HARNESSING THE POWER OF HYDROGEN

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Economic feasibility of hydrogen-based electricity storage units applying price arbitrage in the Italian spot market and their potential grid applications

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ABSTRACT

In this study the economic feasibility of an investment in hydrogen-based electricity storage is investigated together with the potential grid applications of the storage. The Italian day-ahead electricity market shows significant prices differential between peak and off-peak hours. Due to the market structure, this differential is even higher if selling electricity from a frequently congested zone. For this reason the storage - formed by electrolysers (charging), pressurized tanks (storing) and fuel cells (discharging) - is located in Sicily. This zone is also a suitable field test for the grid application of the storage.

Time-shifting electricity from off-peak hours to peak hours the storage is expected to: (1) increase renewable energy (RE) depth of penetration, (2) help preventing transmission bottleneck and (3) increase market competition.

Optimal operation strategy is designed and the net operating income is evaluated by means of the software energyPRO. Current (2014) and future (2025) techno-economic technology development is considered as well as the potential of an incentive scheme for district heating to incentivize the recovered heat. The analysed unit has 3 MW input/2 MW output and 20 MWh energy content.

It is found that the 20-year investment (2,5% real discount rate, 2% inflation) is not feasible, staying to the current techno-economic technology status. On the contrary, when simulating the future techno-economic development for year 2025 the investment economy gets better with a NPV of EUR 0,352 m without incentives and EUR 5,913 m with incentives (IRR 5,4% and 16%, discounted payback period of 11 and 5). These results show that support policies are fundamental for the development of hydrogen technologies today and they will be in the future.

The impact of the hydrogen storage on the overall zonal grid has resulted in the expected grid benefits. In the analysed year 2013, 62% of the hours in which the storage is charging are peaks in RE production and in 81% of the hours there is lack of zonal RE production. In 98% of the hours in which the storage is discharging is helping to prevent zonal transmission congestion in import and in 22% of the hours in which is charging is helping prevent zonal transmission congestion in export. These result produce an higher market competition which is evaluated by means of the RSI index.

Power companies are going to have to come to grips
with the reality that millions of local operators,
generating electricity from fuel cells on-site, can produce
more power more cheaply than can today's giant power plants.

— Jeremy Rifkin, The Hydrogen Economy

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ABBREVIATIONS

CAES	Compressed Air Energy Storage
CES	Community Energy Storage
CHP	Combined Heat and Power
EIA	Environmental Impact Assessment
GC	Green Certificate
GME	IPEX market operator
IER	Institute of Energy Economics and the Rational Use of Energy
IOM	Marginal Operator Index
IPEX	Italian Power Exchange
NREL	National Renewable Energy Laboratory
PEMFC	Proton Exchange Membrane Fuel Cell
PUN	Average National Price spot price weighted by market zone
PHS	Pumped Hydro Storage
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy System
RSI	Residual Supply Index
SIC	Zonal spot price in Sicily market zone
SOFC	Solid Oxide Fuel Cell
TERNA	Italian TSO
TOE	Tonne of oil equivalent
ZEB	Zero Energy Building

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Part I

MAKING THE CASE FOR DECENTRALIZED HYDROGEN-BASED ENERGY STORAGE

1 INTRODUCTION

In 1972 an MIT research group published the results of a computer simulation study commissioned by the Club of Rome under the leadership of Aurelio Peccei. They analysed the consequences of increasing trends in world population and Co2 global pollutions, in a finite world with finite natural resources. Different scenarios were generated and explained in the book The Limit To Growth[51]. Issuing a broad warning to the scientific, economic and policy-making sector, their work demonstrated for the first time that the combustion of fossil fuels changes the earth's natural balance, causing global warming.

1.1 BACKGROUND

In the last decades, environmental and socioeconomic concerns have sadly highlighted the problems of the modern society whose energy supply chain is based on fossil fuel. Consequently, increasing attention was given to the importance of renewable energy (RE) at national and international level. In 1988 the United Nations have established the Intergovernmental Panel on Climate Change (IPCC). The IPCC and other institutions drove international leaders in negotiating agreements and treaties like the Kyoto Protocol. Meanwhile, scientists all over the world got involved, making their contribution to the research and disclosure on the topic of anthropogenic climate changes. Leading the international community, the European Union has settled its own environmental goals for year 2020 [32]. The so-called 20-20-20 energy goals are to have a 20% reduction in greenhouse emissions compared to 1990 levels, 20% of the energy consumption supplied by renewables and a 20% increase in energy efficiency compared to 2005 [20].

These policies and binding treaties have the common, global, drivers on the need to [28][39]: reduce CO_2 emission from energy generation through a broader exploitation of RE sources (RES), guarantee security of energy supply and decrease the dependency from politically unstable countries through a new industrial network, central for our economic prosperity.

However when more RE feeds the grid, balancing problems occur. The biggest challenge of the future is, in fact, to coordinate fluctuating RE with the rest of the energy system [46]. Being weather dependent and seasonal fluctuating, solar, wind, wave and tidal power, are intermittent and non-programmable. Only exception are large hydropower units, which can be suitable for electricity balancing in some areas [46].

Energy storage technologies are therefore the key element to increase the availability and reliability of distributed RES. A well connected and smartly managed network of distributed producers and energy storage units can ensure grid stability also in a highly renewable energy system (RES).

One of the most acclaimed books by economist Jeremy Rifkin was named after an expression coined by John Bockris in year 1970, The Hydrogen Economy[66]. Likewise Peter Hoffmann in Tomorrow's Energy[38] he finds a common solution to the problems of greenhouse gas emissions and intermittency of RE: hydrogen as energy vector in a vastly decentralised and reorganised new energy system. In line with this both the United States and the European Union have paid increasing attention to the potential of hydrogen storage [27] [26] and integrated R&D programs led hydrogen technologies to a commercial and near-commercial status.

1.1.1 *The Focus*

Electrolysers are devices splitting water into hydrogen and oxygen using electrical energy.

This study explores concrete aspects of this issue. Cost-benefit analysis is used to calculate the maximum potential operating income of an electricity storage, composed by electrolysers (electricity to hydrogen), storage tanks and fuel cells (hydrogen to electricity), operating in the Italian day-ahead market. Grid-related consequences of the economically optimal operation are then evaluated and expected to improve the overall system performance in terms of: decreased bottlenecks hours, increased market competition (e.g. decreased market power of pivotal operators) and, in a future scenario with greater RE penetration, support to the otherwise curtailed RE. In this way, economic and environmental consequences of the introduction of hydrogen as an energy vector are considered. The simulation is undertaken in a highly renewable and partially isolated energy system. As a case study the electricity system of the Italian island of Sicily is analysed.

Fuel cells are electro-chemical devices which produce electricity directly from a fuel, typically hydrogen, without any combustion.

Firstly, data of hourly consumption, production and spot market price are gathered. This first data collection allows assessment of bottlenecks hours, RE production profiles and market competition, on a hourly base, for year 2013. Secondly, the hydrogen based storage is designed and a techno-economical analysis outlines its capital cost and performance factors. The study then focuses on the operational optimization of the hydrogen system. The maximum net operating income is calculated and the on/off distribution match with the peaks in RE production and bottleneck hours is analysed. The Residual Supply Index (RSI, see Section 7.3) is used to evaluate the storage impact on market competition. Sensitivity analysis is finally undertaken, with a view to the European Horizon 2020 goals.

The problem of the electricity network bottleneck between Sicily and the mainland is considered and a price arbitrage strategy is applied to the storage operation on the Italian day-ahead market.

This Chapter now introduces the main topics of the study. Relevant problems linked to a high degree of penetration of RE are explained In Section 1.3. Section 1.4 introduces the main features of hydrogen as an energy vector together with technical details of the technological state-of-the-art. Section 1.6 reviews the relevant literature, point of departure for the formulation of the research question of Section 1.7. The problems related to the Italian electricity grid are now explained in Section 4.1.2, motivating the choice to locate the study in Sicily and the scientific interest to model and simulate the functioning of hydrogen storage in the Italian island.

1.2 ITALIAN ELECTRICITY NETWORK

In the last years European electricity networks have changed rapidly and so the Italian one did. Despite an historical north-south net electricity flow a reverse trend is now moving electricity from the south to the centre-north region. This is due to an increased competitiveness of the southern regions (south, centre south and Sicily) which have experienced a high RE penetration. However this fast increase in RE production was not followed by an equally significant development of the grid, both at the transmission and distribution level. The grid of the southern regions is, in fact, the less developed. Some wind power cannot be absorbed in the *distribution* grid and producers are asked and paid to switch off their turbines. The situation gets even more complex considering that also *transmission* interconnections between zones are often overloaded.

It is worth considering two economic aspects of this situation. The first one relates to the fact that the amount of curtailed wind power, in lack of investments in grid flexibility, is going to increase. It was estimated to be 248 GWh in 2013 [34]. At a national level, this is 1,8% of the total wind production. Transmission and distribution grid contribute to cause wind power curtailment as shown in Figure 2.

The second consideration is essential for the purpose of this study. In the case of bottleneck in the transmission grid, the market operator forms zonal day-ahead equilibrium prices. In the Italian day-ahead market producers are paid to the zonal price. Buyers, instead, pay an average of the zonal prices weighted over the zonal electricity consumptions: the so-called Single National Price (PUN). In a well functioning system this should push the oldest power plants out of the market, fostering RE penetration in the deficient zones.

PUN is the single national price which buyers pay in the day-ahead market. Sellers, instead, are paid according to the zonal price.

Two things can happen when the market is divided in zones. If the isolated zone has enough cheap electricity production to cover most of the demand the zonal price can be lower than the PUN. If, instead, old oil fired power plants set the zonal price, the zonal price gets seriously high, affecting the PUN. The two situations are shown in Figure 1 and their effect on the market in Figure 3.

The most evident and frequent grid bottleneck is the one between Sicily and the rest of the country that is now introduced.

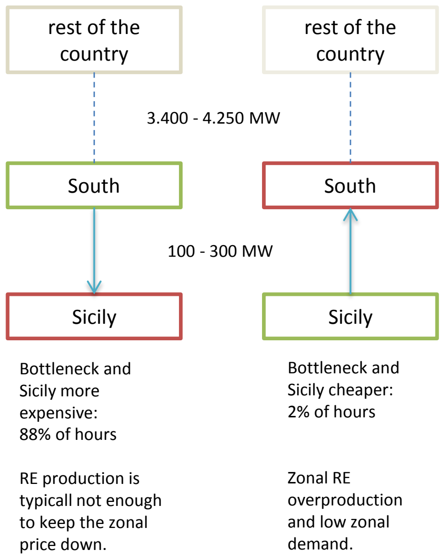


Figure 1: Possible bottleneck situations between Sicily and the mainland.

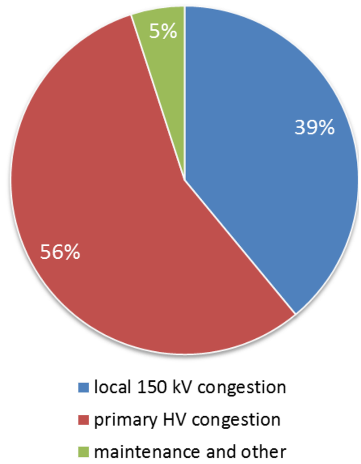


Figure 2: Curtailed wind power by cause. Data from GME.

1.2.1 *The Transmission Bottleneck in Sicily*

Because of too small grid interconnection with the rest of the country, Sicily wholesale market is a distinct relevant market, where dominant speculators can easily exercise their market power. At current status, interconnections allow a 100 MW flow toward the island (300 MW if extra units are committed) and a 250 MW (weekdays 8-23) or 100 MW (rest of the hours) flow from the island (respectively 600 MW and 150 MW if extra units are committed)[48]. Electricity is mainly produced by conventional thermal power plants. Eight of them provide electricity to the grid and other five are used for self-production industrial purposes. Those power plants are the oldest and less efficient of the entire country. Most of them are older than 30 years, producing at 22% efficiency [14]. From year 2003 RE has widely penetrated the market. Ten years later 15% of the island's electricity production is renewable. The zonal day-ahead price reached EUR 0 per MWh, In 94 hours of year 2013.

