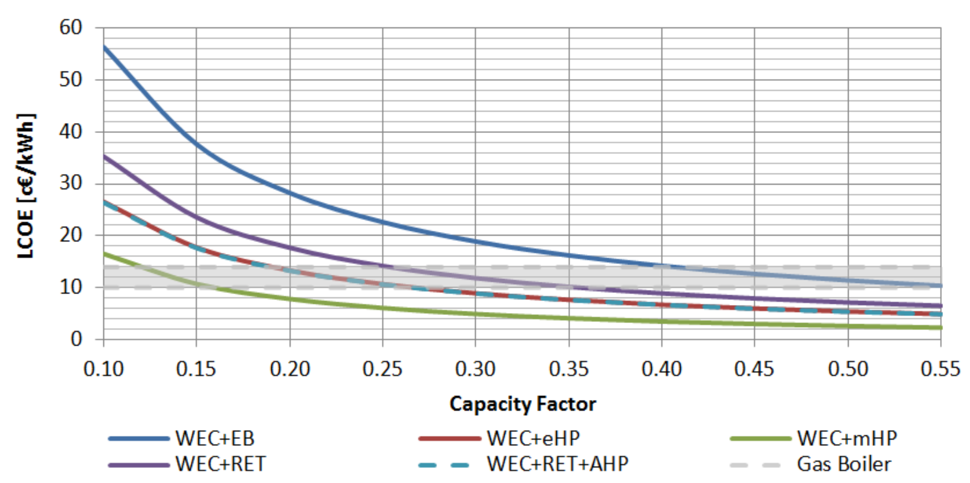


Figure 24 – Small System LCOE

Interesting to point out is the fact that two technologies present almost the same costs for heat generation. Both electrical driven HP and Retarders+AHP systems seem to be a cost-effective solution for small systems when capacity factors over 0.20 are considered. However, considering the fact that small systems sizes are aimed to depict off-grid houses, eHP alternative implies an electricity consumption, which can be avoided by choosing the second alternative of the retarder and the absorption HP.

Medium and large systems present the same ranking of concepts as far as LCOE for each technology is concerned, but large system presents lower costs manly driven by the economies of scale considered. Hence, as Figure 25 and Figure 26 show, the LCEO reduction for a large system is revealed as a shifting in the curves. Additionally, in both graphs a renewable energy based heat generation source (large wood chip boiler) is potted, as well as a traditional fossil fuel based source (large gas boiler). These technologies present $LCOE_{HEAT}$ ranging between 8-11 c€/kWh and 6-7.5 c€/kWh respectively (UNEP, 2015).

