Potential of Renewable Energies in a Small Industrial Facility

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Resumo

O objetivo deste trabalho é avaliar a viabilidade técnica e financeira da integração de fontes de energia renovável (FER) numa pequena unidade industrial. O caso de estudo considerado é uma pequena instalação industrial da Air Liquide, denominada *advanced product supply approach* (APSA), que é usada para produzir azoto. A produção de azoto precisa de grandes quantidades de energia elétrica que é atualmente fornecida pela rede nacional. Em primeiro lugar, é feita uma análise do consumo de energia deste equipamento, seguida da avaliação das tecnologias FER mais adequadas e do cálculo do potencial de FER no local. Existem atualmente diversas ferramentas de planeamento energético que são utilizadas para avaliar a integração de FER em vários setores. No entanto, nenhuma ferramenta existente é adequada para este estudo, pelo que uma nova ferramenta foi desenvolvida. O objetivo desta ferramenta é analisar técnica e financeiramente a implementação de FER em APSAs instaladas em diversos tipos de indústrias pelo mundo. Esta ferramenta considera energia eólica, solar, o uso de calor residual através de um ciclo de Rankine orgânico, células de combustível e baterias como tecnologias de armazenamento de energia. Os resultados obtidos para este caso de estudo mostram que é viável instalar um sistema de FER, sendo que a melhor solução incluí energia eólica, um ciclo de Rankine orgânico e não incluí armazenamento de energia. Isto deve-se ao facto do preço da eletricidade da rede nacional não ser suficientemente alto para compensar este investimento.

Palavras-chave:

Planeamento energético, Energias renováveis, Armazenamento de energia.

Abstract

The objective of this work is to assess the technical and financial viability of integrating renewable energy sources (RES) in a small industrial facility. The case study considered is an equipment of Air Liquide implemented on a metallurgical industry. This equipment is an advanced product supply approach (APSA) that is used to produce nitrogen. The production of nitrogen needs large amounts of power that is currently supplied by the national grid. Firstly, an analysis of the current energy consumption of the facility is carried out, followed by an assessment of the more suitable RES technologies and an estimation of local RES potential. There are currently many energy planning tools that are used to assess the integration of RES in several sectors. However, none of the energy planning tools available are suitable to carry out this study. Hence, a new tool was developed. The objective of this tool is to provide the technical and financial analysis of the implementation of RES in APSAs implemented in several types of industries throughout the world. This tool considers wind and solar power, the use of waste heat through an Organic Rankine Cycle, fuel cells and batteries as energy storage technologies. The results show that the implementation of RES, namely wind power and waste thermal energy, is economically viable, but storage technologies are not because the cost of the power from the grid is not sufficiently high.

Keywords:

Energy planning, Renewable energy sources, Energy storage.

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Nomenclature

Acronyms

AEP	Annual energy produced
APSA	Advanced Product Supply Approach
AS	Annual savings
CAES	Compressed Air Energy Storage
CF	Capacity factor
EEO	Estimated energy output
F	Free
FC	Fuel cell
FOM	Fixed operation and maintenance
GHG	Greenhouse gas
HF	Heat flux
L	Large
M	Medium
MM	Molecular mass
NA	Not available
NFS	Not for sale
OPEX	Operational expenditure
OR	On request
ORC	Organic Rankine cycle
p	Pressure
PD	Power density
PHES	Pumped heat electrical storage
PI	Power installed
PInd	Performance Indicator
PV	Photovoltaic
S	Small
VFR	Volume flow rate
VOM	Variable operation and maintenance

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1 Introduction

1.1 Motivation

Due to the economic and technological developments over the last decades, energy demand has been increasing significantly. In some countries such as India and China, the fast development has doubled the growth rate on energy demand, and countries as populated as these ones can have a large impact on the world energy demand. Not only the past shows a growth on the world energy demand but also the International Energy Agency predictions show that the demand will continue increasing at least until 2040 [1].

Worldwide, the energy consumption of the industrial sector reaches 54% [2], making this a crucial sector to analyze. Figure 1 presents the energy consumption shares of the OECD industrial sector in 2012 and 2040. As can be seen, the metal industry uses approximately 12% of the energy consumed on the OECD (10% on iron and steel and 2% on nonferrous metal) and the previsions for 2040 indicate that the consumption will be stable.

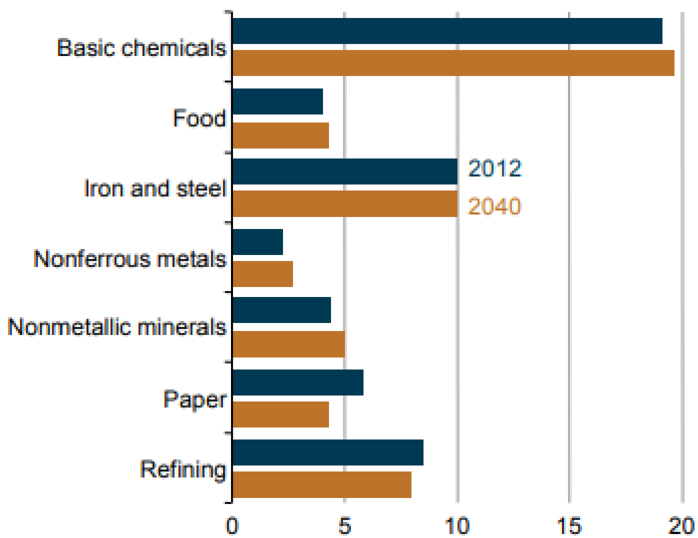

Figure 1 – Energy consumption shares of OECD industrial sector, 2012 and 2040 [2]

Nowadays, the non-renewable energy sources are the most used to produce electrical energy, generating more than 80% of the electrical energy used worldwide. The non-renewable energy sources are efficient and can produce large amounts of energy, even in small systems, when compared to other types of energy sources and are also, usually, more interesting from an economical point of view. However, there are many drawbacks related to the use of non-renewable energy sources such as; the finite reserves of coal, natural gas and oil and the fact that they are sometimes located in inhospitable places; the safety issues involved to their use, since some of them are highly inflammable, and the greenhouse gases (GHG) emissions involved with the energy production [1].

The renewable energy sources (RES) have a big potential because they are available in nature in large quantities, so they will not finish like the conventional sources. In addition, renewable energy sources can have zero greenhouse gas emission. The renewable energy sources can also be interesting from the economical point of view. Each situation has to be studied because the time that it takes to return the investments is highly dependent on the situation and its characteristics, such as the grid energy price and the amount of renewable energy available, such as solar exposure and wind speed. The cost reduction is still one of the most crucial points for the renewable energy development.

Each time renewable energy sources are considered for implementation a study has to be made in order to assess which renewable energy sources are suited for each case and if investment it is worthwhile. There are multiple factors to consider from the energy demand, considered technologies, the available space for RES implementation, the weather on the location where the renewable systems will be implemented. Since the amount of information to correlate is big the use of a RES assessment tool is the best approach. Currently, there are some energy planning tools that enable predictions and simulations based on inputted data for the case study which will be reviewed to find if they are suitable for the current case study.

The case study considered in this work is an Advanced Product Supply Approach (APSA), which is a system that is feed by electrical energy and air in order to isolate nitrogen to be used by the Air Liquids client. This type of system is usually implemented in the industrial sector. The companies from this sector commonly have low temperature waste heat, which can be used to produce electric energy through Organic Rankine Cycle (ORC) technologies. Additionally, some of these companies also use hydrogen which can eventually make the use of fuel cells viable. Hence, these technologies, in addition to the more commonly used wind and solar PV power, will also be considered.

1.2 State of the art

1.2.1 Energy planning tools

There are currently many energy planning tools that are used to assess the integration of renewable energy sources in multiple situations. Generically these tools need several inputs to predict or simulate the integration of different energy sources to fulfill a given energy demand.

Since there are many different situations in which renewable energy sources can be applied, some of the energy planning tools are focused on specific situations. Additionally, the type of analysis can also be different. For instance, some of the tools are built to make a study from the economical point of view where the investment and its breakeven are the primary objectives, others are focused on technical issues related with the systems implemented, and finally others have an environmental perspective where the main goal can be the reduction of the emissions related to the energy production. The energy sources and the energy storage technologies considered depend on the tool used. Some of the tools are more complex than others, this can result in more suitable results, but also involves spending more time to learn how to work with the tool as well as more computational time spent in the simulation. The costs are also an important aspect, multiple tools are free but some of them are sold and the prices can be high depending on the purpose of the study.

The energy planning tool need to fulfill certain specifications. All the energy planning tool require inputs related to the case study. These inputs make possible to perform an analysis to determine which would be the best selection of renewable energy sources for each situation. The user must be able to select the technologies that he intends to use. The choice can be from only one to eventually all the technologies available on the tool. An important aspect is to have available of energy storage, giving to the user the option to use it or not.

Considering this, the concept of suitable tool is very dependent on the situation in which it is going to be applied.

In order to know if there is any energy planning tool suitable for the present case study – APSA, a review was made. The factors considered on the review are the price, the training time, the renewable energy sources available in the tool, the storage technologies and the scale of the system.

In Connolly et al. [2] a review of multiple energy planning tool that aim to analyze the integration of renewable energy sources is performed. The paper reviewed 37 of 68 initially considered energy planning tools. The review of the tools was made following a methodology that takes into account the background information of each tool; information provided by users such as who and how many people used the tool and how the tool could be obtained; the tool properties and its characteristics; the applications for which the tool can be used for; the case studies previously analyzed with the tool. These method result on a review with many characteristics, which the most interesting for the present work are: the price, the investment, the option to make the system 100% RES, the RES technologies available, the storage technologies available, the training time to work properly with the tool. [3]

Besides this paper there is also another one by Ringkjøb et al. [3] that reviews 78 modelling tools for energy systems with large share of renewables. On this paper there are three main aspects reviewed which are general logic, spatiotemporal resolution and technological and economic properties. In these main topics some specific aspects were taken into account namely on the general logic: the main purpose of the tool, the approach used by the tool (if its top-down or bottom-up), the methodology used in the modelling of the energy system; and on the spatiotemporal resolution the location and the time-steps, that can vary from milliseconds in the power system analysis to decades on the economic equilibrium of the models. [4]

Taking both papers into consideration, the information was crosschecked and, some of it, confirmed on the energy tools websites, where updated information is available. Since these papers were made also using information provided by users of some tools there is information that might not be mentioned on the tools literature.

Not all the tools are worth presenting since many of them are practically unused and some are clearly not suitable for the present work purpose. The most relevant tools are presented in Table 1. The characteristics of the tools considered more relevant, for the present study are its suitability, the price, training time, the technologies considered for energy production and storage, and the scale of the case studies on which the tools are usable and if they are oriented for the industrial sector. Regarding the renewable energy sources the tool needs to include at least the PV, SWT, ORC and FC and for the storage it must include the electrolyzer/FC system and the solid state batteries.

Table 1 - Energy planning tool comparison considering the price, training time, RES considered (PV,SWT,ORC,FC), storage considered (FC/electrolyzer, batteries), scale and orientation [2][3]

Name	*Price (€)*	*Training Time (weeks)*	*RES Considered (all needed)*	*Storage Considered (all needed)*	*Scale*	*Industry oriented*
Aeolius	OR		NO	NO	L	NO
Balmorel	F	1	NO	NO	L	NO
BCHP Screening tool	NA	2	NO		S	NO
Compose	F	0.5	NO		L	NO
E4cast	OR		NO			YES
EMCAS	NA	3	NO			NO
Eminent	NA	5	NO			NO
EMPS	54k	5	NO	NO		NO
EnergyPLAN	F	5	NO		L	NO
energyPRO	5.6k	0.5			L	NO
ENPEP-BALANCE	F	2	YES	NO	L	NO
GTMax	OR	2			L	NO
H2RES	NFS	10	NO	NO	L	NO
HOMER	F	0.5	NO	YES	S/M/L	NO
HYDROGEMS	NA	15	NO	YES		NO
IKARUS	250	15	YES	YES		NO
INFORSE	NFS	4	YES		L	NO
Invert	F		YES	NO	L	NO
LEAP	NA				M/L	NO
MARKAL/TIMES	15k					NO
Mesap PlaNet	11k					NO
MESSAGE	NA	2			L	NO
MiniCAM	F	15+	YES		L	NO
NEMS	F		NO		L	YES
ORCED	F	1	YES	NO	L	NO
PRESEUS	OR	2				NO
PRIMES	NFS		YES	NO	L	NO
ProdRisk	OR	1	NO	NO	M/L	NO
RAMSES	NFS	1	YES	NO	L	NO
RETScreen	F			NO	ML	YES
SimREN	NFS		YES	NO	M/L	NO
SIVAEL	F	2			L	NO
STREAM	F	0.1	YES	NO	M/L	NO
TRNSYS16	3k	0.5	YES	NO	M/L	NO
UniSyD3.0	OR		YES	NO	L	NO
WASP	NA	6	NO	NO	L	NO
WILMAR Planning Tool	NFS	15	NO	NO	L	NO

It can be seen on Table 1 that the main problem with the selected tools is the fact that most of them do not provide an analysis considering all the technologies needed, this happens because some of the technologies are not in a point of development that allows them to be implemented in any situation and be economically viable. Most of the tools are not mainly focused on the industry sector, but all of them can be used to make an analysis on this sector, as a general sector.

Homer, IKARUS and TRNSYS16 despite not being entirely industry oriented, they can be applied to an industrial case study and are the most suitable to the case study since they have all the technologies needed.