However, any further increase in the amount of energy produced by renewable sources is today strongly limited both technically, by the limited transport capacity of the grid on the island, and structurally, due to the market set-up, and the needed baseload and bilateral contracts from conventional power plants. The island has got a minimum capacity of pumped hydro plants, but there are no more suitable site for this storage technology due to landscape issues. To complete the picture, there are ownership relations between renewable and old power plants, in evident conflicts of interests.

The two import and export situations of bottleneck outlined in Figure 1 were detailed in the 2013 IPEX annual report [34] and summarized in Table 1.

In 2013 Sicily was separated from the South market zone 88% of the hours, (+4% comparing to 2012). Economic consequences mainly relate to the price formulation dynamics in the day-ahead market. In fact from 2007 the Sicily zonal price is being diverging from the national average PUN. This difference between the zonal price and the PUN reaches a gap of EUR 30,84 per MWh when considering peak hours (8.00-20.00 on working days) in year 2013. This problem shows its increasing trend also in another way, which will be longer analyzed in Section 4.2.1.

Sicily is the biggest Italian region and Mediterranean island. With a population approx. equal to Denmark, it is today the biggest example of a quasi-independent electricity system.

Summing up, Sicilian renewable producers have the highest revenues guaranteed (even if in some hours are asked to switch off) by the market combination with inefficient, price-setter, power plants. The latter ones, on the other side, seem to have a safe long lasting permanence on the market thanks to lack of infrastructural improvements in the distribution grid which has so far banished Sicily in an autonomous day-ahead market.

It results a zonal price which is averagely EUR 29,01 per MWh higher than the national PUN. This represents a huge social cost weighting on the overall Italian consumers and an infrastructural limit in the future development of RE in the island due to a weak grid.

Bottleneck in	Available Capacity		Refused Offer Low	High	Total
Import	⩽ 100 MW	Hours	36%	21%	57%
		ΔPUN (EUR/MWh)	37,6	23,6	32,3
	> 100 MW	Hours	6%	13 %	19 %
		ΔPUN (EUR/MWh)	22,0	14,3	16,5
	All	Hours	41%	35%	76%
		ΔPUN (EUR/MWh)	35,5	20,0	28,4
Export	All	Hours	8%	16%	24%
		ΔPUN (EUR/MWh)	-7,7	-6,9	-7,1
Total	Total	Hours	49%	51%	100%
		ΔPUN (EUR/MWh)	28,6	11,4	19,8

Table 1: Summary of the hours in which there has been transmission congestion to (import) or from (export) the island of Sicily in year 2012. Data elaborated from GME[34].

In the following Section a solution to this problem is investigated through three different approaches. Firstly the historical governing promise to increment the transmission high-voltage power lines between Sicily and Calabria is introduced as well as the main concerns related to it. Secondly, regulatory intervention in the IPEX and debated changes to the PUN structure are explained for a qualitative understanding of the existing possibilities in matter of changes in the market regulation. Finally, the innovative proposal which is analysed in this study is introduced: an innovative electricity storage based on the electricity conversion into hydrogen.

1.2.2 *Three Different Development Strategies*

Main sources of this Section are the actual documentation of the public debate related to the history of the Sicily grid problems. The TSO talked about an extra interconnection in the Strait of Messina for the first time in year 2003. This solution would certainly help solving the bottleneck problem, but more than 10 years later works are barely started, with a great local opposition. This delay, mainly caused by frequent policy changes of the regional Parliament, has recently led the Italian Competition Authority to discuss the possibility of relevant variations to the IPEX price formulation, in order to preserve market competition and its effects on the Italian electricity price [1].

These events are the starting point of the business and socio-economic analyses undertaken in this study, which aims to produce an in-depth investigation on the economic feasibility and grid applications of hydrogen-based green electricity storage, a potential innovative so-

1 This considerations were firstly publicly made in an official letter of the Competition Authority to the regional Parliament of Sicily on the 12th of April 2013 [9].

lution to overcome paralysis in the above described stuck situation.

In the following part of this Section the governing strategy of increasing transmission connection is firstly described. After this, the Competition Authority proposal to rethink the spot price structure is also discussed and finally the innovative proposal of an implementation of hydrogen-based, smartly operated, storage units is introduced. These are the three considered alternative:

Infrastructural: new interconnection. The TSO established a new development plan, leading to new interconnection between Sicily and the mainland. This will surely improve the situation but the regional Parliament is seriously take position against the project. This new underwater transmission line between Sicily and the mainland has been in planning for years and this is, staying to the TSO, the needed escape valve for the Sicilian RE that would also allow more import. Overall effect would be a decreasing PUN. Works have recently started in an atmosphere of contrast between national and regional government, the latter one asking for more time to evaluate and improve the project. With a length of 38 km, 370 m underwater depth, this will be the longest underwater transmission power line worldwide. Starting evaluation cost was EUR 700 mln.[71] However, environmental issues are still unresolved. With no explanation, the project was suddenly changed, moving the main pylons on a hill peak that is exposed to view in the whole area. Local people accuse the authority of having approved the project without even consider the numerous complaints to the EIA [18][4]. In top of this, the TSO is, in some extends, avoiding discussions about the distribution network congestion which will not be solved with this operation.

Regulating: bid cap and PUN structure revision. In 2010 the Italian regulator Authority for Electricity (AEEG) started an investigation on the Sicily electricity system. The investigation shown that the grid bottleneck helped preserving the position of dominants operators, and a picture of a duopoly market was drawn. That year, 45% of the power generating capacity in Sicily was owned by Enel (gas fired turbines, oil and turbogas plants) while another 26% was owned by Edilpower (one big oil fired plant). The resulting merit order market graph is shown in Figure 6. Investigation from the Italian Competition Authority showed that Enel bade high its plants. Gas turbines and turbogas electricity was offered up to three times higher than competitors.

The two dominant and pivotal producers, Enel and Edipower, voluntarily committed to a bid cap of EUR 190 per MWh, from the end of 2011[54]. This price has been annually updated and lasts until june 2015. However, despite the optimism of the antitrust regulator, this was not considered enough by the most. Bid cap was probably too high and the expected effect on the market dynamics did not take place. At the same time renewable fed the grid increasingly, putting even more value on the old power plants as balancing and baseload units.

In April 2014 another regulative change was discussed by the Competition Authority, as a response to the delay in building the new interconnections. The discussion is about removing Sicily from the PUN formulation dynamic, in a way to produce an immediate PUN decrease. In this study, this is not considered as a feasible strategy but, contrarily as a provocation and incentive to push through the necessary procedure to start bulding the new underwater interconnections between Sicily and the mainland. Separating the island from the Italian spot market, would finally give even more power to pivotal operators, living consumers of this area alone with no chances to reach a reasonable situation.

Innovative: hydrogen electricity storage. Increasing transmission line capacity in a congested region will surely produce good economic consequences. However the lack of alternative proposals does not ensure transparency in the process of choosing the most effective investment for decreasing the Italian electricity costs. As it is later discussed in Section 1.4.3 a highly renewable, partially isolated system could be the best lab for emerging energy storage technologies, like hydrogen storage. This has happened in Corsica with the project Myrte, a full scale 200 kW electricity to hydrogen storage system, which was inaugurated in January 2012. In Sicily this possibility was not even considered to be worthy of being publicly analyzed, not even for tests or first-of-a-kind innovative projects.

This study analyzes this third option to solve the economic and structural problem of the Italian grid. the economic consequence of a distribute installation of electricity storage units, close to the most congested distribution points in Sicily. The basic idea is that, if more RE is absorbed and stored in hours of overproduction, less electricity would be needed from the outer zones in the hours of peaks in demand, preventing grid congestion.

Moreover, another aspect needs to be considered. In the first two weeks of October 2013 something rare has happened. Because of a TSO's routine maintenance of the transmission power line, Sicily was unplugged from the rest of the world. It resulted a critical (but predictable) zonal price increase, with 40% of the hours of October being over EUR 130 per MWh. This was a clear alarm signal indicating that, especially with an increasing RE making it harsher for the TSO

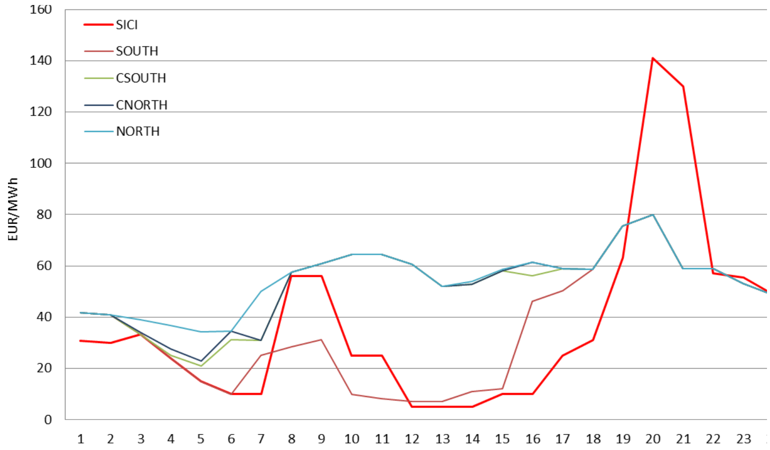


Figure 3: Zonal day-ahead prices in the IPEX. 4th of March 2014. Sicily is congested the whole day. From 19.00 until 22.00 its zonal price is higher than the one of the other zones.

to secure the balance of the network in Sicily, the island should be ready to stand alone, if needed, for medium-term periods. This is another reason why energy storage technology can play a prominent role: relieving the consequences of interrupting transmission system. The safety of supply could be therefore provided by a coordinated match between a high RE rate and a distributed network of electricity storage.

Today's market shows PHES storage as the safest both technologically and economically. However they are all located in the north of Italy. In Sicily, lack of rain and rivers and landscape reasons do not allow any further implementation of PHES storage. On top of this, owning 44,5% of the Italian PHES installed capacity, Enel would probably end up building this storage also in Italy, and free market competition problems would not be solved.

In Section 1.3 the problem of balancing tasks is introduced from a broader perspective, leaving Sicily aside for a while. This section leads to Section 1.4 where an introduction to hydrogen-based storage is finally given.

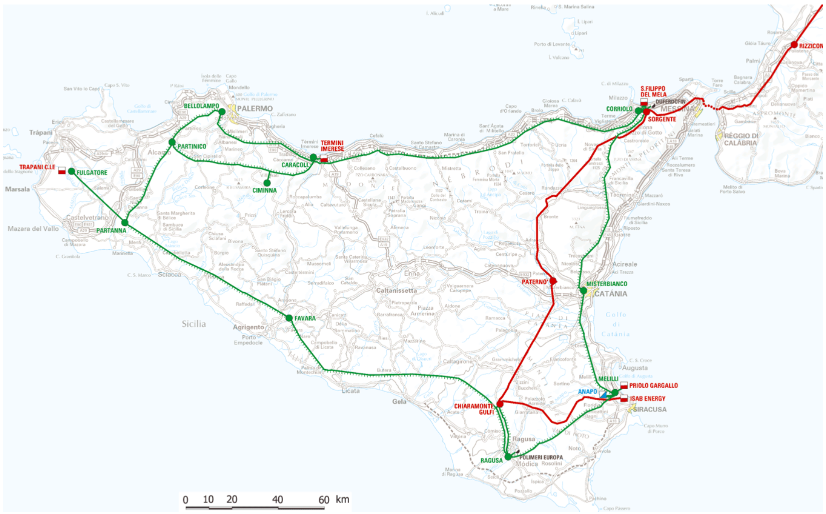


Figure 4: High (220 kV) and ultra-high (380 kV) voltage electricity grid (respectively, in green and red) in Sicily. Copyright Istituto Geografico De Agostini, 2002.