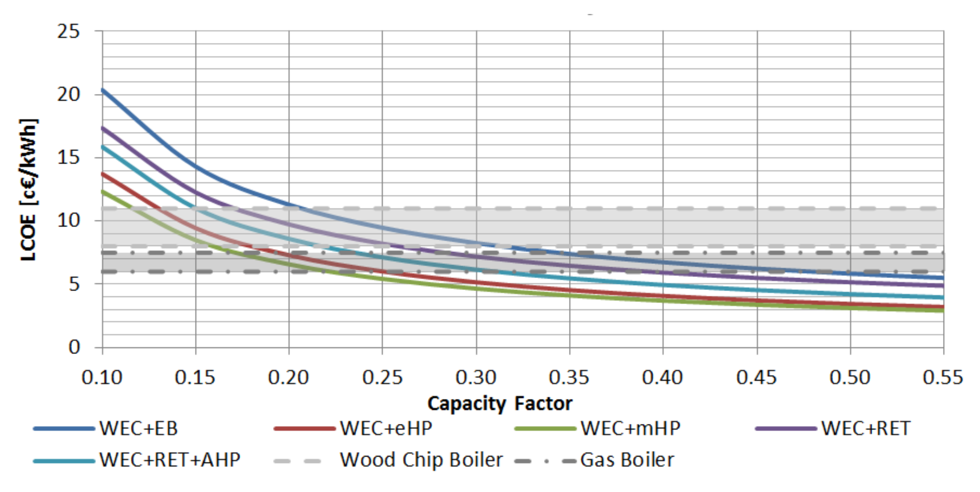


Figure 25 – Medium System LCOE

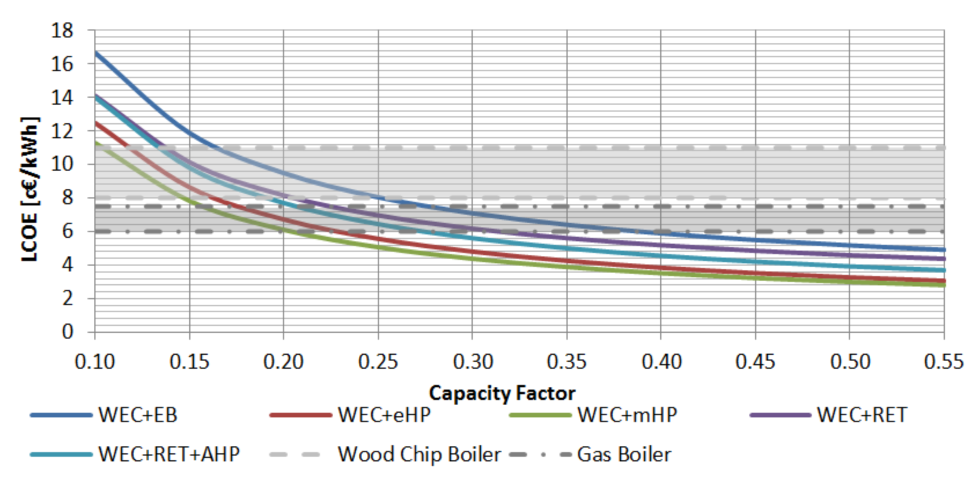


Figure 26 – Large System LCOE

Like for small systems, EB still present the highest LCOE of all WTES concepts. However, when comparing WTES's LCOEs with traditional heat generation sources, all concepts may be cost-effective alternatives at medium CF ranges. In contrast with small systems, eHP presents remarkably lower LCOE compared to RET+AHP. However, mHP still emerges as the most cost-effective WTES alternative independent of the system size.

LCOE SPECTRUM FOR DIFFERENT SCENARIOS

The following analysis clarifies how the LCOE of each WTES concept scatter when considering upper and lower costs boundaries. Figure 27 shows how WTES concepts scatter in small size systems. EBs present the highest cost boundary of all WTES concepts but its lower boundary overlaps even with the lower ones corresponding to eHP and RET+AHP. Both eHP and RET+AHP almost have the same upper and lower boundaries and mHPs still emerge as the most cost-effective alternative for small WTES with almost no overlapping areas.

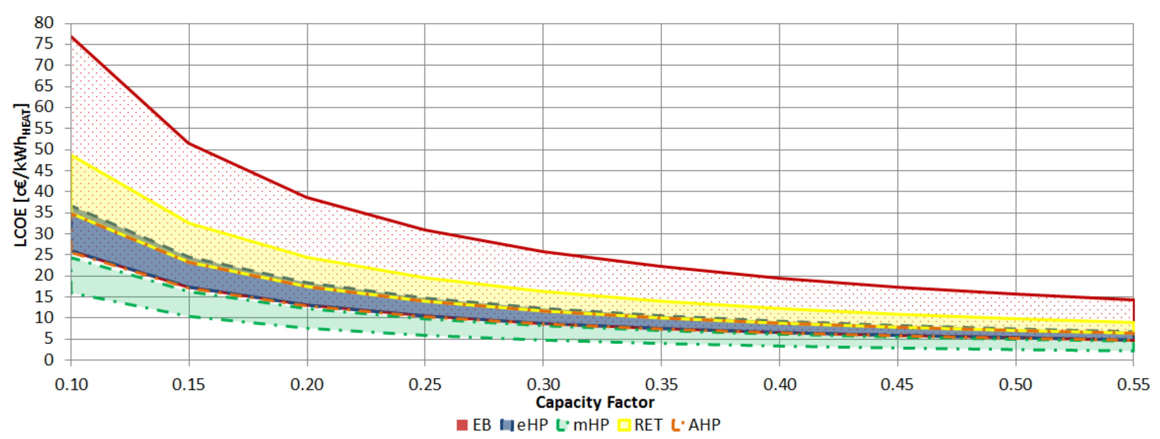


Figure 27 – Small System LCOEs for Maximum and minimum scenarios

The costs ranges of all medium WTES concepts overlap, as Figure 28 depicts. EBs still present the most scattered LCEO and mHP shows the lowest cost boundary. The overlapping effect is even denser when large systems are considered (Figure 29). Furthermore, when analysing large systems, it is not clear which WTES concept is the most cost-effective alternative due to the overlapping phenomenon, which results in a not so straight forward interpretation when compared with small systems results (Figure 27). However, mHP still presents the lowest costs boundary.