Homer is a tool developed by the USA national renewable energy laboratory, it has been downloaded more than 32,000 times and the users can be using the tool after just one day of training time [3]. Homer simulates and optimizes both, stand alone and grid connected power systems and has been used in multiple cases, some of them at national scale, this makes the energy planning tool proven. Also, nowadays, the Homer has been updated more than 40 times, this shows that the tool is regularly being updated, preventing outdated simulation results.

IKARUS is a tool developed by the institute of energy research at Jülich Research Centre, Germany, and it is focused on cost optimization. The energy planning tool main focus is national energy systems scenarios. IKARUS has been used multiple time on investigations aiming carbon emission reduction and also to backup political decisions. At this moment more than 20 versions have been released which means the tool is regularly updated.

TRNSYS16 is a transient system simulation that is maintained by a international collaboration between the Thermal Energy System Specialists, the University of Wisconsin-Solar Energy Laboratory, the Centre Scientifique et Technique du Bâtiment, and the TRANSSOLAR Energietechnik. The tool was updated more than 16 time over the years. TRNSYS16 is a modular tool and has an open source code. Its primary objective is to simulate the performance of entire energy systems by breaking it down to its individual components. This tool has solid results as it has been extensively used to simulate energy systems on conventional buildings.

Having analyzed the tools the main problem is that none of the tools consider the ORC, some consider Rankine or other thermal cycles for energy generation. But, since the industries where, APSAs are usually implemented, have low temperature waste heat, these types of cycles are not suitable. Additionally, some of the tools assessed have a relevant learning time and price. Finally, the case study scale is also a problem, being most of the tools unsuitable.

With the tool comparison made and the certainty that there is the need to develop a new tool, the considered RES technologies (PV, SWT, ORC and FC) and the energy storage methods (FC/electrolyzer and batteries) will be briefly explained and analyzed how they can be included in the tool.

1.2.2 Photovoltaic systems

Solar energy is a renewable, free, clean and noise free energy source. Solar energy can be converted into electric energy, through photovoltaic (PV) panels or, into thermal energy using solar thermal collectors.

The photovoltaic panels are formed by solar cells that convert the sunlight photons energy into electricity. There are nowadays multiple types of PV cells with different characteristics, where the efficiency is one of the most relevant. The first PV cells were developed in the late 1950s and were used on small electronic devices and space stations. Nowadays PV cells can be used on small applications such as calculators, or on large applications such as PV power systems [5]. Photovoltaic systems can be divided into two main groups, stand-alone and grid-connected systems. Stand-alone systems are not connected to the grid so, the energy produced by the PV panels is directly consumed or stored. These systems can combine more than one energy source. The grid-connected systems are connected to the public electric grid. Stand-alone systems are a good option when grid-connection is not possible and a decentralized energy system needs to be considered or when it is intended to have a smart energy system, a sustainable and 100% renewable system that uses synergies to maximize the efficiency and reduce the costs [5]. Grid-connected systems are simpler since they do not require storage, although there will still be energy consumed from the grid. The installed power of stand-alone systems, when compared to grid-connected systems, is usually more than two times bigger, since the system has to produce energy to be directly consumed and energy to storage to be used during the hours when there is no energy production. The grid connected systems only produce to consume directly and when the system is not producing the energy is consumed from the grid.[6]

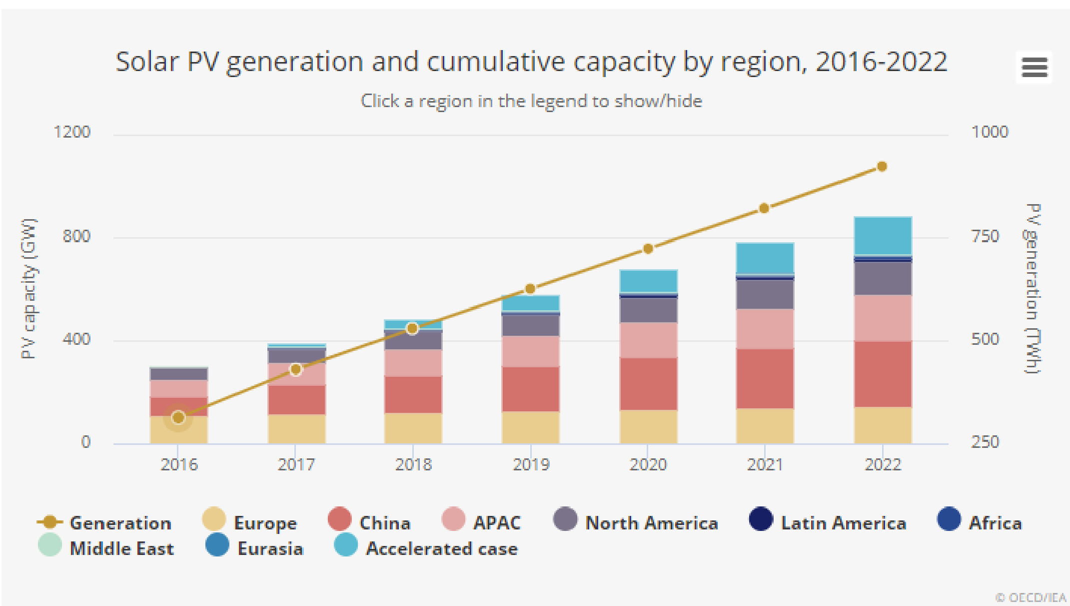

Figure 2 – Solar PV capacity 2016-2022 [7]

Figure 2 shows the PV capacity forecast evolution between 2016-2022. As can be seen the PV capacity is increasing in the world and will continue to increase until 2022.

1.2.2.1 Advantages and Disadvantages of PV systems

The electricity produced by PV systems is clean and silent. PV systems are very flexible and can be easily dimensioned on a wide range of sizes accordingly to the energy needs. They can be installed on unused spaces such as roofs and are visually not obstructive. Additionally, PV panels can be operated for a long time with very small maintenance.

There are although some drawbacks when PV systems are considered. The production of PV systems involves the use of toxic chemicals, which have a negative impact on the environment however this can be controlled by proper disposal of the harmful residues. Electrical energy production through PV systems is still considerably more expensive than the use of conventional energy sources, mainly due to the cost of manufacturing and to the low energy conversion efficiency. Additionally, PV systems have the problem of the intermittent production since the solar exposure is cyclical. [8]

1.2.2.2 Typical System Components

A photovoltaic system is composed of several components represented on Figure 3, including the PV array that is made by several photovoltaic modules composed by photovoltaic cells sealed to protect the components from the environment. The remaining components are the Balance of system equipment (BOS), this includes the wiring, the mounting systems that are used to apply the solar panels, the dc-ac inverter, meterings for system performance control, and safety features as ground-fault protection and overcurrent protection for the modules. For stand-alone systems, storage units (battery banks) will be added. [9]

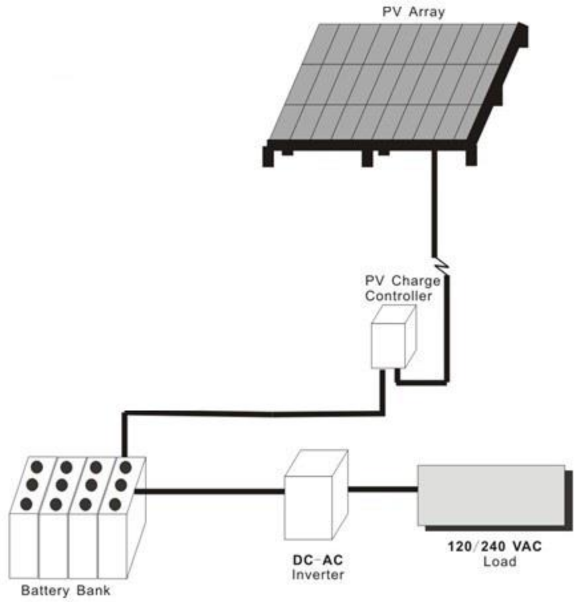

Figure 3 – PV system schema [10]

1.2.2.3 Technology Trends and Recent Developments

Solar photovoltaic technology is one of the most promising renewable technology and its development is ongoing. China's photovoltaic related companies have been playing a major role in the photovoltaic technology development. The research has been focused on new materials and new methods aiming the increase of the panel's efficiency. Nowadays, the efficiency of monocrystalline PV cells can be up to 24.4%. The most common PV cells on market, on the present days, are presented below on Figure 4, Figure 5 and Figure 6. The average efficiencies of each type are 15%, 13%, and 7% respectively [11].

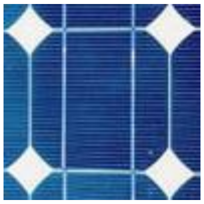

Figure 4 - Monocrystalline silicon [11]

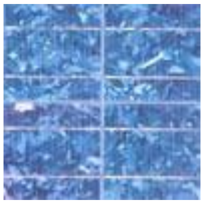

Figure 5 - Polycrystalline silicon [11]

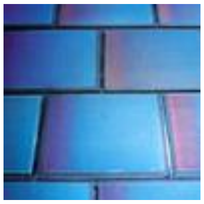

Figure 6 - Amorphous/thin film silicon [11]

Besides this, a lot of developed countries are creating policies to help photovoltaic technology's growth.[12]

1.2.3 Small wind turbines

Onshore wind energy systems are a mature technology and are proven to have great potential. During the last years, the electricity produced by onshore wind is clearly increasing. The power output of the wind turbines, per installed capacity, is also increasing as the turbines are being developed and getting bigger with taller heights and larger rotors. The cumulative grid-connected wind capacity reached 466GW (451GW onshore and 15GW offshore) in 2016 which represented 4% of the global energy production [13].

Aside from the large wind turbines, the small wind turbines (SWT), are a good solution for small renewable installations. The SWT are implemented in two situations, stand-alone systems and grid-connected systems, and their upper installed power is 100kW in most countries. Less attention has been given to small wind turbines and their lower development makes this technology little mature and uncompetitive. Most of the applications will only be economically appellative if the electricity prices will be sufficiently high. [14]

1.2.3.1 Advantages and Disadvantages of Small Wind Energy Systems

The greenhouse gas emissions related to the production of electricity with wind turbines are inexistent. The SWT operation costs are low when compared to other energy production systems and have been decreasing. If the installation region is abundant in wind the energy prices for the electricity produced by the SWT is competitive.

The SWT have some impact on the installation surroundings such as, the visual impact since it will change the landscape, the increase of bird casualties and the noise caused by the rotors, which can be problematic for residential zones. The output fluctuations are a reality since it depends on wind speed.

1.2.3.2 Typical System Components

The SWT systems, represented on Figure 7, are very similar to the PV systems, the BOS includes almost the same components, inclusive due to the lack of development on the SWT, the dc-ac inverters are from the PV system market. Some of the systems are hybrid systems using PV panels and SWT.

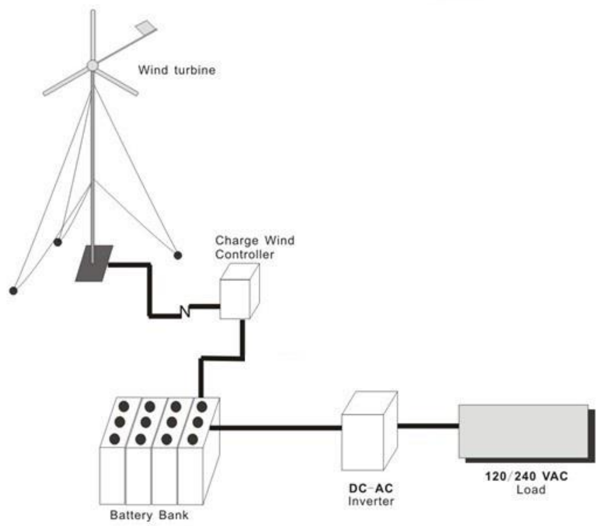

Figure 7 - SWT system schema [10]

1.2.3.3 Technology Trends and Recent Developments

Currently the most deployed small wind turbines have three blades although models with two and four blades are also common. The rotors' diameter is usually below 20 meters and the turbines are typically mounted on towers with heights up to 24 meters. SWT usually use synchronous permanent magnet generators, this is because the permanent magnets make the generators more compact and lightweight. The permanent magnets also make the start-up wind speed lower. Despite these advantages, some manufacturers still use induction generators. The small wind turbines are generally designed for low wind speeds which means larger rotors and taller towers. [14]

1.2.4 Organic Rankine Cycle

About 30% of the global final energy is used by industry and about 40% of the CO_2 emissions derives from this sector [15]. To lower the energy consumption and the CO_2 emissions associated with the industrial processes energy efficient measures have to be taken. The industrial processes waste heat represents a large amount of energy loss [16]. Since the waste heat reduces the efficiency of every industry, before making a study to implement the ORC there is the need to verify if the waste heat cannot be reduced by implementing efficiency measures. After the optimization, the remaining excess heat can, in fact, be considered to use on electrical energy production or to be used on other appliances that consume heat.

A great part of the dissipated heat on industries is low-temperature heat. However, for the low-temperature heat on small and medium industrial facilities, water-steam turbine systems are not compatible [17]. Despite this there are usually some hundreds of kW being dissipated that are worth recovering. In this sense, the development of the technologies to recover low-temperature heat is worthwhile.

Five different technologies for electricity generation from excess heat with low temperatures 200-500ºC were evaluated and compared by Bianchi and De Pascale [17]. The technologies compared were the ORC, the micro Rankine cycle, Stirling engine systems, thermoelectric generation and the inverted Brayton cycle. The ORC was proven to be the technology with the best performance of the five. Law et al. [16] also reviewed technologies for low temperatures. From the three technologies, ORC, Kalina cycle and thermoelectric generator, they also concluded that the ORC is the best option.