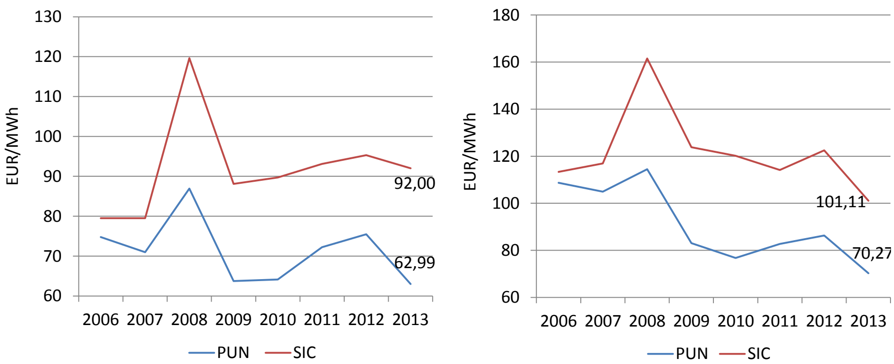


Figure 5: PUN and Sicily day-ahead price yearly trend, average (left) and peak hours, 8.00-20.00 on working days, (right). Data from GME. North, Centre-north, Centre-south and South zones prices (which are not shown) have the highest weight on the PUN formation and are below the PUN.

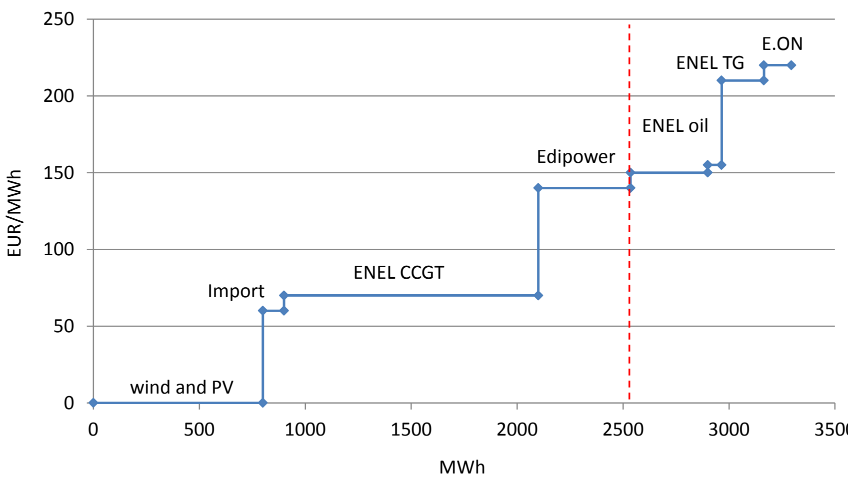


Figure 6: Merit order of Sicily's electricity market in 2010. Red line shows the average peak hours load 2008-2009. Data elaborated from AGCM[54]

1.3 THE NEED FOR FLEXIBLE ELECTRICITY STORAGE

Wind turbines and PV's weather dependency generates the problem of supply intermittency. Even though forecasting strategies are being studied, renewable production is hard to predict. The more RE is injected into the grid, the more precise the forecast needs to be, for grid balancing tasks. 100% RESs require flexibility strategies which cannot prescind from electricity storage.

When using storage units to support the grid in overload situations, the units need to be placed in the right place within the grid. Corollary of the first Ohm's law ($P = RI^2$) sets a limit for the power which can be sustained by the grid and the second Ohm's law ($R = \rho\frac{l}{S}$) relates this limit to the the section, length and resistivity of the analysed power line. If one wants to apply grid storage to prevent *capacity* overload problems, the storage needs to be placed in the point where the grid is expected to fail (e.g. beside a wind farm which is not fully sustained by the distribution grid or beside a big consumer which could suddenly require a peak in demand). Kirchhoff's first law ($\sum_{k=1}^{n} I_k = 0$), instead, says that in every junction of an electrical circuit, "the sum of currents flowing into the node is equal to the sum of currents flowing out"[2]. Meaning that, if aiming to control *energy* overload situation, the storage location does not need to be a specific one, as long as it is in the right side of the grid node.

Beside preventing power systems' overload, storage technologies can be operated to provide different tasks but their implementation is often tied to important environmental requirements. There are three options for big size storage: pumped hydro energy storage (PHES), compressed air energy storage (CAES) and hydrogen storage.

In 2012 about 128 GW of storage power capacity were installed worldwide and 99% of this is PHES.[67]

The volumetric energy density of H2 is lower than those of fossil fuels (see Table 2) but, if compressed, is higher than those of PHES and CAES. [67] A cubic meter of hydrogen has an energy of 2.7-160 kWh (pressures 1-700 bar). The same volume filled with elevated water at 100 meter height differential contains only 0.27 kWh and 2-7 kWh is the energy of 1 m3 of compressed air (pressures 20-80 bar). [67]

For this reason, in lack of natural sites for the cheapest PHES, hydrogen storage may be the best option for absorbing peaks in RE supply. The alternative proposal of this study is, therefore, to analyze the consequences of the installation of smartly operated hydrogen storage units. They would provide support to the RE production, preventing grid congestion both when the island is in over and underproduction.

2 From Wikipedia http://en.wikipedia.org/wiki/Kirchhoff's_circuit_laws#Kirchhoff.27s_current_law_.28KCL.29

1.4 HYDROGEN-BASED ELECTRICITY STORAGE

Hydrogen is the chemical element with atomic number 1. In standard conditions is a colorless, odorless, highly flammable gas. It is the most abundant element in the universe. Pure hydrogen can be produced taking advantage of the chemical conversion of water molecules (H2O) into its constituent elements, di-hydrogen (H2) and oxygen (O), through the use of moving electrons, i.e. *water electrolysis*. In the reverse H2-O reaction, hydrogen can finally release energy in *heat engines* and *fuel cells*. By-product of the reaction is water.

H2 production by technology in 2008 was: 48% NG reforming, 30% pretroleum fraction, 18% coal gasification, 4% electrolysis

Different view points can be found, when getting to talk about hydrogen technologies. Hydrogen is strongly criticised by who does not consider it as a possible solution to the climate changes problem. Mackay[47] asserts that "converting energy to and from hydrogen can only be done inefficiently, at least with today's technology". Beside a low system efficiency, hydrogen, like electricity, is an energy carrier, i.e. it must be produced from a natural source [24]. Today most of the produced hydrogen comes from natural gas reforming and petroleum fraction, but it can also be produced by renewable sources like municipal waste or the already mentioned water electrolysis.

If from one side the needed energy conversions to use hydrogen for storing energy create efficiency problems, from the other side this can, especially in its earlier implementation, represent an added value. In fact, thanks to its ability to convert into different forms of energy, hydrogen can be the unifying missing bridge in the energy transition towards a 100% RES. For these reasons, despite criticisms, it is hard to

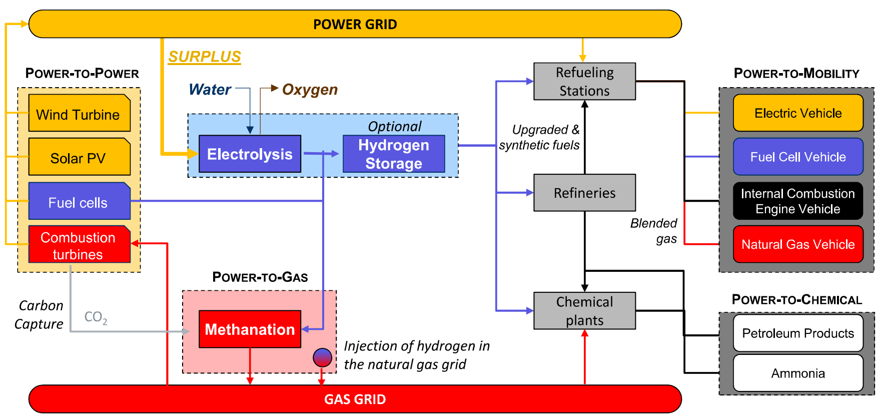


Figure 7: Simplified value chain of hydrogen-based energy conversions. From SBC[67]. This study focuses on the specific power-to-power transition through fuel cells and electrolysis.

deny the potential benefits of a large scale implementation of hydrogen based energy systems.[28] Its relatively easy production process and its abundance in nature solve the problem of fuel scarcity. Moreover, as Figure 7 shows, hydrogen can be used in almost every application where fossil fuels are being used today, without greenhouse gas emissions[13]. In top of this, despite public perception, hydrogen is demonstrated to be as safe as the other common fuels [73][12].

1.4.1 *Costs*

The biggest challenge for hydrogen conversion and storage systems is economic rather than technological [67]. The main factor influencing the cost of producing electricity through hydrogen conversions, is the cost of the electrolysis. However two aspects have to be considered. Firstly the great potential in cost reduction for the proton exchange membrane (PEM) technology, which is the most promising type of electrolyser, under development by Siemens, Hydrogenics and ITM Power. Secondly, the benefits of buying electricity in the off-peak hours and the potential revenues from grid balancing and ancillary grid services [67]. In this study, both of these issues are considered by means of sensitivity analysis and operational optimisation of the designed hydrogen-based energy storage.

1.4.2 *Efficiency, reliability and versatility*

Round-trip efficiency of the electrolysis and re-electrification ranges from 20% to, at best 48%. From an efficiency perspective, hydrogen will not be a competitive storage method. Heat recovering from the the re-electrification process can definitely make the overall process more convenient, increasing the efficiency of the hydrogen-to-electricity (and heat) process to up to 80% when using fuel cells. If efficiency is not a strength of hydrogen based storage, reliability surely is. The lack of moving parts makes fuel cells and electrolysers extremely reliable. Fuel cells power quality is extremely high and they also have very low maintenance requirements [67]. These factors are making fuel cells particularly attractive for off-grid (e.g. telecom towers or military basis) and uninterruptible power supply (e.g. data centres and hospitals).

Finally, hydrogen is versatile. As Figure 7 shows, it can be used for generating electricity (power-to-power), heat houses or fuel vehicles (power-to-mobility). It also have non energy-use: today industry is the largest consumer of hydrogen. This includes the ammonia plants (power-to-chemical) , but also other applications like semi-conductor and food industry or hospitals. On top of this the developing idea of power-to-gas (injecting hydrogen into the gas grid), could represent one more crossroads of energy sources and network.

H2 consumption by sector in 2008 was: 50% ammonia, 37% refineries, 4% others, 1% space.

	m energy density MJ/kg	V energy density MJ/L
Hydrogen liquid	141,86	8491
Crude oil	46,3	37
Biodisel oil	42,2	33
Hydrogen (690 bar, 15oC)	141,86	4,5
Alkaline battery	0,67	1,8
Lead-acid battery	0,17	0,34
Compressed air at 300 bar	0,5	0,2
Natural gas	53,6	0,0364
Hydrogen gas	141,86	0,01005
Water at 100m dam height	0,001	0,001
Coal	46	
Wood	16,2	
Household waste	8	

Table 2: Mass and volumetric energy density for different energy sources (nuclear fission, chemical or electrochemical energy) and storage (potential energy). From Wikipedia.

The analysis undertaken in this study uniquely moves in the power-to-power (i.e. electricity storage) framework, considering heat recover.

1.4.3 *Public support and Social Acceptance*

As already explained in the introduction of Section 1.4 the main uncertainties about the role of hydrogen as a substitute of fossil fuels have an economic nature. Reduction in investment cost is a prerequisite to make the overall hydrogen investment cash flow more attractive[67]. At the same time support from the public sphere is needed to foster market penetration. This could either be in the form of feed-in tariffs, transmission fee exemptions, tax exemption or green certificates. In addition, international authorities must soon issue specific codes and regulation.

Remote areas and islands with a high penetration of RE offer good test opportunities to monetize social benefits (for instance grid balancing service) and to calibrate incentives or economic rewards.

Finally, as every technological change, social acceptance needs to be overcome [46]. Hydrogen as an energy carrier is a new and alternative concept and it needs to be correctly explained to the population. In order to do so, demonstrative installation and widespread education are essential.