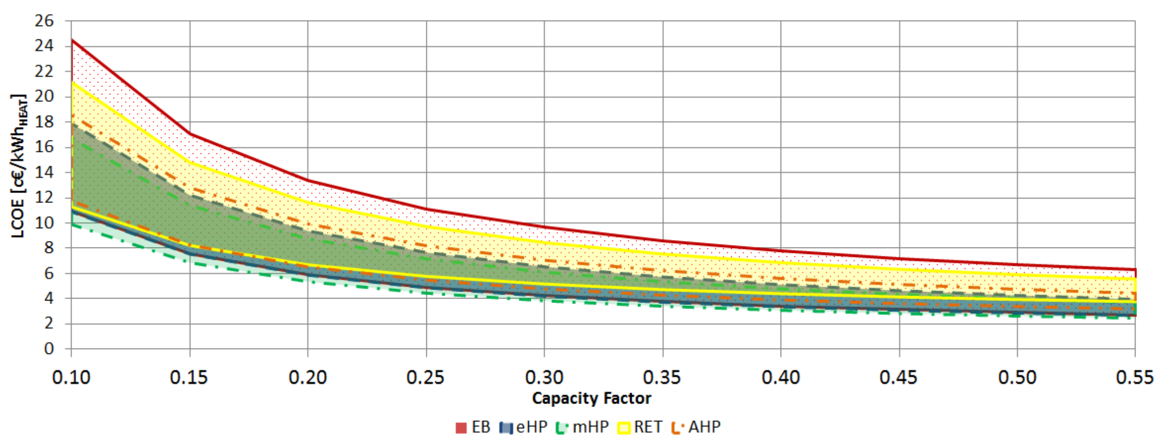


Figure 28 – Medium System LCOEs for Maximum and minimum scenarios

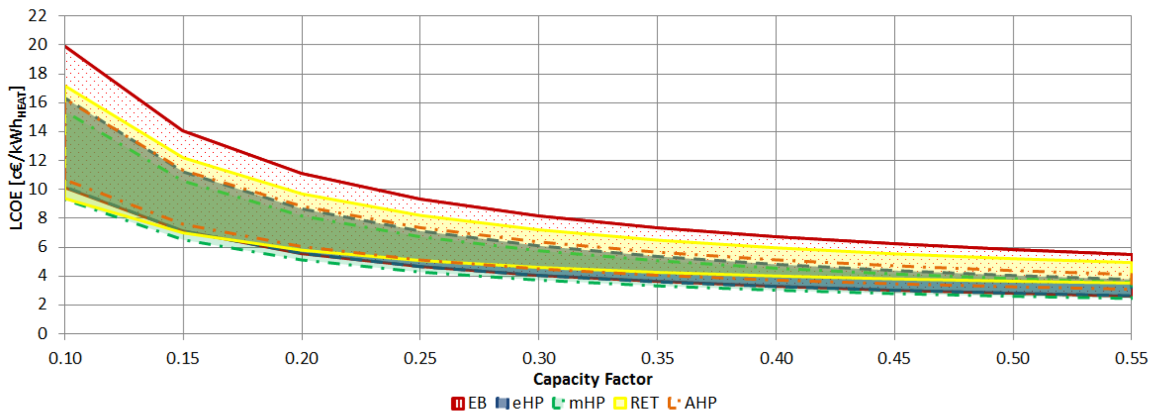


Figure 29 – Large System LCOEs for Maximum and minimum scenarios

Interesting to point out is that, when low CFs are considered RET technology presents LCEO really close to those obtained by mHP. It can be assumed that for CFs lower than 0.25 mHPs and RETs are the leas-cost alternatives for heat generation, while for higher CFs mHP and eHP still emerge as the best alternatives.

LCOE AS FUNCTION OF THE DISTANCE

This study is performed only for large systems with a CF of 0.25 since this value is around the European average, as shown in Figure 12 in page 22. This analysis aims to analyse how far away a WTES windfarm can be from the final heat demand if the TES is built close to the WTES. Storage close to the final demand could be constructed smaller since it would not have to store the transportation losses. However, here a system with a TES close to the WTES was chosen since it was assumed that the area for the construction is more readily available out of town.