The ORC is a thermodynamic cycle that uses heat to produce mechanical energy which will be converted into electricity. It is similar to the steam Rankine Cycle, namely the main components such as the evaporator, expansion device, condenser and pump are the same. The difference is that the ORC works with an organic compound instead of water. [18]

The configuration and the working steps of the ORC are the following and are represented on a schema and on a thermodynamic graph on Figure 8.

The organic fluid is vaporized on the ORC evaporator (4-5); and flows through the turbine (5-6), which is connected to the electric generator. Vaporized fluid flows through the regenerator (6-7) , where the hot fluid preheats the cool fluid (2-3); and finally the fluid is cooled on the condenser (7-8-1) and then pumped back to the evaporator (1-2). [19]

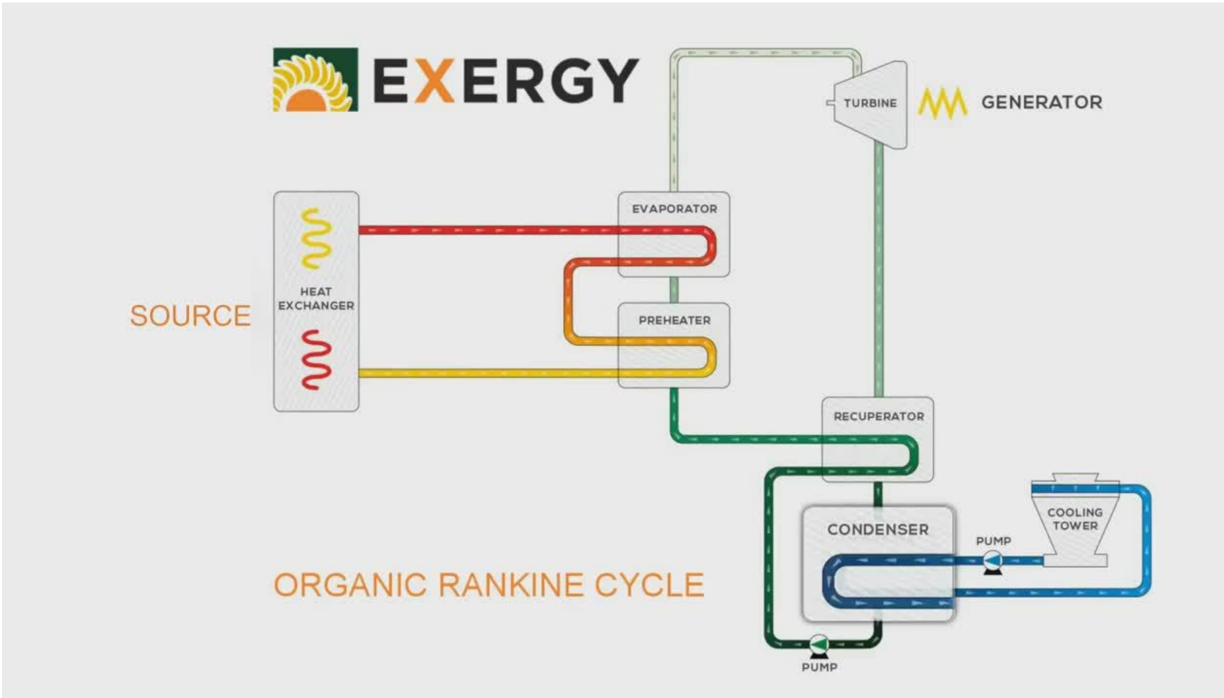

Figure 8 - ORC circuit diagram [20]

1.2.4.1 Advantages and Disadvantages of ORC systems

ORC systems are suitable to the use of low heat sources to electricity production. The ORC systems have a better performance on electricity production than other low-temperature systems. Since it uses an organic compound instead of water, there is no blade erosion due to moisture. The lower temperatures make the materials requirements lower than on other cycles. The systems are easy to start and stop and can be used on a wide range of loads. Additionally, the operation of the system and its' maintenance are very low.

The downsides of the ORC systems are that some of the compounds used are toxic or flammable and that the cycle efficiency lowers with the degradation of the fluid, which is expensive when comparing to fluids used on similar cycles. Due to the characteristics of the fluid thy cycle must be sealed. [21]

1.2.4.2 Technology Trends and Recent Developments

At the end of the year 2016, the ORC technology represented an installed capacity of 2700MW distributed over 1754 units. This technology was developed for a few decades exclusively for geothermal application but since 2003 the manufacturers started to consider the industrial waste heat and created smaller units. Nowadays most of the manufacturers of the ORC are focused on the small waste heat which ranges from 10 to 150 kWel. Between the years 2003 and 2008 there was a decline in the ORC market but after the decline, the market started to grow again. Most of the ORC systems are implemented nowadays on the metal (11.3%) and waste (9.3%) industries. The cost of this type of technology is still relatively high when compared to other small energy technologies, especially in units with less than 500kW. [22]

1.2.5 Fuel Cells

Fuel cells (FC) are by definition electrical cells. However, unlike common storage cells (solid state batteries), the fuel cells use fuel to provide electrical energy. The fuel provided to the cells make them able to sustain a power output for an indefinitely amount of time. Fuel cells convert hydrogen or hydrogen-containing fuels into electrical energy and heat through an electrochemical reaction that transforms hydrogen and oxygen into water, as shown on Figure 9. This process is the reverse of electrolysis. Being a cogeneration technology producing electricity and heat, it can reach very high efficiencies of up to 80%.

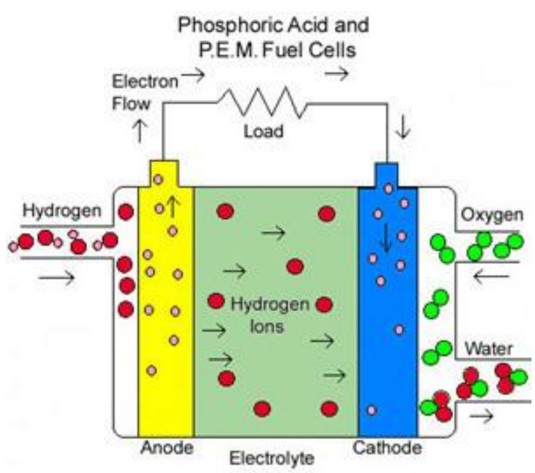

Figure 9 - PEM hydrogen FC process [23]

One of the most relevant issues when talking about hydrogen-fueled cells is the hydrogen source. The fuel cells can be considered renewable energy sources if the hydrogen is isolated sustainably, in this case, there will be no emissions directly related to the production of energy by the fuel cell. [24]

The fuel cells can be used on stand-alone systems as a primary energy supply or as a backup power. These systems can be implemented in locations where there is no grid available or, if it is economically better than being connected to the grid. As backup, the fuel cells can be started in seconds and supply all the energy needed. Like on stand-alone systems, on grid-connected fuel cells can be either a primary energy supply or be used as backup power. The primary energy supply applications can provide a base-load power working continuously. [24]

1.2.5.1 Advantages and Disadvantages of Fuel Cells

The fuel conversion into electricity is more efficient than on conventional electrical fuel-based generation technology. There are no moving parts on the fuel cells, which makes them very reliable and quieter than generators. Unlike batteries, that have to be disposed after a certain period of time, the FCs do not degrade and can be refurbished after its lifetime. Not only big fuel cells can achieve a high efficiency, small-scale fuel cells can also have a high level of efficiency which makes them good for portable systems. The fuel cell systems are flexible and can be applied incrementally making the costs to change the installed power smaller than in other technologies. [25]

In opposition, fuel cells are still very expensive, the fuel supply can be difficult in some locations. Besides this, the hydrogen characteristics make it hard to store and to transport. Other issue is the source of the hydrogen because to consider the energy produced renewable the hydrogen isolation must be made using renewable energy. [25]

1.2.5.2 Technology Trends and Recent Developments

The fuel cell market is growing rapidly since 2014, namely due to the transportation sector where fuel cells are applied to a large number of vehicles such as buses, trucks, material handling equipment, locomotives, trams and other specialized vehicles. Besides the transportation sector, the stationary power sector also covers a big share of the fuel cell market. On the stationary power sector, the fuel cell systems are divided into two groups, large scale of more than 200kW and small scale of less than 200 kW. The stationary sector includes applications on retail, residential, data centers and telecommunications. [26]

1.2.6 Energy Storage

One of the greatest challenges that came along with the use of renewable energy sources, namely intermittent ones, is the energy storage. Over the years the energy storage industry has been evolving. There is nowadays a wide range of energy storage technologies like, solid-state batteries, flow batteries, flywheels, compressed air energy storage (CAES), pumped heat electrical storage (PHES), pumped hydro-power, electrolyzer. [27]

Regarding small scale energy storage systems, large pumped hydro, compressed air and thermal should be excluded because of its bulk capacity characteristics. Flywheels, super magnetic energy storage and supercapacitors are considered environmentally friendly and can be considered. However, on small-scale systems reeling on intermittent renewable energy, accordingly to Psomopoulos et al. [28], the lead batteries are the best compromise between performance and cost. The Lithium-ion batteries have better performance, but the price is still too high to worth considering. [28]

The solid-state batteries have different electrochemical storage solutions, including chemistry batteries and capacitors. The solid-state batteries consist on sets of electrochemical cells that can convert stored chemical energy into electrical energy. Developments on this technology, namely on the materials used, have increased the reliability storage capacity on modern battery systems. The battery costs have also been decreasing dramatically over time. [29]

Like the fuel cells the electrolyzers are composed by an anode, a cathode and an electrolyte, its functioning is basically the reverse of a fuel cell. Electric energy and water are provided to the electrolyzer and it separates the hydrogen from the oxygen. The hydrogen is than stored for future use on fuel cells.[30]

1.3 Objectives

The objective of the present thesis is to develop a computer tool to assess the technical and financial viability of installing RES in APSAs located in industrial sites. Since there are multiple APSAs installed by Air Liquide over the globe the goal is to make a RES assessment tool that allows the use of the developed methodology on any APSA just by introducing the case study inputs. The developed tool has to be able to simulate the most used RES as well as some technologies of energy storage. APSAs are implemented on specific industries, as metallurgic, refineries and factories, which have some characteristics in common such as the production of heat and the use of hydrogen. These characteristics are very specific and allow to consider unusual technologies like ORC and FC. The literature review performed regarding energy planning tools revealed the need to develop a suitable tool for this type of cases, which will be performed on this thesis.

1.4 Thesis Outline

This thesis is divided in four chapters. Chapter one includes the motivation, the literature review and the objective of this thesis. Chapter two presents the case study that will be analyzed and chapter three the methodology used. The results and discussion are presented on the fourth chapter, it’s in this chapter where the performance of the tool is accessed. The fifth and last chapter includes closure and presents the future work that could be made to evolve the tool to a different level of performance and robustness.

2 Case Study

Air Liquide is a French multinational company present in 80 countries. Air Liquide works on four business lines within the gas industry, namely production, pipeline transport, tanker trailers transport and gas packing. The company works with many different types of clients from the healthcare market to large industries of different sectors such as chemical, refining, energy and metal industry.

Some of the Air Liquide ‘s clients have high consumption of certain gases. When the gas in question is nitrogen, they can supply the gas to the client through an Advanced Product Supply Approach (APSA). The Air Liquide ‘s APSA product line offers on-site equipment to isolate nitrogen that is customized to each specific case depending on the client’s requirements.

The main reasons to install APSAs, instead of having the nitrogen supplied by another source, are the reduction of the costs, the high-quality product and the reliability. The reduction of the costs is related to the APSA’s high efficiency and the elimination of nitrogen distribution costs, the continuous remote monitorization of the APSA and the reduced power consumption when the nitrogen demand is below the nominal flowrate. The high-quality product is guaranteed due to the elevated level of purity of the nitrogen isolated by the APSA (99.999%). The APSAs are extremely reliable due to the remote monitoring system and the liquid nitrogen tank used for the LIN Assist function during the start-up of the APSA to maintain the required low temperatures within the Cold Box and also as a backup system to ensure the continuous product supply to the Customer during the maintenance (either corrective or preventive) or over-demand periods.

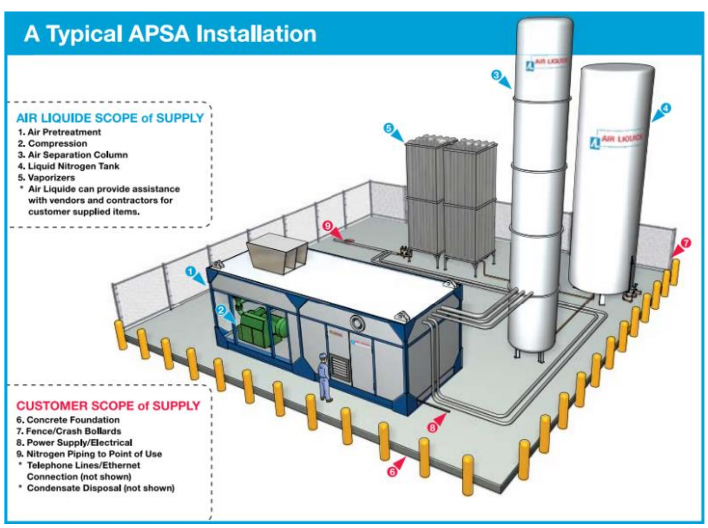

Figure 10 – APSA typical installation [31]

APSA process

The APSA main components are presented on Figure 10 where a typical APSA installation is represented.

The working process of the APSA consists of four main steps.