1.5 MAKING THE CASE FOR HYDROGEN

Summing up, despite the low round-trip efficiency of the conversion process (electricity-to-hydrogen and hydrogen-to-electricity), hydrogen-based storage can, in theory, be a competitive alternative to the other storage possibilities. This fact was demonstrated by several case studies in the SBC [67] report.

In practice, the main applications of hydrogen-based storage solutions are expected to combine the three leading advantages of chemical storage: versatility, energy density, reliability. These futures make it particularly suitable for large-scale, long-term re-electrification applications, as well as niche markets that benefit from its reliability.

Large-scale applications benefit from negligible losses during the storage phase. This allows long-term storage unlike, for instance, batteries. Also, hydrogen-based technologies are not affected by erratic demand pattern and can perfectly manage fast fluctuations in storage requirements. In top of this, hydrogen high energy density, allows extensive storage capacity with a lower space need than PHES.

Off-grid and power quality applications, i.e. telecom tower and data centres, can leverage the hydrogen storage high reliability which ensures constant and high quality power supply. In these systems hydrogen fuel cells could become the standard supply, having the grid as a back-up connection.

1.6 LITERATURE STUDY

Three research fields were scanned when establishing the foundation of the study: hydrogen technologies economic feasibility evaluations, peak-shaving and optimised storage operation strategy, techno-economic analysis of the Italian electricity market structure.

Several articles have analysed the problem of the Italian electricity price trying to find policy or organizational solutions.Petrella[62] has analysed the impact on the Italian day-ahead market of measures like White Certificates. Bonenti et al.[16] focused on the effect of the EU Emission trading scheme and Bosco et al.[17] have suggested a new price-capping strategy to decrease price-setter operators power. Researchers have also analysed the problem of the lack of sufficient interconnection between Italian islands and mainland. Between this, the closest to the interest of this study is Boffa et al.[15] that have looked to the benefit of new potential interconnection between Italian market zones. However no one has specifically considered the potential of electricity storage as balancing units in the Italian network.

Figure 18 clearly shows that this option is particularly attractive in Italy, with even greater price differentials due to the zonal price in the sell-side.

A recent publication by the SBC Energy Institute has selected and presented nine hydrogen centred case studies, a few of these involve the sale of electricity, using hydrogen storage for energy time-shifting purpose in different applications. The outstanding PURE projects has shown an increase of 18% in utilised wind power, in the Scottish island of Unst[64]. The HARP project in Bella Coola has implemented diesel savings up to 15% in a diesel-generator and the hydrogen storage installed in Ramea Island lead local wind turbines to cover 90% of the island annual electricity consumption [63] [43]. However, economically speaking, the two Canadian projects implemented in Ramea Island and Bella Coola are showing that the cost of adding an hydrogen system is unlikely to be covered by energy savings, but this is not surprising for a first-of-a-kind technology application. A scenario with PEM fuel cells operating in a intraday market economic optimisation was simulated by the National Renewable Energy Laboratory in 2010 [57]. Finally IER has studied the need for electricity storage on a country-wide scale in a future highly renewable (35%, 50% and 80%) energy system. The study demonstrates that hydrogen become the best storage solution for Germany, when RE penetration mix reaches the Energiewende objective of 80% in 2050 (intermittent production reach 55% and there are about 3.000 hours of free electricity on the market) due to a lack of pumped-hydro storage capacity. This solution could also compete with investment in new market interconnections [41].

It follows the problem formulation, leading to the research question that will be answered in the study.

1.7 RESEARCH QUESTION

Italian day-ahead electricity price is 30% higher than the European average and two times the Nord Pool price. When considering network fees and non-recoverable taxes, an Italian industrial consumer (500 to 2.000 MWh per year) pays an average price of EUR 20 per MWh for its electricity consumption, against an European weighted average of EUR 12,5 per MWh. The same Italian industrial consumer would pay less then half if living in Scandinavia. This is mainly because of three factors: a high gas price due to generous international agreements, a non optimal energy mix and a deficient electricity grid. It has an important part in this, the problematic grid balancing situation of the island of Sicily.

In the Italian day-ahead market sell-side price and buy-side price are different and depend on zonal congestions. On the one hand this structure protects consumers living in the worst connected zones (Sardinia and Sicily), on the other hand the whole nation pays a higher price for electricity due to interconnection problems which are limited to some areas. Moreover, recurring congenstions do not allow a complete absorption of intermittent RE. In fact, the most congested zones are the ones having the highest share of RE.

Traditionally, grid congestion are solved reinforcing the transmission capacity through zones. However, RE is decentralising power generation and energy storage technologies can strongly limit the need to import from other zones. Energy storage systems can increase power system stability and support the integration of a higher share of intermittent RE. But the utilization of energy storage will remain limited until they will ensure a safer investment with an attractive internal rate of return.

In this study, the profit-maximizing price arbitrage operation mode is used to find the highest operating income of a hydrogen-based electricity storage which is modelled by means of the software energyPRO and located in the island of Sicily. The grid benefit for the Italian power grid are evaluated. The study furthers the understanding of the needed change for reaching better synergies in integrating RE and innovative electricity storage. It identifies socioeconomic beneficial solutions addressing how the economically optimal storage operation can also provide important grid services. It follows the research question:

Staying to the state-of-the-art research, what is the profitability of a decentralized hydrogen-based electricity storage unit and to what extent this technology can support the grid in an increasingly renewable and mostly congested power system?

1. What is the operation strategy which maximizes the operation income of the hydrogen-based electricity storage operating in the electricity day-ahead market?

2. What is the optimal configuration and the profitability of the overall investment?

3. What are the potential benefits for the overall electricity network, in terms of increasing RE depth of penetration, preventing bottleneck and increasing market competition?

1.8 STRUCTURE OF THE REPORT

This section presents the structure of the report to give an overview and guide the reader in the following chapters. It explains the purpose of each chapter as well as their connections.

Chapter 2 introduces the theoretical background of the study. Large-scale introduction of hydrogen-based electricity storage is framed in the theoretical field of the radical technological changes. Those changes are described in the context of the Choice Awareness theory.

Chapter 3 outlines the main methods applied to the research design. Data collection methods and sources are described. Finally the IT energy modelling and optimisation tool energyPRO is described in details.

Chapter 4 goes in details on the Italian spot market, the techno-economical framework of the case study. The IPEX is firstly described starting from its differences from the Nord Pool, the biggest EU market. In the last part of the Chapter the price formulation dynamics are then described in details.

Chapter 5 introduces the case study in details: the electricity grid and spot market of Sicily. Here a review of the possible energy storage application are also given. Finally, the results of the scoping study are given, in order to quantify the hydrogen storage investment and define the techno-economic performance of the involved technologies.

Chapter 6 and Chapter 7 report the result of the analysis from a private business and grid evaluation perspective, respectively. Chapter 6 shows the resulting NPV when the storage applies price arbitrage in the Italian day-ahead market. Reference scenarios are integrated with a sensitivity analysis. Chapter 7 shows the potential application, of the same storage, in supporting the problematic grid of Sicily, in terms of increase renewable energy depth of penetration, increase market competition and transmission bottleneck prevention.

Finally Chapter 8 concludes the study, reporting on the research question answers.

2 THEORY

From a decades-long experience, the Sustainable Energy Planning research group of Aalborg University has established a research method for the analysis of energy investments, RE scenarios and energy policy design. Having as a testing lab the pioneering environment of the Danish energy system and society, strategies have been formulated and field-tested. This work has also lead to the development of several IT support tools, like energyPRO that is used in this study.

When getting to the large-scale implementation of RE system, Denmark represents an important case. Lund[46] says that the Danish objectives and innovative strategies for the future, have been realised thanks to a constant interaction between the Parliament and the society. The technical description of new technologies and alternative energy plans by analyst and researchers is the basis of the Choice Awareness theory. This theoretical approach is applied in the study.

The following Sections are based on the book Renewable Energy System by Lund[46]. Firstly the concept of technology and technological change is introduced, secondly the Choice Awareness theory is enunciated and its application in this study is justified.

2.1 TECHNOLOGICAL CHANGE

Technology was defined by Muller[53] as "the means by which mankind reproduces and expands its living conditions", a combination of four elements: *technique*, *knowledge*, *organisation* and *product*. Hvelplund et al.[40] later adds *profit* as a fifth element. He also defines radical technological change as a change that involves more than one dimension. The more dimensions are involved, the higher is the degree of change.

For Muller[53], if one dimension is changed, it will be followed by at least one of the other. If the second change will not take place, the initial change will languish over a relatively short period of time. It is remarkable that the fifth element, *profit*, is particularly relevant when considering changes within the energy field.

In a *neoclassical economy* approach, institution are considered static and unchangeable. The Adam Smith *free market* concept, defines public regulation as neutral upon the market processes. When many, mutually independent, rational and fully informed buyers and suppliers act on the market to maximize their individual profits, the market will lead to a socially optimal outcome. However this approach turns out to be far from reality, when considering technological change [40].

Institutional market economy moves from the concept of *free market* to the one of *real market*. The latter one considers the market with its specific institutions. In this case, historical and technological context must be considered, including private market power relations, public policy, accessibility to information, etc.

Because of the conservative nature of the existing institutional setup, technological change is often a change from undifferentiated solutions held by a few single-purpose actors to differentiated solutions implemented by many new multi-purpose organizations.[46] Indeed, this is the case for a large scale introduction of hydrogen based storage.

The *institutional market economy* approach is applied in this study. The market situation is therefore considered variable and changes from the current "invisible hand" equilibrium are not necessarily a loss for society. Instead, new policy design can help reaching social objectives, e.g. reducing green house gas emissions.

2.1.1 *Institutional market economy*

Investments in hydrogen technologies, likewise other typical investments in cleaner technologies, take place in a context that is outlined by the energy markets setup. As argued in Section 1.4.2, hydrogen is a versatile energy vector, capable to link different forms of energy needs as, electricity, heating, natural gas fueled processes and transportation. Since this study focuses on the implementation of hydrogen for storing electricity in Italy, only the context of the Italian electricity market is now described.

The Italian electricity market is characterized by large supply companies and many different groups of consumers, e.g. households, public and private enterprises. Supply companies are currently supplying electricity mainly by means of fossil fueled central power plants. The former monopolist, Enel, seems to have a relevant advantage in the price setting process, especially in peak hours. In 2012, Enel sold 25,4% of the Italian electricity demand. The biggest five producers (Enel, Eni, Edison, E.On and Edipower) had 50,3% of the market.

This is an oligopolistic market, with a few dominant suppliers. In many cases, they are not mutually independent but, instead, linked

Operator	Market Share		
	2010	2011	2012
Enel	27,8	26,2	25,4
Eni	10,7	9,3	9,5
Edison	9,8	8,3	7,2
E.On	5,5	5,2	4,4
Edipower	5,5	4,8	3,9
Others	40,8	46,2	49,7

Table 3: Italian main power producing groups and their share of gross energy production. Data from AEEG[8].

through ownership and business relations. Analysis have shown that also information is insufficient[7], often kept secret or hard to get. Most of the premises of the self-regulating *free market* are therefore missing. These actors strive to exercise their power, both economically and politically. It results that public decision making is shaped by the interest of the most influencing groups of the society.

Even if both the distribution and the transmission grid presents bottlenecks problems, in the last years RE units have been widely installed, reaching 31% of the annual production in 2012.[8] Companies know that a significant development of the transmission grid, needs to consider energy storage systems[30] and one of the world major energy storage group, Fiamm, is Italian. On top of this ENEA (Italian Agency for New Technologies, Energy and Sustainable Development) has been investing in the development of fuel cells and hydrogen technologies since years and has released several reports underlining the features of the emerging technologies [52] and guidelines for the decision makers [29]. However today, the only implemented storage technology in Italy is the pumped hydro electricity storage (PHES). PHES generate 7% of the national electricity production, but they are not used for balancing tasks.