As Figure 30 shows, the WTES sorting is the same as the one shown in Figure 26 but, despite the fact that the five straight lines seem to be parallel to each other, they present slightly different slopes, which implies that different technologies are affected differently by the heat transportation costs.

EB presents an LCOE increase of 0.0258 c€/(kWh*km), while eHP and mHP present the lower LCOE increases per km: 0.0224 c€/(kWh*km) and 0.0217 c€/(kWh*km), respectively.

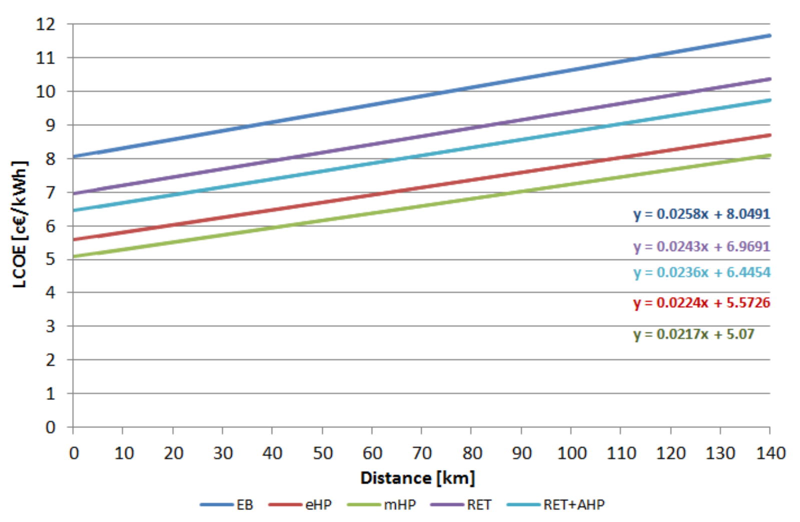


Figure 30 – LCOE = f(distance)

Figure 31 compares two different scenarios for the same WTES concept versus a traditional wood chip boiler and gas boiler. The dark green line presents the LCOE as function of the distance for mHP considering maximum CAPEX, OPEX and a CF of 0.15 (pessimistic scenario). In contrast, the lower light green boundary line considers minimum CAPEX, OPEX and a CF of 0.40 (optimistic scenario).

The aim of these scenarios is to present the entire LCOE spectrum for the most cost-effective WTES technology when affected by heat transportation. Therefore, mHP is chosen for this analysis since this WTES concept presents the undermost cost trend boundaries for the LCOE spectrum scenario analysis. Nonetheless, this study can be performed for any WTES concept and, consequently, the result is going to be different regarding the slopes from the upper and lower boundary lines.

The green shaded area depicts the cost-effective zone where mHP WTES system are cheaper that traditional heating sources. The dimension of this area is strongly dependant on the CAPEX, OPEX, CF and distance from the heat demand. Additionally, further parameters which are not considered in this study affect this estimation i.e. land rent contracts, feed-in tariffs for heating purposes, etc.

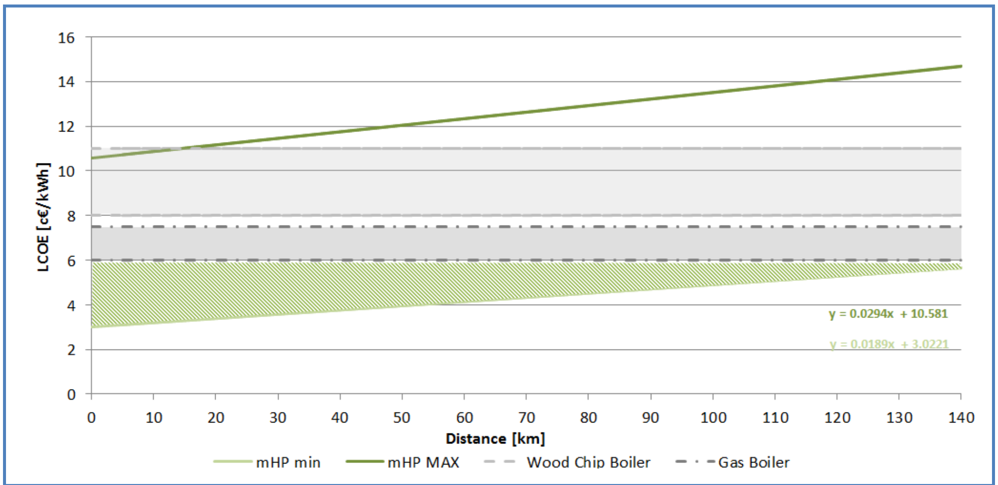


Figure 31 – LCOE = f(distance) – mHP particular case

Furthermore, this study does not take into account the influence of the distance in the heat generation costs for traditional heating sources. This consideration intends to estimate how far away a new WTES windfarm can be in order to replace an already operating heat generation plant.