1. Air compression - firstly the air is compressed in a rotary screw compressor, which provides the efficient turndown.
2. Air purification - a set of molecular sieve beds and filters remove the air impurities such as CO_2 and moisture on compressed air.
3. Heat exchange - in order to keep the column cold, the air entering the distillation column is cooled while the products of the distillation are warmed. Together with the LIN assist function of the back-up facility, this heat exchanger ensures the temperature required to process stability within the Cold Box.
4. Distillation - on the distillation column the liquified air is separated into its components. The low temperature required for the distillation is maintained through the LIN Assist function.

Since the isolation of nitrogen is made using air, the main cost associated with the APSA operation is the cost of the electricity. The APSAs can work on a wide range of its production capacity and feeds the nitrogen directly to the client. The nitrogen cannot be stored. It is common for some clients to have a constant consumption of nitrogen so the APSAs are built to work continuously, ideally stopping just once a year for maintenance.

The present thesis case study is an APSA implemented by Air Liquide on a Portuguese metal industry, Lusosider located at 38°36'46.5"N 9°04'08.0"W (Figure 11).

Figure 11 – Lusosider location and APSA installation site [32]

On this specific case, the Air Liquide 's client has a consumption of almost the nominal capacity of the APSA which, accordingly to the information provided by Air Liquide is 125kW, 110kW due to the APSA's main consumer, the compressor, and 15 kW due to other small consumers.

This Air Liquid client uses ovens on their activity which, dissipate hot gases. Information on these hot gases was provided in order to include the ORC systems on the study. The hot gas data provided is presented on Table 2.

Table 2 - Waste heat data of Lusosider

Parameters	Values	Units
Cold Temperature	297	K
Pressure	100.7	kPa
Hot Temperature	558	K
Absolute Pressure	100.7	kPa
Molecular Mass	28.5	$g\ mol^{-1}$
Flow Speed	6.2	$m\ s^{-1}$
Volume Flow Rate	7.01	$m^3 s^{-1}$

Since the implementation of RES, namely PV and SWT systems, involve the use of significant amount of space, the areas available on the case study site where characterized in order to determine the possible capacity of the implemented systems.

These areas were limited, tagged and measured as showed in Figure 12, Figure 13 and Figure 14.

Figure 12 - Area 1 (roof) [32]

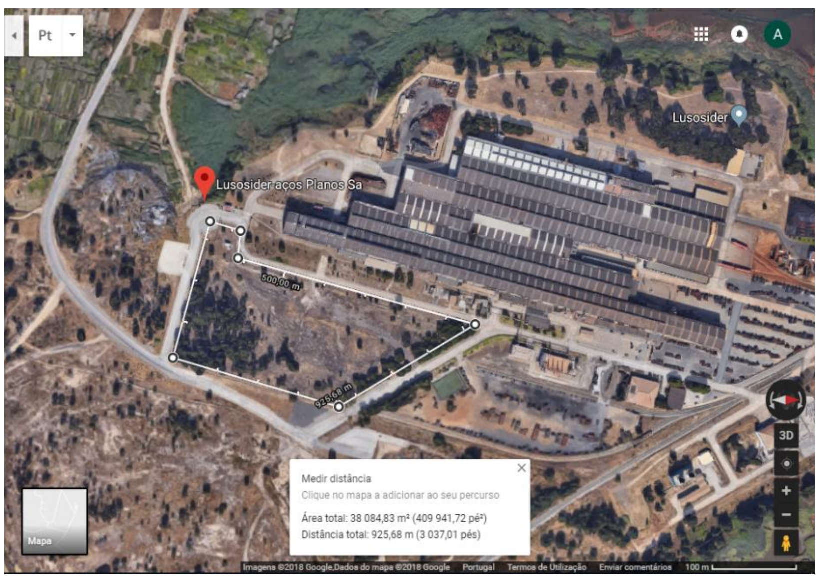

Figure 13 - Area 2 [32]

Figure 14 - Area 3 [32]

Area 1, 2 and 3 have, respectively, 61, 38 and 37 thousand square meters, which makes a total of 136.000 m^2.

3 Methodology

3.1 General Tool Guidelines

The energy sources considered in the tool are Thermal (ORC), Solar (PV), Wind (SWT) and Fuel cells (FC). The ORC was selected because many industries that use APSAs have a big heat waste and this technology allows the industries to improve their efficiency by using the wasted heat to produce energy. The PV and SWT were selected due to the development status, these are the most developed and mature RES that can be implemented on this case. The fuel cells can also be a renewable energy source if the hydrogen is isolated using RES. Typically the energy produced using this technology is more expensive, however since Air Liquide is a hydrogen producer this can, eventually, reduce the costs. Besides this, the FC can be used with an electrolyzer and work as energy storage (the electrolyzer produces hydrogen using the energy excess from the ORC, PV and STW that can be later used on the FC)

The tool was developed in Microsoft Excel. This prevents the need to install other software and turns the tool easier to learn since Microsoft Excel is a software used worldwide.

To perform the calculations needed, the tool requires, as other planning tools, several inputs from the case study that will be assessed, namely location and weather conditions, space availability to install renewable energy technologies, waste heat and energy demand. The calculations are made on an hourly base since the power output of renewable energy sources has big fluctuations, depending on the hours of the day.

For each hour, the tool calculates the energy that can be produced by each renewable energy source and verifies if there is overproduction, to assess the need of energy storage. If energy storage is needed the tool updates the parameters related to the storage.

After calculating the yearly energy sources power output, a cost assessment is made. Technology implementation costs and operation and maintenance costs, for each energy sources technology are already included on the tool. The tool makes a yearly cash flow considering the initial investment and the operation and maintenance costs depending on the installed capacity of each energy source technology.

The flowchart on Figure 15 represents the main steps of the tool to make the simulation.

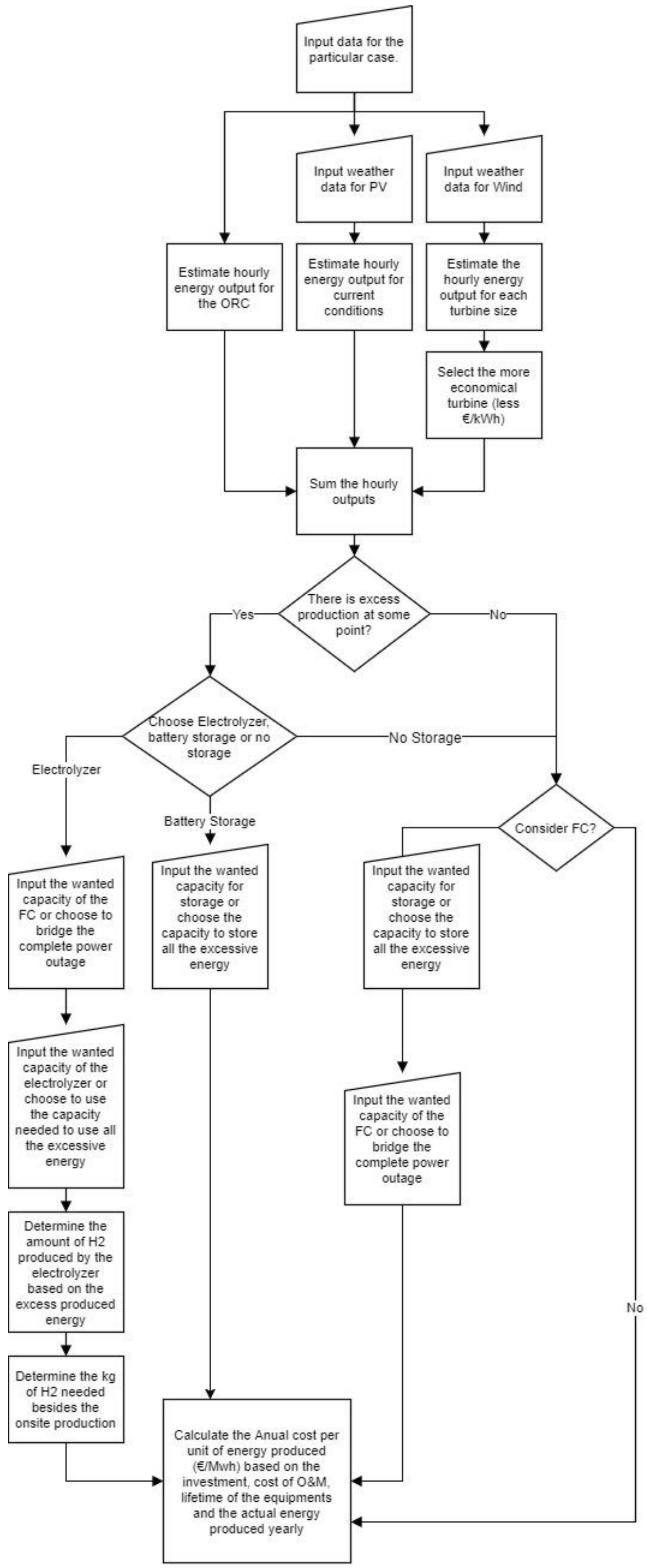

Figure 15 - Energy planning tool flowchart

3.2 Organic Rankine Cycle

ORC are, usually, dimensioned accordingly to the industry waste heat. ORC systems are not very used but are a growing technology. Some assumptions, as the ones explained below, have to be made in order to determine the amount of heat wasted but these should not have a major impact on the result obtained.

Minimum temperatures are needed to optimize the ORC systems (from 80 to 350º C), in this sense the waste heat temperature needs to be higher than this minimum. If this is not the case the tool automatically considers that the ORC power output is zero. Since the analysis on the tool is made on an hourly base it is also possible to consider fluctuations on the heat source and the impact that the fluctuations will have on the power output. As the data provided was not obtained continuously over a year, a yearly constant value was considered. If the user wants to input the waste heat data for each hour of the year the tool can be easily adapted.

The thermal energy recovered from the hot gases depends on the heat exchangers, a crucial factor when ORC is considered. The ORC systems (ORC and heat exchangers) are usually dimensioned for the specific case. On this specific case, it was considered that the heat exchangers are able to reduce the hot gas temperature to the ORC minimum temperature specified by the ORC manufacturer, which is 90ºC for the present study. This value allows the user to have an estimation, since heat exchangers efficiency highly depend on the materials used and on the size and shape. In this sense a more detailed study needs to be made to the real implementation of this technology.

Having the values presented on the Case Study chapter, the heat flux entering the ORC system can be calculated using equation (1) which uses the parameters and units described on Table 3.

$$HF = Cp \times (Th - Tc) \times MM \times \left(\frac{p}{R \times Th}\right) \times VFR \qquad (1)$$

Table 3 - Heat flux calculation units

	Abbreviation	Units
Heat flux	HF	kW
Heat capacity	Cp	$kJ\ (kg \cdot k)^{-1}$
Max gas temperature	Th	K
Needed gas temperature	Tc	K
Molecular mass	MM	$kg\ mol^{-1}$
Pressure	p	Pa
Perfect gas constant	R	$J\ (K \cdot mol)^{-1}$
Volume flow rate	VFR	$m^3 s^{-1}$

The energy output can be calculated with the system efficiency which is typically between 5% and 8% [18].The chosen value was the average, 6.5% but can be easily changed at any time. The energy output is the result of equation (2)

$$Energy\ Output = HF \times Efficiency \tag{2}$$

3.3 Photovoltaic Systems

The energy production from PV systems depends directly on the solar exposure of the PV panels and on the installed PV capacity.

One of the user inputs is the suitable available area to install PV panels. Once the area is inputted the tool calculates the maximum power that can be installed in that area based on equation (3). Where PD is the power density which, in the present tool, is a constant equal 0.1 kW/m^2. This value was given by a PV system installation company in Portugal and can be changed by the user.

$$PI = PD \times area \tag{3}$$

Another input needed is the solar exposure. Since the solar exposure is not constant along the year and since it depends on the location, there is the need to introduce the solar exposure data in order to estimate the energy output of the PV system. To have a solar exposure prediction an average of historical data must be made. This data is available on the website https://www.renewables.ninja/. This platform has datasets that contain whether data from past years. Besides having the data available, the website itself makes an estimation of the PV systems power output based on the historical data from one year. The following data must be inputted on the website: location; the year of historical data to use; the installed capacity; the system losses; the PV panels tilt and orientation. The website output is the energy output. The tool developed needs, as input, the capacity factor (CF) instead of the energy produced. In this sense, on the renewable.ninja website, there is the need to introduce an installed capacity of 1kW.

In order to have a more reliable result, the tool needs to have the CF of 5 past years, 2010, 2011, 2013, 2014 and 2015 (years with 365 days for format reasons). An example is presented in the Annex.

The tool averages the historical data and with the power installed power (PI) information calculates the hourly estimated energy output (EEO) based on equation (4).

$$EEO = \frac{CF1 + CF2 + CF3 + CF4 + CF5}{5} * PI \tag{4}$$

3.4 Small Wind Turbines

The data needed to estimate the power output of a SWT energy system is the wind speed, the installed power and the power curve of the installed turbines.

The installed power on SWT systems is more difficult to determine than on PV systems. When the wind reaches the turbine, it will make the SWT rotor spin, the air flow going through the turbine will be disturbed, an air wake will be formed. If the SWT will be to close to each other, air flow will not have the same impact on all the SWT. Due to this reason, the distance between the SWT needs to be properly defined otherwise the SWT system 's power output will be compromised. Accordingly to the Planning Portal the distances between each turbine are from 3 to 10 diameters, depending on the characteristics of each site [33]. This distance depends a lot on the wind prevailing direction. If the terrain geometry is not regular the estimation of how many SWT can be fitted is much more difficult. In this sense, for the tool, the dimensions of the area available for SWT installation must be rectangular and one of the sides of the rectangle must be aligned with the prevailing wind speed. The distances between the turbines are 4 diameters on the direction perpendicular to the wind prevailing direction and 6 diameters on the direction aligned with the prevailing wind speed. It is also assumed that one of the wind turbines is installed in the corner of the area and the remaining are distributed as shown in the Figure 16.