PHES need water supply and natural altitude gaps, which are rare in the south, where the fluctuating RE plants ask for balancing units. Moreover if, in theory, PHES could be considered for balancing tasks, there would be, again, a competition issue. In fact today Enel, owns 44,5% of the PHES capacity, and it could be hard for competitors to enter the market.

These factors open a window for a new form of energy storage which is not being considered by the decision makers until today.

2.1.2 *Hydrogen storage implementation*

When PHES storage conditions are not satisfied, hydrogen storage may be the best option for absorbing peaks in RE supply. The technology was proven in several field tests and it is being commercialised [67]. In this stage, its main challenge is economical. Beside capital cost reduction, the turning point to make hydrogen technologies economically attractive could be the implementation of new policy to monetize grid balancing services. In fact, despite PHES, hydrogen storage can be settled wherever it is the best for the grid infrastructure, without any constraints (e.g. need of mountains of water flows).

In the perspective of feasibility studies which are based on socioeconomic evaluations, the social benefits of distributing the storage capacity rather than having just a few large units have to be evaluated, and can be significant.

Community Energy Storage (CES) are storage undertaking the tasks of RE support, demand shifting and peak-shaving.

Storage can be implemented at the distribution level or at the residential level. In general batteries, supercapacitors and flywheels are suggested as innovative distribution level storage units, owned by electric utilities. Their advantage is typically to support RE penetration, helping electric system regulation. The concept of Community Energy Storage (CES) is adopted, referring to systems able to carry out tasks such as RE support, demand shifting and peak-shaving.

Balancing tasks can be also carried out by energy storage at a residential level. This consumer point installation moves toward the idea of active consumer, typical of a smart grid. In this case, consumer would get direct economic benefit from the storage installation. Application could be particularly interesting for zero energy building (ZEB).

Linking the three aspects of technical development, economic feasibility and policy design is considered fundamental for finding a business case for hydrogen storage application. Both community and residential hydrogen storage represents a technological change. They would require and enable changes in organizations, products, knowledge and profit distribution. Moreover, it will influence the general perception of choice in society, developing a new technology layout.

2.2 CHOICE AWARENESS

The main objective of this project is to raise awareness about innovative possibilities to support a faulty grid, analysing the feasibility of a specific investment in hydrogen storage and, eventually, what is needed to make it economically more attractive. This is why Choice

Awareness theory is useful. Firstly, to identify the reasons for the current failure of hydrogen technologies and secondly to enable a coherent description of the alternative scenarios, highlighting hydrogen benefits.

Being a radical technological change, a widespread introduction of hydrogen based technology would need significant institutional reorganization. That is why the dominant actors, strongly tied to the current setup, will use their power to eliminate the perception of alternatives [46]. Power companies and other organizations representing existing technologies will then use discourses and choice-eliminating mechanism to support the current technological setup.

Lund[46] designs a methodology to foster radical technological changes in society (Figure 8). These theoretical guidelines are later put into context in Section 3.1. They consist in four steps for an effective design of alternatives:

1. Identify and present alternatives which have the main technical features of the dominant choice and are in line with the national energy policy objectives.

2. Conduct socioeconomic feasibility studies with a concrete institutional economy approach. This can enable consideration about a wider range of social benefits, helping to identify the differences between alternatives and the best alternative for society.

3. Design concrete proposal for short-term market regulation measures. In fact, being the socially most favourable does not entail being business attractive. The market institutional barriers of the different options can be examined through a comparison between socioeconomic and business economic feasibility study.

4. Finally, more general institutional barriers needs to be considered (lack of organisation, lack of knowledge, etc.).

2.2.1 *Designing technical alternatives*

The study aims to further the understanding of hydrogen storage to prevent grid congestion in Sicily, as a substitute of new a underwater high-voltage interconnection with the rest of the country. A structured design of the alternative is the essential first step to raise choice awareness of possible technological innovation (step 1 Figure 8). This would eventually end in a change in the public discussion. Technical alternatives involving radical changes have to be analysed with different time horizons. In this way economic outputs of the feasibility study are considered with relation to the evolution in time of the overall system (step 2 Figure 8). This process enables an understanding of the best technical alternative, independent of existing technological systems. Finally, policy design (step 3 Figure 8) is the tool to help visionary politician to implement the technological change, considering the needed institutional changes (step 4 Figure 8).

It follows Chapter 3 which describes the research design, the data collection methods and the modeling IT tool energyPRO, used to model, analyse and optimize the hydrogen-based energy system.

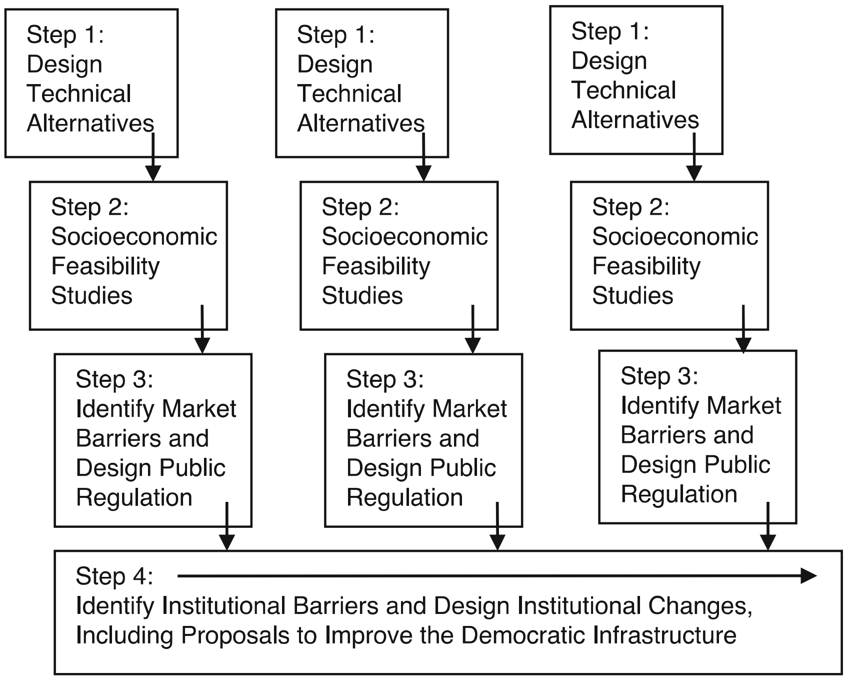


Figure 8: Four steps research method. Technical alternatives and socioeconomic evaluations lead to the identification of, first, market barriers and, second, other institutional barriers. From Lund[46].

3 METHODS AND TOOLS

This Chapter introduces methods and tools in use in the study. It starts describing the research design. Further, the data collection method and IT model are introduced.

3.1 RESEARCH DESIGN

Starting point of the research design is the Choice Awareness theory background and the four-step approach outlined in Section 2.2. In this study the Choice Awareness process is initiated in its first two steps (Figure 8 on the facing page), through a feasibility study which has analysed the hydrogen storage investment both from the business point of view of the storage operator and from the social point of view in terms of grid applications in the problematic quasi-isolated grid of Sicily.

Problem, dominant solution and possible alternatives are identified and a socioeconomic feasibility study is conducted with the following detailed method:

1. **Problem framework.** In this step the case is selected defining the technological pathway to be analyzed. Starting problem is the need for grid-balancing and RE support, causing zonal congestion and spot price increase. In order to analyze the problem, a suitable case study is selected: the island of Sicily, a nearly-isolated electricity system. A in-depth analysis of the case study enables a complete understanding of the dominant scenario which finds the solution in a new high-voltage interconnection. Alternative scenario is finally identified in the introduction of distribution level hydrogen storage.

2. **Background analysis.** Main activity of this step is to collect information from researchers and literature. In this way, the Italian electricity market (IPEX) is understood in details as well as the state-of-the-art hydrogen system's performance and configuration. Outcomes of this analysis are: technical status of the technologies, general assumptions, other relevant issues and concerns to be considered.

3. **Scope analysis.** Techno-economic analysis based on information from developer aims to a complete system definition. The bill of materials is defined, estimating capital costs, system efficiencies as well as a complete operational cost benefit analysis.

In this part is defined every parameter and equation needed to implement the energyPRO model.

4. **Energy System Modeling.** The model is finally implemented and run in energyPRO. In order to optimise the system in a price arbitrage strategy an appropriated operation strategy is calculated in an external Excel model.

5. **Model validation.** At this point, steps 2-4 are repeated until results are confidently validated. The goal is searching for errors in the model. This procedure includes variable synchronization and adjustment according to the same assumptions and constraints.

6. **Sensitivity analysis.** Variables ranges and domain of the equations are identified. Run the model changing the basic scenario with the one-factor-at-a-time method. Compare new results with the basic scenario in order to increase the understanding of the relationships between input and output variables of the system.

3.2 DATA COLLECTION METHOD

In this Section the sources and methods of data collection are described and divided into groups.

3.2.1 *Electricity Market data*

The IPEX provides real time data and archive them in its publicly available website. This is the main source for: hourly national day-ahead price (PUN), hourly Sicily day-ahead zone price (SIC) and hourly volume exchange per zone. From this, the amount of hours with congestion in the Sicily zone and the consequent PUN increase was calculated. The IPEX also provides data of the calculated amount of volumes sold in situation of non-competition, for every market zone, on a hourly base. This can be used to evaluate the residual supply index (RSI), which is a measure of pivotality of dominant operators, and the level of competition of the market. In this study it is used to evaluate improvements in market competition, and it is later explained in Section 7.3 on page 82.

The TSO, Terna, web link *Transparency Report*, was used for hourly data with actual zonal RE production, per type.

Data are collected for year 2013, which is investigated in the simulations. When the provided files were in a daily format, Excel macros are used for a faster generation of yearly spread sheets.

3.2.2 *Techno-economic data*

Beside market data, the model includes energy conversion units and other technological systems. These are the ones forming the hydrogen-based storage: electrolyser, compressor, pressurized tanks and fuel cell. In the technology scoping, reliable techno-economic data for these units are researched.

Electrolysers' performance and cost parameters refer to Colella et al.[23] and NREL[56]. These studies were commissioned by the U.S Department of Energy (DOE) and are the foundations of the analysis tool H2A[25]. These reports give both data for the current situation (reference year 2010) and for a future situation (year 2025), considering technology progress and price reduction. Data from these reports are used with permission of the authors. Colella et al.[23] synthesized the views of some of the main electrolyers companies (see Table 4) which have discussed with the authors and reported specific information about: system status, efficiency and operating conditions, variable and fixed expenses, capital costs, replacement costs and 2025 techno-economic status. Costs in USD are converted in EUR with change rate of the 1st of April 2014.

Company	Technology	Max Capacity (Kg/day)	Max H2 pressure (bar)
Avalance	Unipolar Alkaline	10	450
Giner	PEM	8	86
H2 Technologies	Alkaline	1.000	1
Hydrogenics	PEM	127	25
IHT	Alkaline	1.500	32
Proton	PEM	13	30

Table 4: Commercial or Near Commercial H2 Production PEM and Alkaline Electrolysis Technology. Data from [56].

Compressors' industries have been interviewed. After discussing technical performance, costs for a 50 to 500bar hydrogen compressor were asked and the resulting information are shown in Table 5.

Fuel cells' data are in Table 6 and result from a market analysis which was made specifically for this study. Three companies are considered and selected on the base of their accessibility to technical information: Hydrogenics, ClearEdge Power and Ballard. Current costs and efficiencies are from the online available technical papers. Their evolution in time is based on the energinet.dk evaluations [31].

Company	Outlet Pressure (bar)	Efficiency (%)	Investment (EUR)
Ventos	500	90	220.000
RIX Industries	500	-	260.000
Hydropac	210	91	-
Hp System	up to 4.000	> 90	-

Table 5: Data for diaphragm compressors, from interviews with representatives from Ventos and RIX Industries. Efficiencies calculated with the energy density of 10,8 MJ/Nm3.