Important to point out is the fact that the pessimistic scenario presents LCOE as a function of distance with around 53% steeper slope than the optimistic one: 0.0294 versus 0.0189 c€/(kWh*km).

SUMMARY AND CONCLUSION

This study assesses in a techno-economical approach five different WTES concepts (electric boiler, electrical driven HP, mechanical driven HP, retarder, retarder and absorption HP), considering three different system sizes (a house hold, a WEC and a windfarm), as far as heat demand is concerned: 23.6 MWh/yr – 11,800 MWh/yr – 118,000 MWh/yr

The technical assessment is performed based on literature research, determining the corresponding strengths and weaknesses for each WTES concept. Furthermore, particular cost breakdowns are done in order to determine their influences in the economical assessment, which is performed based on levelized cost of energy analysis.

Three analyses are developed. Firstly, LCOE is estimated assuming average costs in order to sort the different WTES concepts according to their heat production costs. Then, maximum and minimum cost scenarios for each WTES are analysed, so as to study their scattered behaviours and, finally, large system's LCOE as function of the heat transportation distance is estimated. This final study aims to analyse the potential of WTES system for replacing a traditional fossil fuel heat generation plant.

Small system LCOE are remarkably high when compared with medium/large systems, mainly driven by its more than 3 times higher CAPEX (6 versus 1.97 M€/MW). Small system's least-cost WTES technology is mHP which presents lower LCOE along the entire CF spectrum, when compared with traditional gas boilers. Furthermore, as small systems are aim to represent a heat generation for off-grid houses, the selection of an eHP implies an additional electricity consumption, that can be avoided by choosing either mHP or RET+AHP, since both technologies present the lowest LCOE behaviours. Regarding EB, it is not only the most expensive technology, but it also presents most uncertainties, resulting in highly scattered LCOE. Concerning the retarder technology, its LCOE is not so scattered but its lower cost boundary is above the one obtained for EB, indicating that this technology is little-cost competitive.

In other to provide figure, regarding the costs involved for a small system, the following question is going to be answered: If the owner of an off-grid house hold wants to replace its old fossil fuelled based heat generator with an environmentally friendly WTES, how high would be the costs?

Then, the following assumptions are done: a typical heat demand of 23.6 MWh/yr , a CF of 0.25 (since it is the European average) and a mHP system is assumed. Consequently, under the mentioned considerations and according to the results obtained in this work, the investment costs of the system is around 17,300€ and the fixed annually O&M costs are 120 €/yr. This costs results in the already estimated LCOE of 6,11 c€/kWh heat generated

Both medium and large systems present promising heat costs. Either WTES system sizes present the same ranking concerning the WTES technologies LCOEs but large systems result in lower costs mainly due to economies of scale. Furthermore, all technologies can be considered as cost-effective alternatives, even when low CFs are considered. However, it is interesting to point out that in large systems when low CFs are considered, RET technology presents LCEO which are slightly higher (15%) than those obtained by mHP, when CFs lower than 0.25 are considered. This 15% can be even lower since, according to the retarder's manufacturer VOITH GmbH, retarder's capital cost presents economies of scale and its CAPEX is strongly dependent on the number of pieces ordered.

When higher CFs are analysed for large systems, mHP and eHP emerge as the best choices.

Finally, when analysing the influence of the heat transportation in the LCOE, EBs present the highest increase of LCOE 0.0258 c€/kWh*km, while eHP and mHP present 0.0224 c€/(kWh*km) and 0.0217 c€/(kWh*km) respectively. Concluding, some suggestions for the further proceeding are given.

Outlook

Regarding the further work recommendations, a detailed assessment concerning the TES arises as an interesting topic. It might be important to assess which TES is the most efficient and cost-effective for every WTES. Considerations like system size, WTES technology and land rent costs for TES, among others, are recommended.