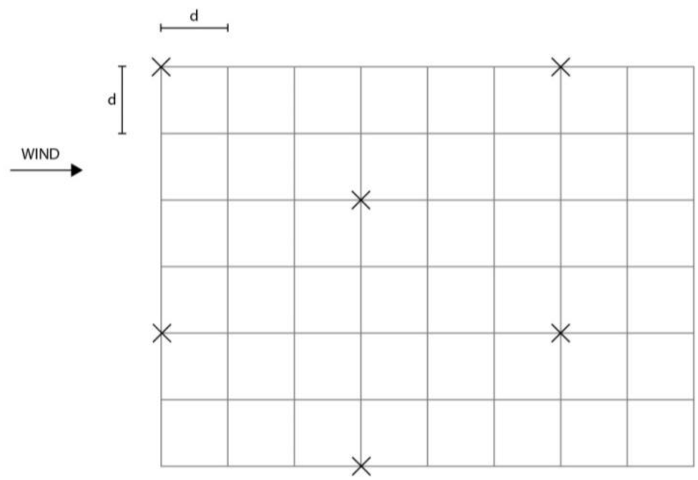

Figure 16 – SWT proper spacing in order to have the power output maximized, 4 times the turbine diameter by 6,

The wind speed data must be downloaded from the renewable.ninja website. The procedure is similar to the PV, the location and year must be inputted and the checkbox “Include Raw Data” must be checked. The .csv file can be downloaded. The useful information on this file is the wind speed that must be copied to the energy planning tool. An example is presented on the Annex.

Once the wind speed for the five different years is inputted the energy planning tool averages the wind speed for the five years and rounds the number to the same number of decimals on the SWT power curves.

The power curve of the wind turbine is a relation between the wind speed on which the turbine is working and the turbine power output. An example of a power curve is presented on Figure 17 - Aeolos Wind Turbine (5kW) power curve.

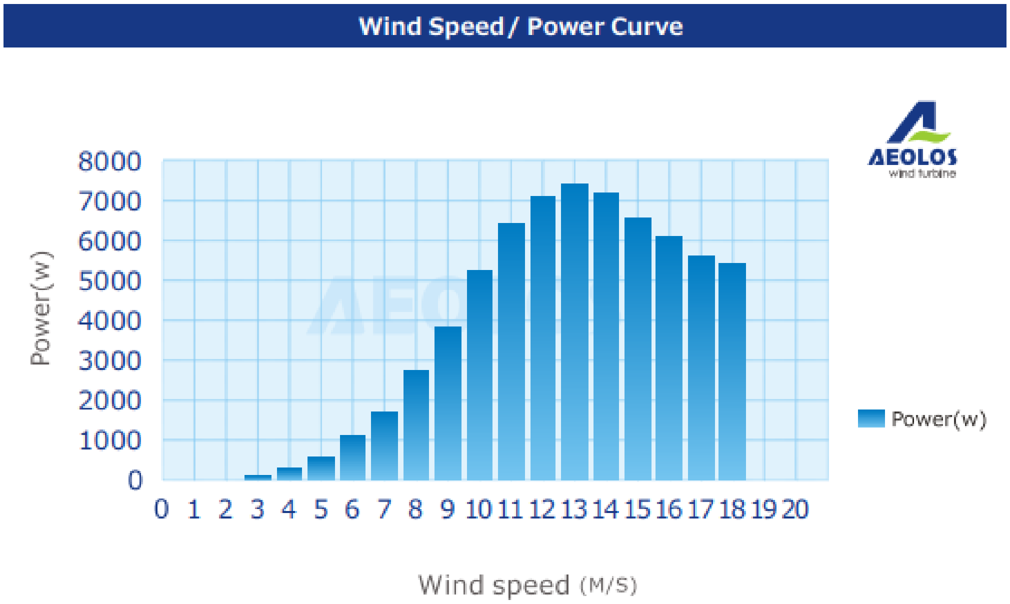

Figure 17 - Aeolos Wind Turbine (5kW) power curve [34]

On the energy planning tool five different SWT power curves are available. The turbines are Aeolos Horizontal SWT models of 300W, 1kW, 5kW, 10kW and 20kW.

The tool after having the average wind speed, the number of SWT and the power curves inputted can estimate the power output of each turbine and since it is possible to have more than one turbine, the power output of each model is multiplied by the number of turbines (of the respective model) that is possible to have on site. The tool predicts the final power output for each model of SWT. The turbine is automatically selected based on the smaller investment per kW produced annually.

3.5 Fuel Cell Systems

The user firstly has to choose if the FC is supposed to produce all of the remaining energy needed to supply the APSA or not and, in this case, the user must input the capacity of the FC. If the user does not want to consider the FC the inputted capacity should be zero, and in this way the tool will not consider the FC.

Based on the previously explained methods the energy planning tool will check for each hour, the system energy consumption and if the ORC, PV and SWT systems combined can meet the demand. If these systems combined are enough the FC remains unused, although if the systems cannot achieve the needed energy, the fuel cell will produce the remaining energy up to its maximum capacity. This energy production requires hydrogen, this topic will be approached on section 3.6.2.

The size of the FC is not relevant when compared to the PV and Wind systems so the restriction regarding the area available to install the FC was not considered.

3.6 Energy Storage

For the energy storage systems only two technologies will be considered. According to the literature review carried out, the more suitable energy technology storage system to use on an intermittent RES is lead batteries. However, if FC are considered as an energy source the electrolyzer should also be considered, since the excess energy produced by the ORC, PV and wind systems can be used to isolate hydrogen, which can be later used for energy production by the FC. If the user wants to consider energy storage one of the two energy storage technologies must be selected, as the tool does not have the option to use both technologies simultaneously.

3.6.1 Battery Storage

Regarding the battery storage, the user has the hypothesis to select if, the battery storage system ‘s capacity will be automatically estimated in order to store all the excess energy or if, this value is an input. If the user does not want to consider battery storage the capacity of the batteries should be zero.

The simulation of battery energy storage follows a method. The hourly energy production from the ORC, PV and wind systems is estimated and an energy balance is performed to verify if the energy produced is greater than the consumption. If there is energy excess and if there is storage availability in the batteries, the energy is stored. If the battery capacity is not enough the tool will show the amount of excess energy produced. On opposition, if the energy production is lower than the consumption the tool verifies if there is energy stored in the batteries, and if yes, the stored energy will be used to feed the APSA. In the case that the stored energy is not enough to face the energy consumption, the missing energy is provided by the grid.

The stored energy on the batteries is updated on an hourly base, this update is made as already explained taking into consideration the energy production, the consumption and the battery status. Since the efficiency of the batteries is not 100% when updating the stored energy on the batteries the tool will assume a 90% efficiency which is a typical value. Besides the efficiency, the batteries should not be completely emptied so the used capacity of the batteries is only 90% of the installed capacity.

3.6.2 Electrolyzer

As referred, when the FC is considered, it is also interesting to consider the use of an electrolyzer as an energy storage hypothesis. As previously explained, the electrolyzer uses electric energy and water to produce hydrogen. To consider the use of the electrolyzer four inputs are required, two binary inputs: one where the capacity of the electrolyzer is calculated based on the excess of energy, and if this is not wanted the user must input the desired capacity; other to select if the hydrogen storage unit capacity must be enough to store all the produced hydrogen, and if not the user must input the desired capacity. If FC is not considered the tool automatically eliminates the hypothesis of the use of an electrolyzer, but if FC is used and the user does not want to consider the electrolyzer, there is the need to input the value zero in the electrolyzer capacity.

The method to calculate the influence of the electrolyzer on the system is similar to the one used on the battery storage. If there is excess of energy production from ORC, PV and SWT systems and if there is enough capacity on the electrolyzer, the energy excess is used on hydrogen production. If the capacity of the electrolyzer is not enough to use all the excess of energy the remaining excess is lost.

The hydrogen produced by the electrolyzer is stored and used by the FC. The tool checks for every hour if there is enough hydrogen stored to meet the needs and, if there is not, the hydrogen is considered to come from an outside source.

3.7 Cost analysis

A cost analysis of the implementation of renewable energy sources on the APSA is also performed on the energy planning tool. Each technology has a different investment cost and a different cost of operation and maintenance. For the ORC, PV, FC, battery storage and electrolyzer, the investment cost (IC), fixed operational expenditure (FOPEX) considered were on the form €/kW, the variable operational expenditure (VOPEX) were considered on the form of €/MWh. The FOPEX are a percentage of the investment costs. Table 4 presents the different costs available in the tool.

Table 4 - RES costs [35][36]

Technology	Investment cost	FOPEX	VOPEX	Lifetime
	€/kW	% of IC	€/MWh	years
ORC	6600	2.2%	0	30
PV	1100	2.0%	0	25
FC	15000	0%	45	3.3
Battery	175 (€/kWh)	1.4%	0	10
Electrolyzer	260	20.0%	0.8	

In the case of SWT the cost calculation is different because the turbine prices per PI depend on the model. In this sense, it is considered that, the investment cost for each turbine is the sum of the turbine cost and the cost of the BOS needed for that turbine (this BOS is in fact in the form of €/kW). Adding to this the annual OPEX considered is 2.4% [35] of the investment cost. The typical lifetime of SWT systems is 22 years.

Using these costs, a cashflow is made. This cashflow is divided in three sections, the investment in equipment, the savings and the annual OPEX.

The investment costs are obtained multiplying installed power (PI) by the investment cost per kW (€/kW) for each used technology. Then accordingly to the lifetime of the equipment its replacement is considered. The annually produced energy is considered to result in direct economic savings. The energy produced from the RES will replace the energy from the grid, representing a revenue. The revenue calculation is based on the annual energy production and the grid electricity cost. The OPEX is taken into account every year.

The cashflow is used to make a simple breakeven analysis. A balance is made after every year and at the point in which the balance becomes positive breakeven happened.

This cashflow (overall cashflow) considers the revenue based on the total produced energy. Since the APSA might not consume all the produced energy a second cashflow (APSA cashflow) is made and considers only the revenue based on the energy used by the APSA. These two cashflows should be considered on two different situations: if the client can consume all the energy produced by the RES (if the client is using the excess energy for other purposes) the overall cashflow balance should be considered; if the RES exclusively feeds the APSA the cashflow to consider is the APSA cashflow.

The tool performs two different cashflows, one showing the overall balance and other showing the APSA balance.

Besides the cashflow, performance indicator (PInd) representing the annual cost per energy produced is estimated for each technology, in order to analyze which technology has a higher impact on the costs. PI is calculated from equation (5), where IC is the investment cost, OPEX, LT the lifetime and EP the expected energy production.

$$PInd = \frac{II + OPEX * LT}{Ep * LT} \tag{5}$$

The tool also calculates the CO_2 emission reduction this is not directly related to the cost analysis but can be a decision factor since the user might want to make the optimization of the system using both the economical and the environmental point of view. This calculation is made using the average emissions of

CO_2 per kWh produced in Portugal which is 0.314 t/MWh [36] and the energy produced by the RES system being simulated.

4 Results and discussion

The developed tool does not perform the sensibility analysis in order to properly dimension the RES system, being so the user must introduce the case study inputs and analyze the output in order to find if the system is over dimensioned. If the system is in fact over dimensioned the user must reduce the capacity of the RES system, to do this the input data has to be changed in order to reduce the system's production. The reduction of the production can be made reducing the availability to implement each of the RES technologies. This means that the user has to make an iterative approach to the problem, inputting the case study data and analyze the outputs, if the output does not properly suit the case study the inputted data has to be adjusted until the simulation results meet the user's objective. To make the study to implement a RES system on this case study five different approaches were made to have three different configurations of the system with the output that is needed by the client using the APSA.

First approach

The energy consumed by the APSA, is considered constant, so the consumption is the same on every hour of the year. The value considered was 125kW which is the nominal power.

According to the information provided by Air Liquide 's engineers, there is waste heat on this case study, the waste heat information is presented on the Table 2 , being so the ORC implementation can be considered.

Since the measures of the ovens hot air flow were made only twice a year and based on the information that the ovens work continuously, it is considered that the heat flux is steady along the year. This can have an impact on the energy planning tool output.

The areas of the case study were measured using google maps as shown on chapter 2.

On Figure 12 - Area 1 (roof) *[32]* we can see that the roof inclination of the facility is oriented to East and West, this is a factor that, as can be seen on Table 5, reduces a lot the PV system capacity factor. This area should not be considered for the PV system, at least on a first approach.

Table 5 - Capacity factor depending on the azimuth [38]

	PV system Azimuth (orientation)	**Mean CF**
Ideal	180º	19%
Area 1	90º	15.5%

The prevailing direction of wind speed in this location is north, however the second most common wind direction is west thus the implementation of wind turbine should be on the area 3 because the building can disturb the air flow when the wind direction is west and compromise the power output [37]. Area 2 will be considered for the PV system installation.

Since the area 3 will be considered to the wind turbine implementation, this has to be transformed in a rectangular area with one of the sides aligned with the prevailing wind speed direction. It's shown on Figure 18 shows the transformed area.

Figure 18 - Area 3 transformed [32]

Table 6 presents the areas that will be an input for the tool.