Company	Technology	Capacity Output (kW)	Efficiency (%)
Ballard	PEM	1.000	54
ClearEdge Power	PEM	400	42
Hydrogenics	SOFC	200	55

Table 6: Data of the commercial PEM and SOFC fuel cells considered in the study. Data from [11][21][37].

3.3 ENERGYPRO

EnergyPRO (EMD International) is a modelling software for energy projects which is intended to carry out detailed technical and financial analyses [69]. Since it was firstly developed at Aalborg University, it has been used to design almost all small CHP-plants in Denmark [69]. The software has been also recently successfully used to analyse the feasibility and the optimal operation of a pumped hydro electricity storage (PHES) and compressed air electricity storage (CAES), within the project stoRE[68]. Input parameters are later discussed in details in Section 6.2 on page 61. They are generally related to fuels, capacities, efficiencies, time series for heat and electricity demands, the operational strategy, energy prices (spot market hourly values or user defined contracts) and other external conditions (e.g. temperature time series). On the base of those inputs, that can be in the form of time series or formulas, the model derives a dispatch strategy, usually in time steps of 1 hour, for all the heat and electricity production units. The dispatch strategy can also be externally calculated and insert as an input in the model. Storage units can be involved and their functioning optimized through a what-if step-by-step analysis.

In each time step the input time series and formulas generate a value for every economic and energy variable. EnergyPRO calculates the production of each unit and selects the cheapest one. On the base of these values, the most favorable production periods are selected in a non-chronological method. Every time step is then tested for possible production going backward in time.

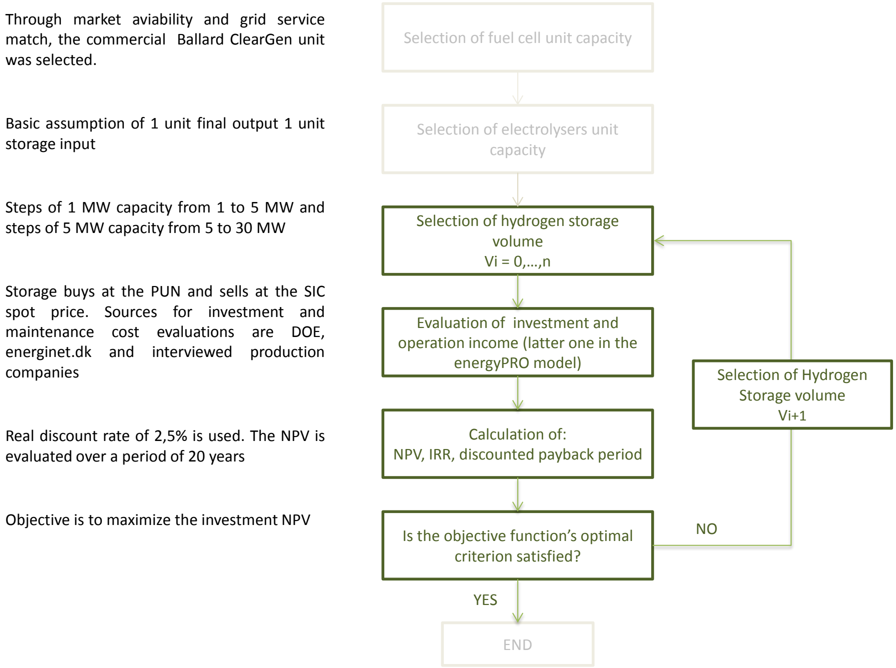


Figure 9: Flow chart of the hydrogen-based storage sizing procedure. On the left side, main assumptions are also shown.

In this study the design mode is applied, calculating energy conversion and operational economy in a specific year. The operation strategy for electrolysers and fuel cells is externally calculated in Excel and then imported in the model.

3.4 STORAGE SIZING

The hydrogen-based electricity storage is composed by three independently sizable units: the electrolyser (charging), the storage tanks (storing) and the fuel cells (discharging). To find the optimal size of each component is a 3-variable problem and, in order to make it simpler, assumptions are needed. In order to simulate a readily available solution, commercially available decentralized fuel cells were investigated and a 2 MW-e unit was finally selected. From the available sources, detailed costs and performance parameters for electrolysers with capacity of 1.500 kg/day were found and this size was fixed in the model. Considering efficiency, this represents a 2:3 ration between charging and discharging power. At this stage, the energy/power ratio was optimized using the software energyPRO (Figure 9). An optimal ratio of 10 MWh/MW was calculated.

3.5 SENSITIVITY ANALYSIS DESIGN

The techno-economic analysis is based upon 4 main scenarios deriving from the techno-economic storage development in year 2014 and 2025 and the two situation with and without incentives economic support. Specifically, the Italian Green Certificates scheme is applied and is later explained in Section 6.2.1. From now on, those 4 scenario are referred as 2014, 2014-GC, 2025, 2025GC (Table 7).

Scenario	Techno-economic development	Green Certificates
2014	current	no
2014-GC	current	yes
2025	2025	no
2025-GC	2025	yes

Table 7: Basic scenarios implemented in the simulations.

Sensitivity analysis is then undertaken on these 4 scenarios, to understand how the output changes with gradual variations of selected inputs. This tests the robustness of the results of the model analysing the most interesting aspects and the uncertainties. In this way, sensitivity analysis is different than risk analysis, in which an event is supposed to suddenly change one of the assumptions.

Most interesting aspects analyzed in the sensitivity analysis are: the strong dependency from heat value, the quite unpredictable technology development also due to the great push by Horizon 2020, the trend of increasing RE (just considered the qualitative effects on the grid-service and not the quantitative effects on, for instance, spot market price development).

In interconnected calculation in energyPRO and MS Excel the sensitivity analysis is so undertaken:

1. fixed the best storage size and every other variable except by the one under analysis.
2. if varying an investment variable, fix the operational income and check how different investment costs change the final NPV output in the Excel spread sheet.
3. if varying on an operational variable, find the new optimal operation strategy, adjust the energyPRO model, run the simulation to find the new optimized operational income. Then check how this new operational income impacts on the NPV.
4. produce graphs

4 ELECTRICITY MARKETS SURVEY

In order to design possible structural changes in the electricity supply and consumption structure, e.g. introduction of private or public electrolysers and smart operating fuel cells, an in-depth analysis of the current situation is needed. In this Chapter, the Italian power exchange (IPEX) is described in details, starting from a comparison with other European electricity markets. A complete understanding of its functioning is essential to take stock of the situation to calibrate the proposed innovative measures.

4.1 EU MARKET LIBERALIZATION

European market liberalization started in the end of the 1990s. Initial boost was given by the Florence Forum which involved every actor taking part to the electricity industry: regulatory authorities, TSOs, traders consumers and power exchanges representatives [65]. Liberalisation Directive 96/92/EC had to be transposed into national law by Member States by 2004.

The European electricity network can be divided in geographical regions. Biggest ones in terms of power exchanged are: Scandinavia, Germany, Italy, Spain and France. Every region has a system operator, managing power exchange through bilateral contracts and spot market exchange. The biggest challenge of today is to rise homogeneity in both market structures and regulatory frameworks among member states. For instance, power sold through the spot market represents over half of the volume in Scandinavia, while just a small fraction in the UK [33]. One way of rising homogeneity could be reinforcing international connections [65] to keep on fostering a wider competition.

This Chapter now gives an introduction of two different European electricity markets. Starting in Section 4.1.1 with a description of the biggest power exchange platform, the Nord Pool, then continues from Section 4.1.2 describing in-depth the IPEX, which is relevant for this case study.

4.1.1 *Nordic Market (Nord Pool Spot)*

The Nord Pool market includes Scandinavian and Baltic countries. It can exchange electricity with continental Europe through Poland, Germany and Netherlands. Nord Pool Spot was the world's first multinational electricity exchange and it is the largest one in the world. It is structured with a day-ahead (Elspot) and an intraday (Elbas) market.

The Elspot market is an auction-based electricity trading. Sellers commit electricity delivery for the next day. The market is divided in 15 geographical zones limited by transmission capacity. Producers offer a price assuming that there are no bottlenecks between areas. This is the situation in about 60% of the hours of the year, in this hours the 15 zones have the same price. The *system price* for each hour is the equilibrium value, intersection of the aggregate supply and demand curves for the entire Nordic region. Instead, if the auction results exceed the physical flow limits; zonal prices are calculated for producers and consumers belonging to the congested zones [55].

After the day-ahead, the intraday market starts. This is also managed by the Nord Pool and tradings end one hour before delivery. Traders can adjust their production and consumption on a first-come, first-served basis.

Finally the balancing market set up the more fine adjustments for balancing supply and demand. This platform is directly managed by the national TSOs: Statnett (Norway), Svenska Krafnat (Sweden), Fingrid (Finland) and Energynet.dk. Elering (Estonia), Litgrid (Lithuania) and AST (Latvia).

In parallel, negotiations run in the financial market, settling forwards contracts. However the biggest part of the Nordic electricity consumption is traded in the spot market.

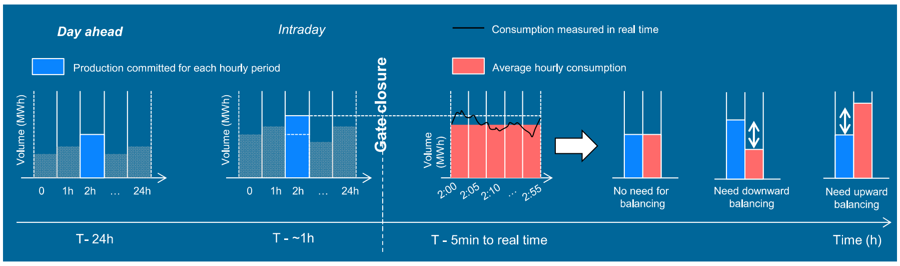


Figure 10: Electricity market structure formed by day-ahead, intraday and balancing market. Figure from SBC[67].

4.1.2 *Italian Power Exchange Market (IPEX)*

In 1999, Legislative Decree 79/1999 (Bersani decree) restructured the Italian market according to the EU Directive. The former monopolist, Enel, had to unbundle its generation, transmission and distribution activities. Ownership of the transmission grid was given to a new state-owned TSO, Terna (named GRTN until October 2005). In this process another state-owned company was also founded, GSE (Gestore dei Servizi Energetici) which is currently in charge with the task of monitoring and promoting RE production. The liberalization's highest point was the IPEX inauguration, in April 2004 [62] .

Likewise the Nord Pool, the IPEX is formed by two markets: the spot market (MPE) and the forward electricity market (MTE). The spot market is, in turn, composed by: day-ahead market, adjustment market and balancing market (Figure 10). GME (Gestore Mercati Energetici) is the system operator for the electricity exchanges until one hour to the delivery time, i.e. day-ahead and adjustment markets[62]. The TSO instead, manages the balancing markets and it is in charge for grid stability tasks. A merit order principle is on the base of the aggregate supply and demand curves of the day-ahead market.

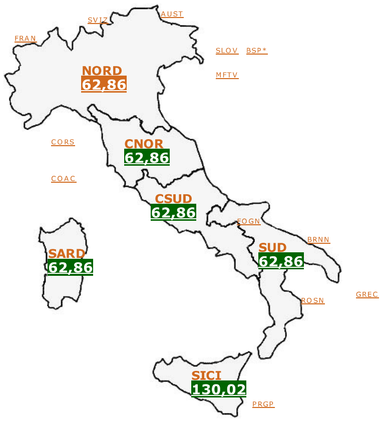
The Italian spot-market trades around 77% of the national power consumption [34]. The remaining power is traded via bilateral contracts in the MTE platform.

Even if, in principle, competition should lower mark-ups for electricity producers, AEEG[6] shows that in Italy customers in the free market (25% of the total) paid an average of 12,8% more than customers in the protected market in 2012. Between others, Mastropieri[49] and Noce[54] find the most relevant reason for this counter-intuitive tendency in the role of the former monopolist, ENEL, which today operates as a dominant player in both sides of the market, thought the generating company (ENEL Produzione) and the retail company (ENEL Energia).