Furthermore, since mHP WTES technology presents the most cost-convenient LCOE, it is really important to develop a detailed cost breakdown in order to reduce the uncertainties derived from the assumptions considered. Additionally, due to the fact that the three WTES concepts with upgrading devices (eHP, mHP and AHP) present the lower cost trends in every result, it might be advisable to analyse how their CAPEX and OPEX may evolve in the upcoming years and then, develop different scenarios for different cost trends analysing the resulting LCOEs.

Moreover, regarding the LCOE as function of the distance, it might be interesting to analyse how it may be influenced when placing the TES close to the demand, in order not to store the losses for the heat transportation. As a result, this consideration may lead to further cost reduction for heat transportation and, thus, in a more cost-convenient outlook for WTES.

Another interesting study is to develop a case study for an off-grid house. The assessment must consider technic and economic advantages of every WTES concept; total CAPEX and OPEX required for the project; energy efficiency considerations regarding the house’s thermal insulations and a detailed assessment of the heat demand pattern.

Finally, it might be really valuable to develop a time series analysis for all the WTES concepts, not only for the wind regime, but also for the heat demand. Considerations like different wind regimes, seasonal wind behaviours and different heat demand patterns for different system sizes might be really interesting to analyse. It might be possible that not all of the heat generated can be used and TES partially attenuates this problem. Hence, a time series analyses provides a reliable quantification concerning the amount of unused energy that might be expected.

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ANNEX A: $LCOE_{HEAT}$ RESULTS

Levelized Cost Of Energy (LCOE) for Average cost trends															
Capacity Factor	Traditional WEC + EB			Traditional WEC + eHP			Wind turbine + mHP			Wind turbine + RETARDER 2,5%			Wind turbine + RETARDER+AHP		
	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
0,10	56,37207	20,37462	16,66404	26,57467	13,73293	12,47626	16,53599	12,32950	11,28319	35,29644	17,35491	14,09882	26,41623	15,87167	14,00022
0,15	37,64028	14,31617	11,87798	17,75869	9,44313	8,64089	10,74242	8,49342	7,83142	23,57320	12,27303	10,13784	17,65306	11,01518	9,80309
0,20	28,27439	11,28694	9,48496	13,35069	7,29824	6,72321	7,84563	6,57538	6,10553	17,71158	9,73208	8,15735	13,27148	8,58694	7,70452
0,25	22,65486	9,46940	8,04914	10,70590	6,01130	5,57260	6,10755	5,42456	5,07000	14,19461	8,20752	6,96905	10,64253	7,12999	6,44538
0,30	18,90850	8,25771	7,09193	8,94270	5,15334	4,80553	4,94884	4,65734	4,37965	11,84996	7,19114	6,17686	8,88989	6,15869	5,60595
0,35	16,23253	7,39222	6,40821	7,68328	4,54051	4,25762	4,12118	4,10933	3,88654	10,17521	6,46516	5,61100	7,63801	5,46491	5,00636
0,40	14,22556	6,74310	5,89542	6,73871	4,08089	3,84669	3,50044	3,69832	3,51671	8,91915	5,92067	5,18661	6,69910	4,94457	4,55667
0,45	12,66458	6,23823	5,49658	6,00404	3,72341	3,52707	3,01765	3,37865	3,22906	7,94222	5,49718	4,85653	5,96883	4,53986	4,20691
0,50	11,41579	5,83433	5,17751	5,41631	3,43742	3,27138	2,63141	3,12291	2,99894	7,16067	5,15839	4,59247	5,38462	4,21610	3,92710
0,55	10,39406	5,50387	4,91645	4,93544	3,20344	3,06218	2,31539	2,91367	2,81066	6,52122	4,88120	4,37641	4,90663	3,95120	3,69817