Table 6 - Areas characteristics

Technology	Area (m^2)	Wind direction (m)	Other direction (m)
PV	38.084	-	-
SWT	28.713	360	80

The average kWh used from the grid on the industrial sector has a cost of 0,08€ according to the client.

With this information all the site related inputs are complete. Table 7 and Table 8 shows the results obtained. In Table 7 there is information on the annual energy production per RES technology.

Table 7 - First Approach results I

Technology	Annual energy production (MWh)
ORC	513.61
PV	5,917.96
SWT	2,076.44
FC	0

Table 8 - First Approach results II

Annual energy production (MWh)	**8,508**
Annual energy used by the APSA (MWh)	1,094
Annual energy overproduction (MWh)	7,414
Annual energy needed from the grid (MWh)	0.784
Annual savings (€)	680,641
Annual savings on the APSA (€)	87,553
Breakeven (years)	9
Breakeven APSA (years)	-

The cost analysis output of this approach is presented on Figure 19 and Figure 20 representing respectively the cashflows over the time for the total energy produced and for the APSA's used energy.

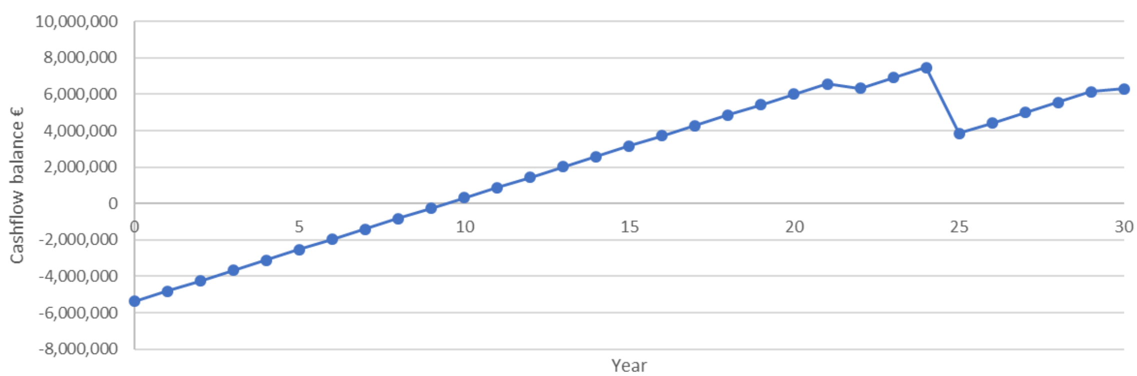

Figure 19 - Overall Cashflow balance (first approach)

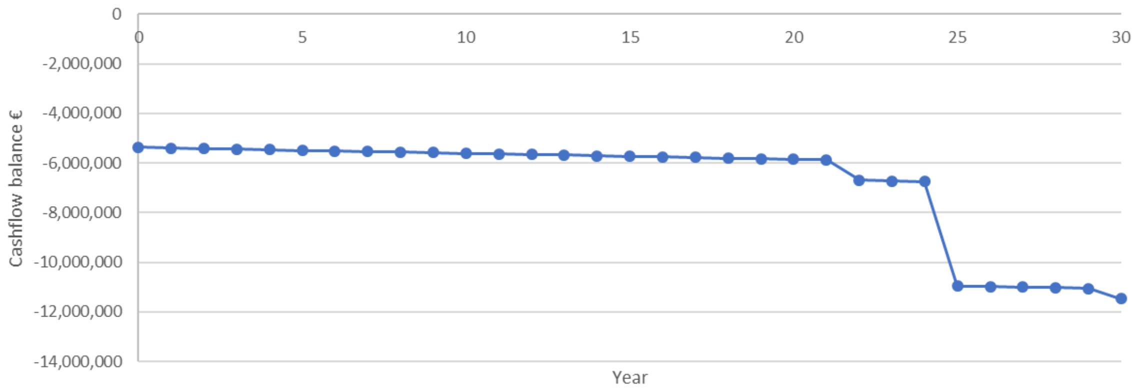

Figure 20 - APSA cashflow balance (first approach)

Analyzing the results on Table 7 and Table 8, it can be verified that, if all the area is being used for PV and SWT the energy produced by the renewable energy system is much higher than the energy needed, it is in fact 778% of the energy needed to feed the APSA. This means, or the excess energy is used for other purposes or the energy system capacity should be reconsidered. Since without energy storage the energy needed from the grid is zero, it is not worth considering at this point. In this case the overall breakeven (if all the energy is being used) happens during the ninth year (Figure 19), if considering that the systems is only feeding the APSA the breakeven never happens (Figure 20). This is understandable since the system is over dimensioned.

Second approach

To reconsider the installed capacity, the total investment per energy produced, over the lifetime, was verified. The values are 0.0417, 0.0424 and 0.027 €/kWh for the ORC, PV and SWT respectively. The SWT have a price per kWh significantly lower than the ORC and the PV. So, the capacity will be firstly lowered on the ORC or the PV, since the PV is an interment power source the capacity will be decreased first on the PV system. The reduction is made by decreasing the area available for the PV system. The next step was checking the average energy produced by hour. The hourly consumption its known (125 kWh) and the renewable energy sources averages were 57.57, 675.64 and 237.04 kWh/h. Analyzing this data it is noticed that probably the PV system can be eliminated, since the ORC and the SWT summed averages are bigger than the consumptions and the power outputs of these technologies are steadier than the PV.

Eliminating the PV system from the considered technologies the result obtained are in Table 9 and Table 10 which presents the comparison between every approach made until this point:

Table 9 - Second Approach results I

	First approach	Second approach
Technology	Annual energy production (MWh)	
ORC	513.61	513.61
PV	5,917.96	0
SWT	2,076.44	2,076.44
FC	0	0

Table 10 - Second Approach results II

	First approach	Second approach
Annual energy production (MWh)	8,508	2,590
Annual energy used by the APSA (MWh)	1,094	1,092
Annual energy overproduction (MWh)	7,414	1,497
Annual energy needed from the grid (MWh)	0.784	2.722
Annual savings (€)	680,641	207,205
Annual savings on the APSA (€)	87,553	87,399
Breakeven (years)	9	6
Breakeven APSA (years)	-	20

The cost analysis output of this approach is presented on Figure 21 and Figure 22 representing respectively the cashflows over the time for the total energy produced and for the APSA's used energy.

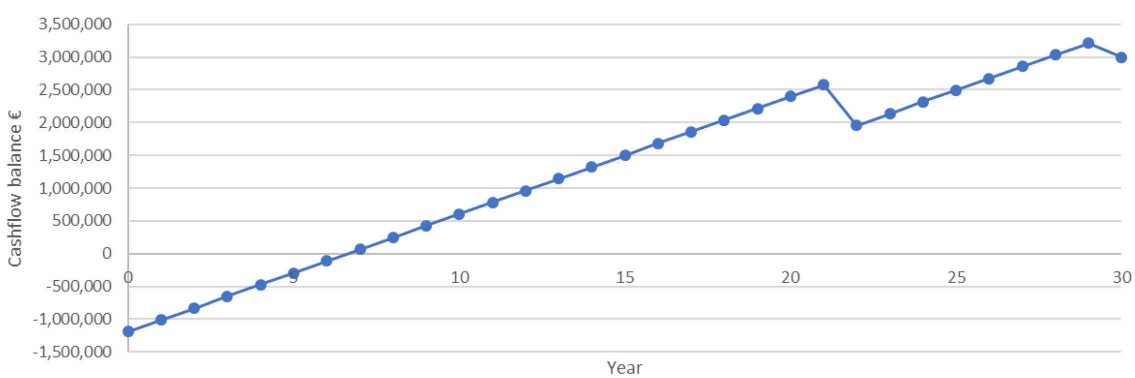

Figure 21 - Overall Cashflow balance (second approach)

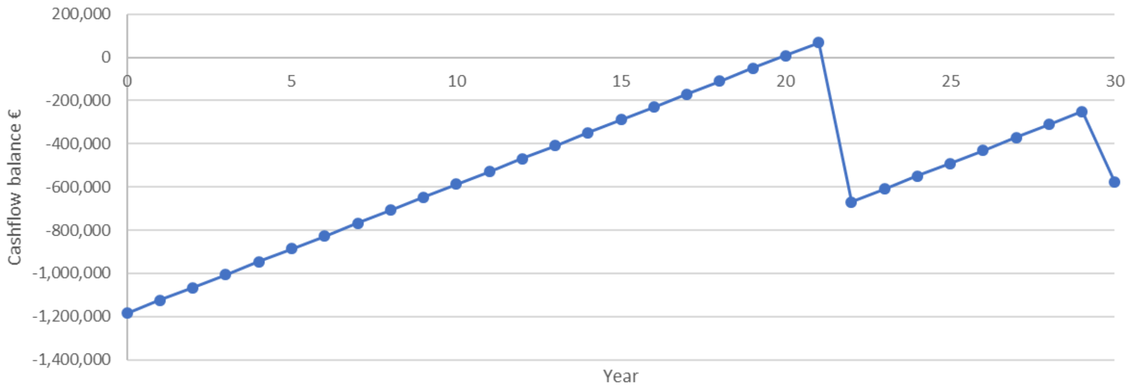

Figure 22 - APSA cashflow balance (second approach)

Analyzing the results of Table 9 and Table 10 we can see that the energy produced by the renewable energy system is still 235% of the APSA consumption. On this case the overall breakeven happens on the sixth year (if all the energy is being used) and on the twentieth year if the system is only feeding the APSA (Figure 21 and Figure 22). There are sudden crashes on the cashflow that represent the investment on new equipment since they have a limited lifetime and when it is reached there is the possibility to have the need to make its replacement. The overproduction is still high on this approach but there are some energy shortages during the year obliging the use of the grid. The next step will consist in lowering the SWT capacity since it is the other intermittent energy source.

Third approach

After a few attempts and a simple analysis of the results it was decided to lower the area dedicated to install wind turbines to 9,600 square meters, 120m (wind direction) x 80m (perpendicular to wind direction).

This approach result is presented on Table 11 and Table 12 on which is the results of every approach made until this point of the study:

Table 11 - Third Approach results I

	First approach	Second approach	Third approach
Technology	Annual energy production (MWh)		
ORC	513.61	513.61	513.61
PV	5,917.96	0	0
SWT	2,076.44	2,076.44	666.03
FC	0	0	0

Table 12 - Third Approach results II

	First approach	Second approach	Third approach
Annual energy production (MWh)	8,508	2,590	1,179
Annual energy used by the APSA (MWh)	1,094	1,092	1,053
Annual energy overproduction (MWh)	7,414	1,497	126
Annual energy needed from the grid (MWh)	0.78	2.72	41.71
Annual savings (€)	680,641	207,205	94,317
Annual savings on the APSA (€)	87,553	87,399	84,266
Breakeven (years)	9	6	8
Breakeven APSA (years)	-	20	9

The cost analysis output of this approach is presented on Figure 23 and Figure 24 representing respectively the cashflows over the time for the total energy produced and for the APSA's used energy.

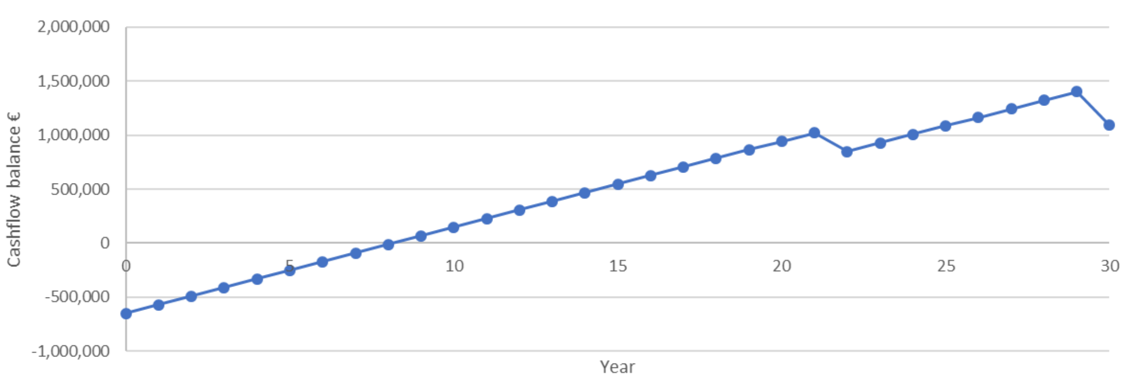

Figure 23 - Overall Cashflow balance (third approach)

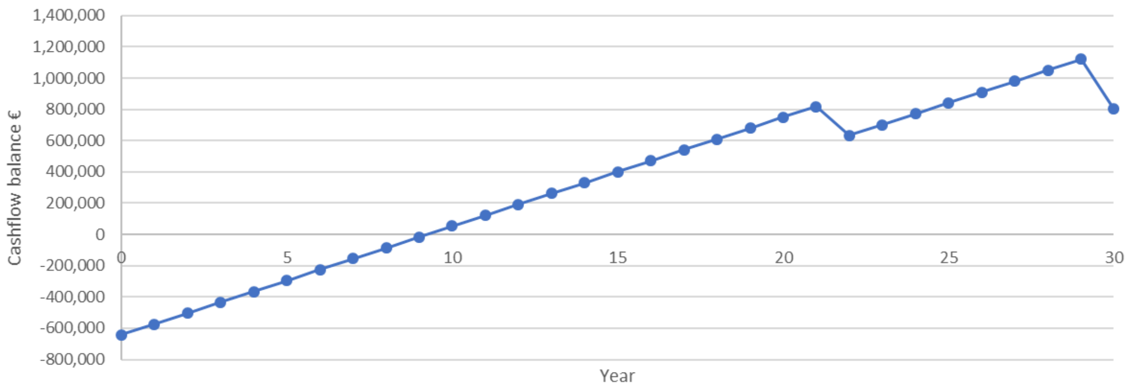

Figure 24 - APSA cashflow balance (third approach)

Analyzing the results on Table 11 and Table 12 it can be seen that on this approach the annual renewable energy system ’s production is now 102% of the APSA consumption. Not only the annual consumption but also the savings, overall and APSA related are closer which means the capacity of the renewable energy system is closer to the wanted size. The breakeven, overall and APSA related, happen on the eighth and ninth year respectively as can be seen on Figure 23 and Figure 24. Two other values that might be interesting to evaluate are the annual energy needed from the grid, which is 42MWh and compare it with the annual overproduction, 126MWh.