The Italian spot market price is now analysed to gain a deeper understanding of its variation. Data are from the last IPEX annual report [34]. This in-depth analysis is intended to initiate considerations on the working strategy of the hydrogen storage involved in the study.

4.2 DAY-AHEAD MARKET IN ITALY

Merit-order principle is applied to defined the supply and demand curve and the consequent equilibrium price. Same price, renewables are prioritised as well as high-efficiency CHPs. If the market dynamics exceed the transmission capacity constraints the grid is split into zones. There are six different geographical zones: North, Centre-north, Centre-south, South, Sardinia and Sicily. In this situation of market splitting the IPEX distributes buyers' money differently than, for instance, the Nord Pool market.



Market	Demand MWh	Price (EUR/MWh)
North	20.026	62,86
Centre-north	3.903	62,86
Centre-south	6.698	62,86
South	4.167	62,86
Sardinia	1.473	62,86
Sicily	2.816	130,02
Italy	39.083 MWh	
PUN	67,70 EUR/MWh	

Figure 11: Table and map showing market data for a representative hour. 7th of August 2013, 12.00.

In the IPEX there are zonal prices in the sell-side and a single average price in the buy-side. In other words, a zonal equilibrium price is calculated in each zone. Electricity producers, in the case of congestion, are paid the zonal price. Buyers, instead, pay a national average of the zonal prices weighted by the zonal electricity consumptions: the so-called Single National Price (PUN). In the current situation, zonal price of congested zone is most likely higher than the final PUN.

Figure 11 shows an example in which the only congested zone is Sicily. In this specific case, without the Sicily congestion, buyers all over the country would have paid a price of EUR 62,86 per MWh. Due to the congestion and the Sicily price peaking to EUR 130,02 per MWh buyers pay almost EUR 5 per MWh more because of an average price of EUR 67,70 per MWh.

4.2.1 *Congestion Rent for the TSO*

The Italian TSO earns some money implicitly from parties operating in the day-ahead market by receiving the difference between the values of purchases (based on the PUN, which is the same in every market zone) and of sales (in case of congestions, based on zonal prices), the so-called congestion rent. This earning is equal to zero if the payments on the buy-side are equal to the revenues on the the sell-side, i.e. in a situation with no bottlenecks.

On the contrary, increasing congestion rent for the TSO reveals an increasing utilization of the transmission lines and increasing separation-frequency. Mathematically the congestion rent is calculated as the price difference between the two zones multiplied by the existing transmission capacity, K

$$R_{congestion} = K(P1 - P2). \tag{1}$$

Market actors could, in theory, deliberately increasing the difference $(P1 - P2)$. Specifically pivotal operators in the import zone could increase their profit by keeping a high P2. Similarly, if convenient, pivotal operators in the export zone could act in the interest of keeping a low P1. When transmission capacity is increased, in the case of congestion, the revenues for the TSO become

$$R_{congestion} = K'(P1 - P2) - C(K') \tag{2}$$

where C(K') is the investment cost for the new capacity K'. As it was previously mentioned $(P1 - P2)$ decreases with increasing K'. Market dynamic, and the Regulatory Authority, should therefore incetivize the TSO to reduce congestion, investing in the socially optimal K'. However, it is clear that the TSO has market power, essentially because of the monopoly in the activity of expanding transmission capacity.

The overall congestion rent for the Italian TSO increased in 2012 (+27% comparing to 2011) and so it did in 2013 (no official data yet). In this case, no data are available for the specific situation of the Sicily market zone.

4.2.2 *Spot price fluctuations*

Electricity markets have some features which are also typical of the financial markets, such as price peaks and seasonal patterns [69]. Peaks in the electricity spot price can be caused by the normal consequence of the demand and supply curve (maybe influenced by capacity limits in generation or transmission) or by unexpected outages. From the demand side, electricity consumption follows predictable daily, weekly (Figure 13 on page 45) and monthly (Figure 14 on page 46) patterns. However it is still impossible to forecast consumption variations perfectly [67]. In the IPEX the price is usually higher during specific peak hours (8.00-20.00 on working days) and lower in the remaining off-peak hours. Time-shifting electricity from off-peak hours to peak hours would result in revenues for the storage operator.

Deviations from the wanted efficient market competition can be caused by mechanism failure and, more often, the already mentioned capacity limits in the network [69].

The IPEX has experienced a great RE penetration since year 2007 (Figure 17 on page 58). Since most of the RE (e.g. wind and solar) are intermittent sources which production is hard to predict, this increased

RE share is making market dynamics more complex. The relation between RE production and spot market price is shown in Figure 12.

Figure 12: Day-ahead PUN in relation to wind and solar production in Italy. Low intermittent RE results in high electricity prices, while high RE results in low electricity prices. Data elaborated from GME[1].

4.2.3 *Energy component of the retail price*

The electricity system demand and supply features impact on the final electricity retail price for industrial as well as household consumers. Other components of the retail price are fees to maintain the infrastructure (e.g. old plants decommissioning) or to incentivize investment in renewable energy, grid service and taxes.

Retail price for Italian households is slightly lower than the price for Germans and Danish consumers (all of them above the EU average). However, the greatest part of the Italian bill is due to spot price and dispatch cost (45% of the final retail price) while, in the German and Danish case, the greatest cost is due to levies (Figure 37) which are largely due to the national RE support schemes.

When considering industries, the spot price quota represents the 50% of the final retail price, in Italy. This, together with fees and taxes, makes the Italian final retail price for industries the highest one in Europe, only after the island of Cyprus (Figure 38).

Part II

THE CASE STUDY. HYDROGEN-BASED ELECTRICITY STORAGE IN SICILY: PRICE ARBITRAGE AND GRID APPLICATIONS

5 HYDROGEN-BASED ELECTRICITY STORAGE IN SICILY

The biggest barrier to overcome in the diffusion of hydrogen-based technologies is economic rather than technological. The cost of both sustainable hydrogen storage and fuel cells must be reduced. More and more countries are setting road maps with this specific objective, to initiate a faster market development of fuel cell and hydrogen technologies. The technology is today at a non-fully commercial status. At this point, it is fundamental to implement tests and first-of-a-kind experiences where it could be economically most attractive. In parallel awareness of hydrogen potential both in terms of grid services and energy system unification, needs to be risen.

In this study, Sicily is identified to be a promisingly test environment for hydrogen technology. After all, Southern Italy and Mediterranean islands are not new to hydrogen-based large scale experiments. Most important ones, the Ingrid project in the Puglia region of Italy [2] and the Myrte project, in Corsica [3]. Both of them are on-going and supported by the European Community energy programme.

These on-field tests have underlined that hydrogen could find concrete and immediate applications in areas where access to electricity is problematic, because of lack of power lines or distance between production and consumption sites. Hydrogen storage is particularly adapted to the island context. The hydrogen industry should therefore target these specific sites, where the issues of increasing national grid reliability and decentralized grid management can also be addressed. In this way, Sicily is the perfect site for hydrogen storage tests, both technologically and economically.

In the following Section 5.1, motivations for the proposed hydrogen-based storage in Sicily are reported.

5.1 INTRODUCTION ON THE SICILY GRID

Sicily is the largest Italian region and Mediterranean island. With a total of 5 million inhabitants, it is the only Italian region with two cities (Palermo and Catania) in the Italian top ten, in terms of population. Buyers in the Sicily day-ahead electricity market buy 19 TWh per year, 7% of the total volumes sold in Italy (data referred to year 2013). 25% of the zonal electricity demand on the day-ahead market

[34] is today supplied by RE.

If, on the one hand, the day-ahead zonal price on the sell-side incentivizes investment in RESs in Sicily which is a high-price zone, on the other hand has facilitated speculation by, and benefits for, pivotal price-setters. In fact, they can easily predict zonal market outcomes, keeping the zonal price as high as they like. This is even worst with a congested grid where, in lack of serious distribution improvement, RE cannot substantially improve the situation.

Security of Supply in the island is constantly at risk because of the lack of interconnection between Sicily and the mainland as well as between the western and the eastern side of the island. The zone is one of the biggest electricity producers in Italy (23.355 GWh in 2012) and this electricity flow is continuously stressing the old and deficient grid. The island is in a constant blackout alert status [61]. On top of this the great RE penetration experienced since 2008 makes the grid balancing even more complex. Constraints were imposed by the TSO at both the western, Palermo, and eastern, Catania, production poles, in order to protect the needed tension in the 150 kV and 220 kV transmission lines. Main consequences of this situation are:

- Non-optimal electricity exchange in the country. Firstly, the island cannot be reached by the electricity generated in other zones (with great impact of market competition between operators). Secondly the RE which is produced in the island cannot be fully utilized.
- Continuous market isolation, 88% of the hours in 2013, with a zonal price that is averagely 32% higher than the PUN.

This situation is clearly preserving the market power and benefits of pivotal operators generating electricity in the island.

Regulatory Authority solution to those problems and to the demonstrated complicity of the main electricity producers in Sicily was to settle a bid cap for Enel and Edipower equal to EUR 190 per MWh, as introduced in Section 1.2.2. Beside this market restriction running from year 2010, it was clear that an *infrastructural improvement* is necessary. In year 2010 the TSO started the already discussed process for building a new high-voltage transmission line between Sicily and the mainland, in a project that is now in its early stage of implementation.

The new power lines were embraced with enthusiasm by the Regulatory Authority and by industrial associations, well aware of the economic benefit of these public works. Those benefits, originated by a PUN reduction and therefore split among all the Italian consumers, were estimated by the TSO to EUR 1,80 per MWh, for a total of EUR

480 m per year (reference year 2012). In Section 5.1.1 this number is verified obtaining different results. An average saving of EUR 1,07 per MWh is calculated (EUR 1,66 per MWh in 2013), resulting in EUR 318 m (EUR 473 m in 2013). The method applied is most likely more conservative than the one used by the TSO. These evaluations could be therefore aligned and in some extend are already consistent. However, the reference office of Terna was asked for an explanation of the obtained numbers, but no answer has been received.

Even if the potential social benefit as well as the cost of the installation of new transmission lines are not clear at all, *environmental criticism* to the project were immediately moved by a ground swell of opposition. Local and national environmentalist associations started a real fight, asking for the project to be revised. The main change, asked to Terna, is to move some high-voltage pylon in less populated areas and to bury some main lines. In fact, the current project takes place in a Special Protection Area that, in some extend, is also declared Site of Community Importance. This situation might be in contrast with the UN principles of sustainable development [72]. Also, arguments are use for the risk of increasing cancer rate for the 50.000 living in the closest area and the high earthquake danger, an event that would probably destabilize the pylons.

These criticisms, that were spontaneously initiated by locals and green associations, were increasingly supported by local administrations and lately by the regional Parliament. The EIA complaints were not fully listened by the authorities, resulting in legal actions against the project which have delayed the project start.

The Sicilian parliament asked for new and more detailed health impact evaluations and for a study that would also consider different locations and under earth lines. In a recent public notice Terna defines under earth lines "technically impossible", saying that, however, different locations might be designed, "but only with the work being completed" [61].

In this atmosphere of institutional chaos the Antitrust Authority, in a letter to the Sicilian parliament, has settled an ultimatum for the project implementation. Without considering the environmental problem in its merit, the Authority says that the situation is creating a barrier to overcome a problem of market performance which is weighting upon industries and household of the whole country. In a last, dour, note the Authority says that if the delay would still spin out, the national energy strategy might be revised, and a public discussion could be open on the structure of the PUN.

As introduced in Section 1.2.2, this study analyses a third solution to the Sicily problems. An alternative to the above discussed TSO supported new power lines and to the change in the PUN structure proposed by the Authority which would remove Sicily from the spot price formulation. This third possibility is the introduction of hydrogen-based electricity storage, to prevent grid bottlenecks, support RE and decrease market power of pivotal operators. An innovative proposal which is worth considering, in a long run perspective of grid improvement toward a greener future, in light of the environmental opposition that has already stopped the project for a long time.