SMALL SYSTEMS Levelized Cost Of Energy (LCOE) form MAX and min scenarios										
Capacity Factor	WEC + EB		WEC + eHP		WEC + mHP		WEC + RETARDER		WEC + RETARDER + AHP	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit
0,10	55,452	77,142	25,991	36,694	16,042	24,377	34,855	48,750	25,609	34,790
0,15	37,027	51,487	17,369	24,505	10,413	16,293	23,279	32,542	17,115	23,236
0,20	27,815	38,660	13,059	18,411	7,598	12,252	17,491	24,438	12,868	17,458
0,25	22,287	30,963	10,472	14,754	5,910	9,827	14,018	19,576	10,320	13,992
0,30	18,602	25,832	8,748	12,316	4,784	8,210	11,703	16,335	8,621	11,681
0,35	15,970	22,167	7,516	10,575	3,980	7,055	10,049	14,019	7,407	10,031
0,40	13,996	19,418	6,593	9,269	3,377	6,189	8,809	12,283	6,497	8,793
0,45	12,460	17,280	5,874	8,253	2,908	5,516	7,844	10,932	5,790	7,830
0,50	11,232	15,570	5,300	7,440	2,533	4,977	7,072	9,851	5,223	7,059
0,55	10,227	14,170	4,829	6,775	2,226	4,536	6,441	8,967	4,760	6,429

MEDIUM SYSTEMS Levelized Cost Of Energy (LCOE) form MAX and min scenarios										
Capacity Factor	WEC + EB		WEC + eHP		WEC + mHP		WEC + RETARDER		WEC + RETARDER + AHP	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit
0,10	13,134	24,440	10,892	17,887	9,888	16,698	11,284	21,146	11,753	18,561
0,15	9,489	17,026	7,549	12,212	6,866	11,406	8,225	14,800	8,270	12,808
0,20	7,667	13,320	5,878	9,375	5,355	8,759	6,696	11,627	6,528	9,932
0,25	6,573	11,096	4,875	7,673	4,448	7,172	5,779	9,724	5,483	8,206
0,30	5,844	9,613	4,206	6,538	3,844	6,113	5,167	8,455	4,786	7,055
0,35	5,323	8,554	3,729	5,727	3,412	5,357	4,730	7,548	4,288	6,233
0,40	4,933	7,759	3,371	5,119	3,088	4,790	4,403	6,868	3,915	5,617
0,45	4,629	7,142	3,092	4,646	2,836	4,349	4,148	6,340	3,625	5,138
0,50	4,386	6,647	2,869	4,268	2,635	3,997	3,944	5,917	3,392	4,754
0,55	4,187	6,243	2,687	3,959	2,470	3,708	3,777	5,570	3,202	4,440

LARGE SYSTEMS Levelized Cost Of Energy (LCOE) form MAX and min scenarios										
Capacity Factor	WEC + EB		WEC + eHP		WEC + mHP		WEC + RETARDER		WEC + RETARDER + AHP	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit
0,10	10,955	19,923	10,182	16,342	9,305	15,408	9,377	17,179	10,675	16,272
0,15	8,072	14,051	7,111	11,218	6,512	10,581	6,990	12,191	7,587	11,318
0,20	6,630	11,114	5,576	8,656	5,116	8,168	5,796	9,697	6,042	8,840
0,25	5,765	9,353	4,655	7,119	4,279	6,720	5,080	8,201	5,115	7,354
0,30	5,189	8,178	4,041	6,094	3,720	5,755	4,603	7,204	4,498	6,363
0,35	4,777	7,339	3,602	5,362	3,321	5,065	4,262	6,491	4,056	5,655
0,40	4,468	6,710	3,273	4,813	3,022	4,548	4,006	5,957	3,725	5,125
0,45	4,228	6,221	3,017	4,386	2,789	4,146	3,807	5,541	3,468	4,712
0,50	4,036	5,829	2,813	4,045	2,603	3,824	3,648	5,209	3,262	4,381
0,55	3,878	5,509	2,645	3,765	2,451	3,561	3,518	4,936	3,094	4,111

System LCEO [c€/kWh] - LCOE=f(distance)					
Distance	**EB**	**eHP**	**mHP**	**RET**	**RET+AHP**
5,00	8,18	5,68	5,18	7,09	6,56
10,00	8,31	5,80	5,29	7,21	6,68
20,00	8,57	6,02	5,50	7,46	6,92
30,00	8,82	6,24	5,72	7,70	7,15
50,00	9,34	6,69	6,16	8,19	7,63
75,00	9,99	7,25	6,70	8,79	8,22
100,00	10,63	7,81	7,24	9,40	8,81
110,00	10,89	8,04	7,46	9,65	9,04
120,00	11,15	8,26	7,67	9,89	9,28
130,00	11,41	8,48	7,89	10,13	9,52
140,00	11,67	8,71	8,11	10,38	9,75