Considering this result on the next approach the energy storage is considered.

Fourth approach

On this approach battery storage will be added to the system considered on the third approach. Since the excess of energy, presented on Table 12, is 126 MWh, if it is decided to select the option to store all the excess energy, the storage capacity is 84,788 kWh. This capacity is very high and will have a big impact on the system cost. As can be seen on Table 12 the energy needed from the grid over one year is 45.3 MWh which means that is not worth to store all the excessive energy as only about 53% of it would be used by the APSA. This option is clearly not the appropriate to use on this case. Being so the capacity of the battery system must be estimated by the user.

To select the capacity of the storage system the user must do it iteratively, selecting the capacity, analyzing, either the impact on the cost or the status of the battery capacity over the time and the energy needed from the grid (example on annex), and adjust the capacity until having a satisfactory result. For instance, in the present study, when the value chosen for the capacity of the storage system is 1000 kWh and analyzing the column of the energy needed from the grid, we can verify that most of the small fluctuations of the renewable energy sources are covered by the storage system. Some of these fluctuations are too big to be covered, however selecting a capacity which make the system able to fulfil these fluctuations, will turn the system more expensive and most of the time a big share of the battery capacity will be unused.

This approach result is presented on Table 13 and Table 14 on which is the results of every approach made until this point of the study:

Table 13 - Fourth Approach results I

	First approach	**Second approach**	**Third approach**	**Fourth approach**
Technology		Annual energy production (MWh)		
ORC	513.61	513.61	513.61	513.61
PV	5,917.96	0	0	0
SWT	2,076.44	2,076.44	666.03	666.08
FC	0	0	0	0

Table 14 - Fourth Approach results II

	First approach	**Second approach**	**Third approach**	**Fourth approach**
Annual energy production (MWh)	8,508	2,590	1,179	1,179
Annual energy used by the APSA (MWh)	1,094	1,092	1,053	1,095
Annual energy overproduction (MWh)	7,414	1,497	126	92.20
Annual energy needed from the grid (MWh)	0.78	2.72	41.71	8.58
Annual savings (€)	680,641	207,205	94,317	94,317
Annual savings on the APSA (€)	87,553	87,399	84,266	86,996
Breakeven (years)	9	6	8	13
Breakeven APSA (years)	-	20	9	14

The cost analysis output of this approach is presented on Figure 25 and Figure 26 representing respectively the cashflows over the time for the total energy produced and for the APSA's used energy.

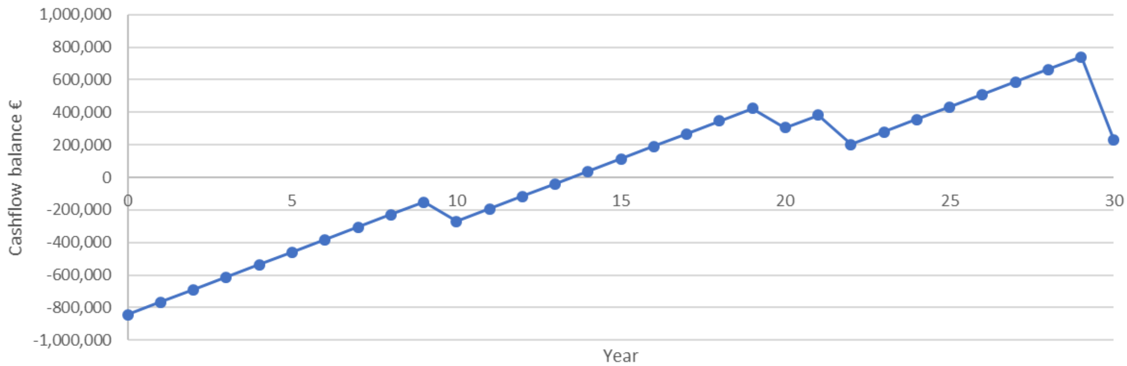

Figure 25 - Overall Cashflow balance (fourth approach)

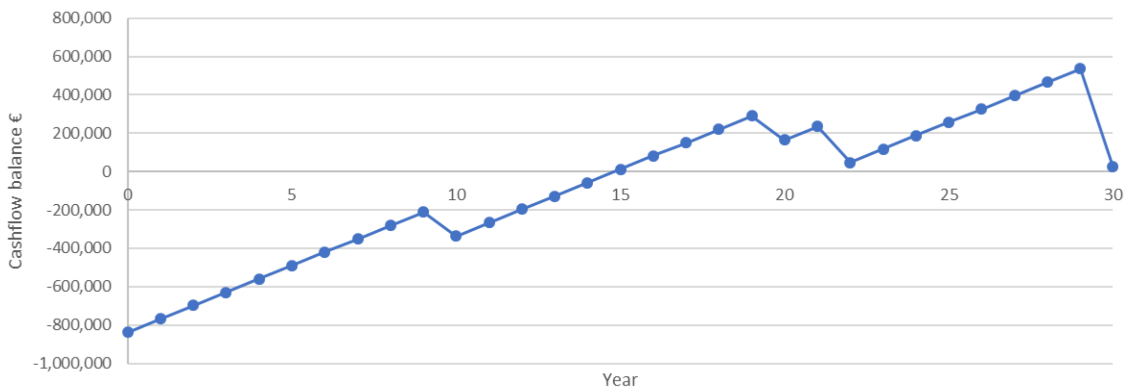

Figure 26 - APSA cashflow balance (fourth approach)

From the results presented on Table 13 and on Table 14 it can be seen that the annual savings related to the APSA cashflow increase when considering the storage, however the annual overall savings remains the same because it is considered that there are other consumers that can use the excessive energy, and, in this sense, there is no need of storage technology implementation. Reviewing the breakeven results on Figure 25 and Figure 26, we can notice that, despite the annual savings being the same for the overall system and higher for the APSA cashflow, the breakeven happens later due to the increased cost of using energy storage. The breakeven happens on the thirteenth and the fifteenth year for the overall system and the APSA related results, respectively. We can see that these results from an economical point of view are not as good as the ones of the third approach, however the user can be more interested on lowering the grid consumption than on the economic impact. Besides this if the energy price would be higher the impact of the energy storage system can reduce the breakeven time, however this would only happen if the grid energy price was significantly higher.

Fifth approach

Instead of the battery system, the fuel cell and an electrolyzer could be implemented as an energy storage system.

Considering that the FC capacity is enough to avoid the use of energy from the grid, which in this case is 70 kW, and that the electrolyzer does not use all the excess energy, the electrolyzer selected capacity is 5 kW. This selected capacity is significantly lower than the FC because the periods on which the electricity production is excessive are more than the ones where the FC need to be used, so if there is enough storage capacity available the electrolyzer can reduce the hydrogen importation without a big investment on its capacity.

This approach result is presented on Table 15 and Table 16 on which is the results of every approach made until this point of the study:

Table 15 - Fifth Approach results I

	First approach	**Second approach**	**Third approach**	**Fourth approach**	**Fifth approach**
Technology	Annual energy production (MWh)				
ORC	504.28	504.28	504.28	504.28	504.28
PV	5,917.96	0	0	0	0
SWT	2,076.44	2,076.44	666.08	666.08	666.08
FC	0	0	0	0	45.32

Table 16 - Fifth Approach results II

	First approach	Second approach	Third approach	Fourth approach	Fifth approach
Annual energy production (MWh)	8,508	2,590	1,179	1,179	1,541
Annual energy used by the APSA (MWh)	1,094	1,092	1,053	1,095	1,134
Annual energy overproduction (MWh)	7,414	1,497	126	92.20	408.00
Annual energy needed from the grid (MWh)	0.78	2.72	41.71	8.58	0
Annual savings (€)	680,641	207,205	94,317	94,317	123,349
Annual savings on the APSA (€)	87,553	87,399	84,266	86,996	90,708
Breakeven (years)	9	6	8	13	16
Breakeven APSA (years)	-	20	9	14	29

The cost analysis output of this approach is presented on Figure 27 and Figure 28 representing respectively the cashflows over the time for the total energy produced and for the APSA's used energy.

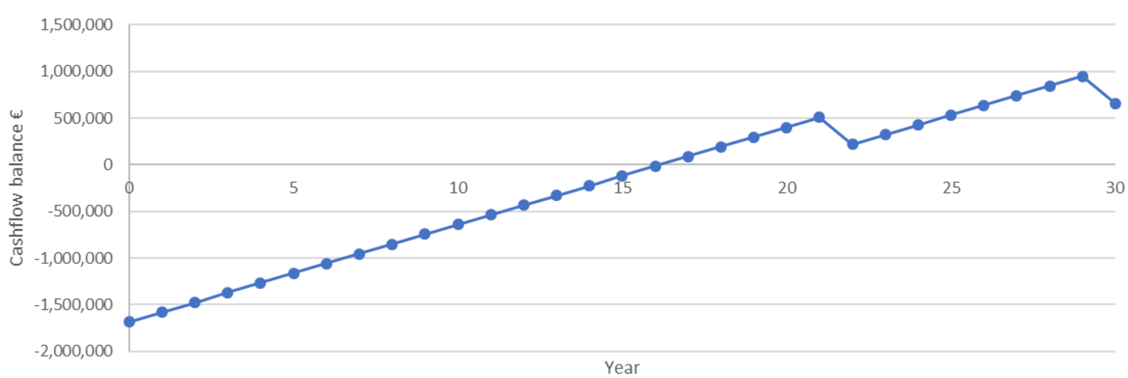

Figure 27 - Overall Cashflow balance (fifth approach)

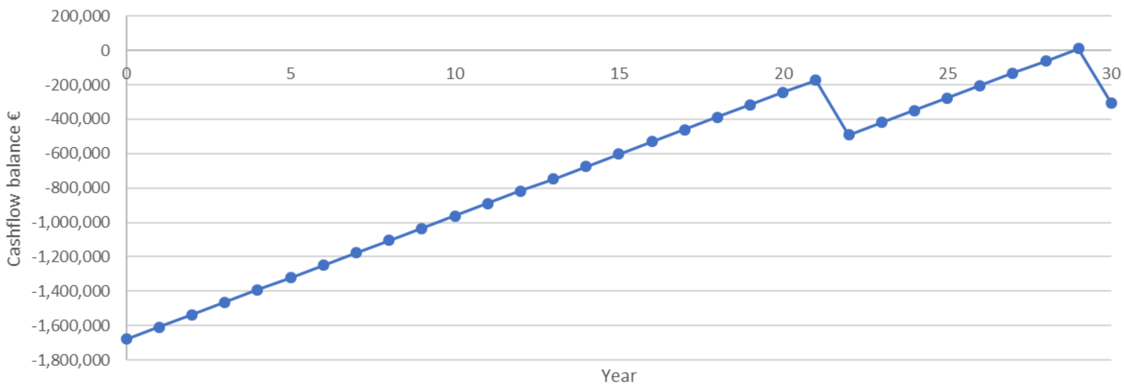

Figure 28 - APSA cashflow balance (fifth approach)

It can be seen in the results presented on Table 15 and Table 16 that there is no energy consumption from the grid, which means that this system could be stand-alone, not considering the energy needed one time per year to the APSA starting. The annual savings are greater than on the fourth approach (battery storage) but the investment and OPEX are higher making the breakeven happen later, on the sixtieth and twenty-ninth year depending if the excessive energy is being used or not. If the electrolyzer is excluded from this configuration, the breakeven happens later which means that, the savings of fuel make up for the investment on the electrolyzer.

Overall discussion

The results seem to be consistent over the five approaches made on the case study. Along the five approaches all the renewable energy sources were considered as well as the two different storage options. However not all the different configurations were tested. Clearly some renewable energy sources are better than other, but the ideal configuration depends on the case study that is being studied. On this specific case, and since the client using the APSA is connected to the grid, the battery storage and the FC/electrolyzer are not a good choice from the economical point of view since the costs increase a lot and the grid energy price is not sufficiently high to make the savings compensate the increased costs. The fact that the SWT have significantly lower cost (€/kWh) than the other renewable energy sources is due to the fact that the turbine selected was the 300kW model which has a power curve that is good for low speed winds. The ORC can be a good choice since the price is not too high and it provides an almost steady energy production if the waste heat is enough to feed it. The PV system ‘s cost is similar to the ORC (€/kWh) but the fact that its production is intermittent might make it necessary to store energy which increases the price of the installed system, the PV can be eventually better if there is more consumption during the day.

Obviously, the different approaches and the final result highly depends on the user sensitivity, not only to make decisions based on the tool results but also to adjust the different parameters on the to have a good simulation. The meaning of good simulation is very ambivalent, it highly depends on the main objective of the user, it can be strictly from an economic point of view, from an engineering point of view in order to make the system more reliable and robust or even from an environmental point of view on which the main goal would be reduce the environmental impact.

5 Closure

5.1 Conclusion

The implementation of renewable energy systems on the industrial sector represents a challenge but can also be an opportunity to reduce costs and emissions, on a medium to long term solution. The intermittency of some of the RES is the main problem to overcome. Being so the RES systems must be designed for each case. The design of a RES system is a different challenge for each case because each case is unique and has its own characteristics, from the energy demand to the local weather conditions.

The APSA Product Line is a standard within the Air Liquide range of products. It is manufactured on a range of sizes long and deeply studied in order to meet the requests of the industrial market. Thus, Air Liquide is able to cost effect cover the needs of a large number of customers, between 200 to 2000 Nm^3/h of pure nitrogen, by producing in situ with the APSA. The APSA Product Line has five different frame sizes, that once combined with a wide range of air compressors is able to meet a really wide range of flows. Being so, studying the possibility to implement RES to feed the APSAs is difficult to standardize. The developed tool main objective is to make easier the study of the impact of the implementation of RES to feed an APSAs.

The final version of the energy planning tool developed met the objective, the consideration of different RES was not limited by the current status of development of the technologies, nor the price and this led to the consideration of four different technologies, ORC, PV, SWT and FC. Adding to the RES, two different types of storage technologies were included, solid state batteries and the electrolyzer, which works with the FC. The tool requires inputs on the case study regarding areas available to implement RES, energy consumption, grid energy price, the local weather conditions history and waste heat data. The tool is supposed to be used iteratively, this meaning that the user inputs the data and makes an analysis on the tool predictions, and then has to adjust the input data until the result will be acceptable or optimal for each case.

Regarding this thesis case study, five approaches were made in order to have three different possible systems to implement. The study was made accordingly to input data provided by Air Liquide and Lusosider (Air Liquide ‘s client) and typical values for the Portuguese market. These three results consider the implementation of ORC, SWT, batteries and FC/electrolyzer. The third approach resulted on a system without storage on which the RES implemented were ORC and SWT. The fourth and fifth approach considered storage, batteries and FC/electrolyzer, respectively. The fourth approach has a larger investment cost than the third and takes more time to breakeven since the batteries implemented still have a big impact on the cost, the breakeven time could be smaller is the cost of grid energy was higher. The fifth approach was the one with the higher breakeven time due to the high investment on FC and electrolyzer technology, because these technologies are in a later stage of development and so have a higher price per kW installed than the other technologies considered.

The three final approaches (third, fourth and fifth) have different breakeven times which was expected from the beginning since the energy storage is still expensive and it's typically only economically better on places where the grid energy price is significantly high or if grid connection is not an option. Being so the best approach from an economical point of view is the third which does not consider energy storage.

5.2 Future Work

The present works objective is to make it easier and faster to have a prediction of the impact of the implementation of RES on small industrial facilities, namely the ones that use Air Liquide s APSAs. Despite achieving the purposed objective, the present work has some limitations namely, the lack of upper limits on the RES installed capacity and the storage capacity. Regarding the upper limits of the installed capacity, the tool limits the installed capacity of the RES system by the available area, the next step would be to upgrade the tool on order to have the installed capacity limited also by the energy demand. The upper limitation of the installed capacity by the energy demand is not easy to do without having an optimization algorithm integrated on the tool. In some situations when it is chosen to store all the excess energy produced the tool oversize the storage capacity, this happens when the excess energy production is higher than the energy needed from storage resulting on an accumulation of stored energy that it is not needed.

Besides these two limitations the tool could also be upgraded in order to import the weather data automatically after downloading the files from the website and to be more robust so that the user would for example be warned if any inputs are not valid or if more than one type of storage is selected (which is currently not supported by the tool).

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Annex

PV data input

The column with the power output from the .csv downloaded from renewables ninja must be copied into the energy planning tool excel to orange shaded cells (column C, D, E, F and G) on the sheet “Local PV DATA” represented on Figure 29.

time	local_time	kWprod / kWinst					Year Avg	Expected
		Year 1	Year 2	Year 3	Year 4	Year 5		kWh
UTC	Europe/Lisbon	2015	2014	2013	2011	2010		kWprod
1/1/2015 0:00	1/1/2015 0:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 1:00	1/1/2015 1:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 2:00	1/1/2015 2:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 3:00	1/1/2015 3:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 4:00	1/1/2015 4:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 5:00	1/1/2015 5:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 6:00	1/1/2015 6:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 7:00	1/1/2015 7:00	0.00	0.00	0.00	0.00	0.00	0.00	0
1/1/2015 8:00	1/1/2015 8:00	0.04	0.00	0.00	0.00	0.00	0.01	0.41
1/1/2015 9:00	1/1/2015 9:00	0.33	0.10	0.26	0.09	0.27	0.21	10.44
1/1/2015 10:00	1/1/2015 10:00	0.53	0.19	0.49	0.31	0.48	0.40	19.89
1/1/2015 11:00	1/1/2015 11:00	0.65	0.20	0.60	0.38	0.56	0.48	23.87
1/1/2015 12:00	1/1/2015 12:00	0.69	0.14	0.61	0.29	0.63	0.47	23.72
1/1/2015 13:00	1/1/2015 13:00	0.68	0.10	0.63	0.34	0.48	0.45	22.33
1/1/2015 14:00	1/1/2015 14:00	0.61	0.07	0.58	0.27	0.26	0.36	17.94
1/1/2015 15:00	1/1/2015 15:00	0.49	0.06	0.44	0.10	0.23	0.26	13.05
1/1/2015 16:00	1/1/2015 16:00	0.29	0.04	0.20	0.10	0.11	0.15	7.4
1/1/2015 17:00	1/1/2015 17:00	0.03	0.00	0.00	0.00	0.00	0.01	0.28
1/1/2015 18:00	1/1/2015 18:00	0.00	0.00	0.00	0.00	0.00	0.00	0

Figure 29 - Screen shot of inputed data PV

SWT data input

The column with the wind speed output from the .csv downloaded from renewables ninja must be copied into the orange shaded cells (column C, D, E, F and G) on the sheet “Local Wind DATA” on the computer tool excel file. This procedure must be done for five different years.

time	local_time	windspeed m/s					windspeed avg m/s
		Year 1	Year 2	Year 3	Year 4	Year 5	
UTC	Europe/Lisbon	2015	2014	2013	2011	2010	
1/1/2015 0:00	1/1/2015 0:00	6.05	6.20	7.52	5.88	10.91	7.31
1/1/2015 1:00	1/1/2015 1:00	6.30	6.42	7.12	5.86	11.16	7.37
1/1/2015 2:00	1/1/2015 2:00	6.36	6.69	6.78	5.80	11.22	7.37
1/1/2015 3:00	1/1/2015 3:00	6.19	6.80	6.82	5.66	11.18	7.33
1/1/2015 4:00	1/1/2015 4:00	5.93	6.89	6.98	5.48	11.48	7.35
1/1/2015 5:00	1/1/2015 5:00	5.82	7.47	7.09	5.40	11.82	7.52
1/1/2015 6:00	1/1/2015 6:00	5.91	7.82	6.91	5.41	11.79	7.57
1/1/2015 7:00	1/1/2015 7:00	6.10	8.26	6.64	5.35	11.19	7.50
1/1/2015 8:00	1/1/2015 8:00	6.28	8.62	6.31	5.39	10.84	7.49
1/1/2015 9:00	1/1/2015 9:00	5.82	8.62	6.08	5.47	10.49	7.30
1/1/2015 10:00	1/1/2015 10:00	5.15	8.69	5.84	5.35	10.50	7.11
1/1/2015 11:00	1/1/2015 11:00	4.73	8.98	5.63	5.40	10.68	7.08
1/1/2015 12:00	1/1/2015 12:00	4.80	9.70	5.53	5.59	10.53	7.23
1/1/2015 13:00	1/1/2015 13:00	4.91	10.50	5.56	5.66	10.23	7.37
1/1/2015 14:00	1/1/2015 14:00	4.86	10.41	5.64	5.75	9.32	7.20
1/1/2015 15:00	1/1/2015 15:00	4.73	10.02	5.75	5.95	8.07	6.91
1/1/2015 16:00	1/1/2015 16:00	4.98	9.91	5.82	6.04	6.83	6.72

Figure 30 - Screen shot of inputed data SWT

Battery status check

To analyze the battery status over the time the values to be checked are present on column "O" (sheet "ORC+PV+Wind+FC") on the excel represented on Figure 31. The energy needed from the grid can be checked on column "P" (sheet "ORC+PV+Wind+FC") also represented on Figure 31.

	B	C	D	F	H	I	J	K	L	M	N	O	P	Q
3		Need	ORC	PV	Wind	Balance	FC	Energy to H2 production	Balance	Total Production		Storage balance	Needed from outer source	Excess Production
4							Remaining energy needed?	Electrolizer for all energy availiable?				Max Capacity needed?		
5						Overproduction:	no	no	Overproduction:			no	YES	YES
6							0.00	0.00				200		
7	Europe/Lisbon				kWp by the selected SWT	Yes	0.00	0	Yes			222.2222222		
8	1/1/2015 0:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0		
9	1/1/2015 1:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
10	1/1/2015 2:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
11	1/1/2015 3:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
12	1/1/2015 4:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
13	1/1/2015 5:00	-125	57.57	0	2.58	-64.85	0.00	0.00	-64.85	60.15		0.00	-64.85	0.00
14	1/1/2015 6:00	-125	57.57	0	2.58	-64.85	0.00	0.00	-64.85	60.15		0.00	-64.85	0.00
15	1/1/2015 7:00	-125	57.57	0	2.58	-64.85	0.00	0.00	-64.85	60.15		0.00	-64.85	0.00
16	1/1/2015 8:00	-125	57.57	2.05	2.4	-62.98	0.00	0.00	-62.98	62.02		0.00	-62.98	0.00
17	1/1/2015 9:00	-125	57.57	52.2	2.4	-12.83	0.00	0.00	-12.83	112.17		0.00	-12.83	0.00
18	1/1/2015 10:00	-125	57.57	99.45	2.4	34.42	0.00	0.00	34.42	159.42		30.97	0.00	0.00
19	1/1/2015 11:00	-125	57.57	119.35	2.4	54.32	0.00	0.00	54.32	179.32		79.86	0.00	0.00
20	1/1/2015 12:00	-125	57.57	118.6	2.4	53.57	0.00	0.00	53.57	178.57		128.07	0.00	0.00
21	1/1/2015 13:00	-125	57.57	111.65	2.4	46.62	0.00	0.00	46.62	171.62		170.02	0.00	0.00
22	1/1/2015 14:00	-125	57.57	89.7	2.4	24.67	0.00	0.00	24.67	149.67		192.22	0.00	0.00
23	1/1/2015 15:00	-125	57.57	65.25	2.4	0.22	0.00	0.00	0.22	125.22		192.42	0.00	0.00
24	1/1/2015 16:00	-125	57.57	37	2.4	-28.03	0.00	0.00	-28.03	96.97		167.19	0.00	0.00
25	1/1/2015 17:00	-125	57.57	1.4	2.4	-63.63	0.00	0.00	-63.63	61.37		109.92	0.00	0.00
26	1/1/2015 18:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		51.39	0.00	0.00
27	1/1/2015 19:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-13.64	0.00
28	1/1/2015 20:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
29	1/1/2015 21:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
30	1/1/2015 22:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
31	1/1/2015 23:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
32	1/2/2015 0:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
33	1/2/2015 1:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
34	1/2/2015 2:00	-125	57.57	0	2.4	-65.03	0.00	0.00	-65.03	59.97		0.00	-65.03	0.00
35	1/2/2015 3:00	-125	57.57	0	1.8	-65.63	0.00	0.00	-65.63	59.37		0.00	-65.63	0.00
36	1/2/2015 4:00	-125	57.57	0	1.8	-65.63	0.00	0.00	-65.63	59.37		0.00	-65.63	0.00
37	1/2/2015 5:00	-125	57.57	0	1.8	-65.63	0.00	0.00	-65.63	59.37		0.00	-65.63	0.00
38	1/2/2015 6:00	-125	57.57	0	1.8	-65.63	0.00	0.00	-65.63	59.37		0.00	-65.63	0.00
39	1/2/2015 7:00	-125	57.57	0	1.8	-65.63	0.00	0.00	-65.63	59.37		0.00	-65.63	0.00
40	1/2/2015 8:00	-125	57.57	1.85	2.4	-63.18	0.00	0.00	-63.18	61.82		0.00	-63.18	0.00
41	1/2/2015 9:00	-125	57.57	37.6	1.8	-28.03	0.00	0.00	-28.03	96.97		0.00	-28.03	0.00
42	1/2/2015 10:00	-125	57.57	66.2	1.8	0.57	0.00	0.00	0.57	125.57		0.51	0.00	0.00
43	1/2/2015 11:00	-125	57.57	84.4	1.8	18.77	0.00	0.00	18.77	143.77		17.40	0.00	0.00
44	1/2/2015 12:00	-125	57.57	98.9	1.8	33.27	0.00	0.00	33.27	158.27		47.34	0.00	0.00
45	1/2/2015 13:00	-125	57.57	96.1	1.8	30.47	0.00	0.00	30.47	155.47		74.76	0.00	0.00
46	1/2/2015 14:00	-125	57.57	83.4	1.8	17.77	0.00	0.00	17.77	142.77		90.75	0.00	0.00
47	1/2/2015 15:00	-125	57.57	64.15	1.8	-1.48	0.00	0.00	-1.48	123.52		89.41	0.00	0.00

Inputs | PV | Local PV DATA | WIND | Turbines | Local Wind DATA | H2 | ORC | ORC+PV+Wind+FC | Cost ...

Figure 31 – Screen shot of variation of battery charge status