5.1.1 *Social cost of the zonal bottleneck*

As already explained, the Italian day-ahead price formulation distributes the cost of the bottleneck in Sicily among the whole Italian consumers, through the national price PUN. A basic estimation of this social cost was made, and thereby shown, according to the following assumptions:

1. The social cost of the Sicily bottleneck is evaluated as the difference between the final PUN (affected by the Sicily price) and the equilibrium price of the country excluding Sicily. This difference can be both positive and negative.

2. Considered only hours in which the only bottleneck is the one between Sicily and the mainland (conservative evaluation)

3. Volumes sold and zonal prices in those hours are collected for years 2012 and 2013

The method used for this calculation is an average of the difference between PUN and Sicily zonal price, weighted over the national day-ahead sold volumes in the relative hour with congestion. Results are shown in Table 8.

	2012	2013
PUN increase if transmission congestion (EUR/MWh)	1,07	1,66
National expense (mEUR)	319	473

Table 8: Estimation of the social cost for the Italian consumers deriving from the grid bottleneck in Sicily.

Implemented electricity storage could work on the base of a predictable demand profile, showing daily and weekly (Figure 13) patterns.

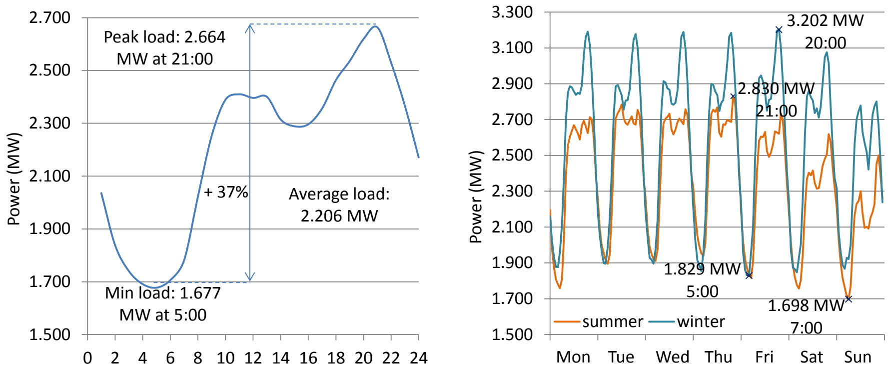


Figure 13: Daily average load curve (left) and weekly load curve (right) in winter (21-282013) vs. summer (1-872013), in Sicily. Data elaborated from GME website. Analysed year 2013.

5.2 ENERGY STORAGE SYSTEM APPLICATIONS IN POWER SYSTEMS

Energy storage systems can ensure grid stability. The greater share of renewable and decentralized energy is injected into the grid, the more important becomes this balancing role [45]. In fact, the intermittent nature of most of the RESs causes voltage and frequency oscillations of the power grid. Recurring situations of over production also result in spot market price volatility. For every wind turbine installation, a balancing power equivalent to 2-4% of the installed wind capacity it is needed to ensure grid stability.

Parra et al.[59] defines the concept of *community energy storage* as an energy storage system which is able to carry out RE support, demand shifting and system regulation. Economically, such a system is particularly interesting in a situation with a high seasonal or daily price fluctuation, like Sicily, it could be supported by grid service subsidies.

If these conditions are satisfied, electricity storage is the key element in energy demand time-shifting through *valley filling* (absorbing electricity from the grid in periods of low demand) and *peak shaving* (sending back to the grid when demand is high) [27][43].

Today in Italy energy is uniquely stored through pumped hydro electricity storage (PHES). PHES can be split into two categories: seasonal regulating reservoirs (filling rate over 400 hours) or modulation reservoirs (filling rate between 2 and 400 hours). They represent 4% and 3% of the national electricity production, respectively. The need for water supply and natural altitude gaps confines PHES storage in the northern regions, geographically away from the fluctuating RE plants, which are instead mainly in the south. This is one of the reasons why they are not used for balancing tasks.

Energy storage can be applied to provide a multitude of services to power systems, depending on the type of storage and its position on the grid. Generally speaking, a storage providing energy service can be located everywhere in the grid, while a storage providing capacity services must be located close to the bottleneck causing congestion. Beside location, most important parameters the power and discharge time requirements (Figure 15).

In this section, the main grid services that can be provided by energy storage systems are reported, on the base of Koohi-Kamal et al.[45] and Pearre and Swan[60].

5.2.1 *Increasing RESs depth of penetration*

The intermittent RE can cause voltage and frequency oscillations in the power grid. To limit the problem, fossil fueled power plants are regularly used to cover the base-load demand. However, the use of conventional power plants for balancing task makes the system more complex than the use of electricity storage units. This is becoming a serious problem in Denmark and Spain where wind power has a great market share, 20% and 10% respectively [45]. As it is explained in Section 5.1, this is also a problem in Sicily, where 25% of the electricity demand was supplied by RE in 2013. An opportunity for a larger exploit of intermittent renewable resources is therefore the implementation of a reliable storage capacity. To avoid curtailment of green energy in highly RESs, transfer electricity from periods of overproduction (low load) to periods of underproduction (high load) can be an effective as well as economically beneficial strategy.

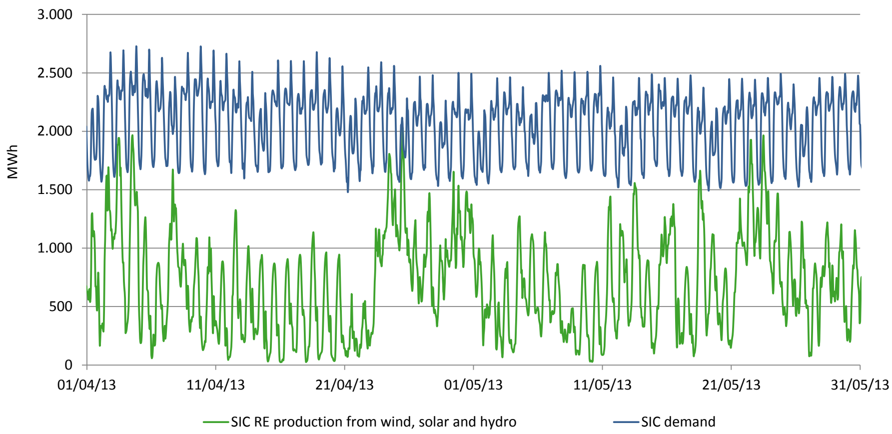


Figure 14: Ex post data of renewable hourly production and Sicily electricity demand.

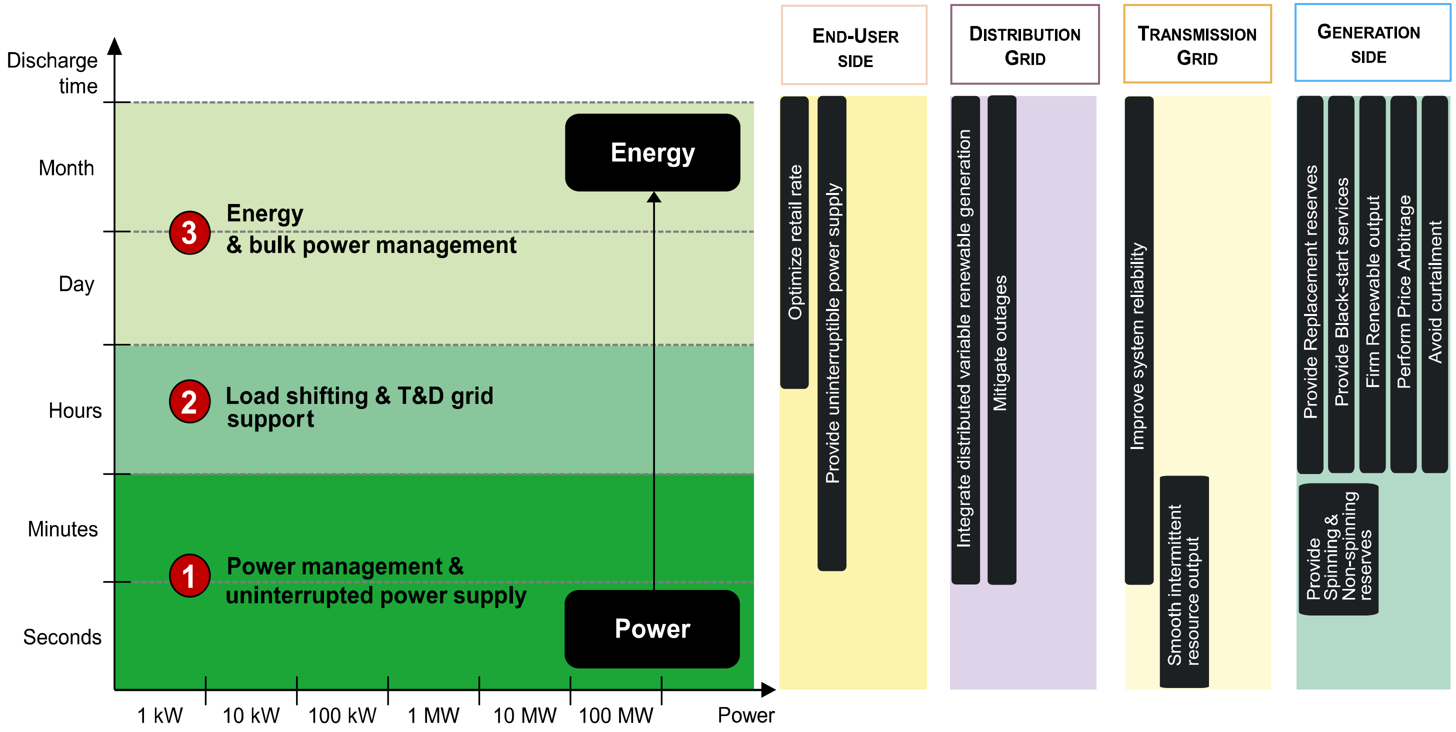


Figure 15: Short-term storage are used as frequency response reserve, to control frequency and voltage. Medium-term storage (hours or days) is used to time-shift the electricity demand to shave daily peaks. This can help avoid grid congestion both at a transmission and distribution level. Depending on the contract structure, the storage operator can benefit from the price differentials between low- and high-demand hours (price arbitrage). Long-term storage is applied to level seasonal fluctuations, ensuring security of supply.

Most applications are typical of the generation side, but TSO and DSO can also play an important role in the storage diffusion as well as the end users. Storage stakeholders are strongly related to the strategic location of stores on the grid. This is a decisive step in avoiding or deferring investment in transmission and distribution lines[67], supporting the integration of distributed RE. Elaboration from SBC[67].

5.2.2 *Time-shifting: price arbitrage and peak shaving*

Koohi-Kamal et al.[45] identify two benefits from the installation of energy storage units: the first is to increase load demand when needed, the second is to remove the need to set up new infrastructures, such as new power lines or feeders. This can be obtained thanks to a peak shaving operating strategy. Peak shaving is commonly intended as the operating policy applied for storing cheap electricity during the off-peak demand period and giving back the stored electricity to the grid during the high demand. This usually takes place in a 1-10 hours time frame. In this way, the strategy is economically favorable since price arbitrage is applied. The operation strategy of the hydrogen storage simulated in this study applies price arbitrage (Figure 19 on page 61) and it is therefore expected to produce good results also in terms of peak shaving.

5.2.3 *Regulation: frequency control and load following*

Power is delivered to industrial and residential consumers in its alternate current (AC) form. Despite the direct current (DC), AC periodically reverses its direction. The advantage provided by alternating current is the fact that, using a device called a transformer, it is relatively easy to change the voltage of the power. Power companies can then use very high voltages to transmit power over long distances, producing relevant economic savings in the power generation and transmission processes. AC frequency varies by country and it is the fundamental system parameter to preserve system stability. AC frequency of the European electricity system has to be kept between the well defined boundaries of 50 Hz, meaning that electrons oscillates 50 times per second.

Frequency adjustment depends on the consumption and injection of power in a short time frame of 1-2 seconds. For this reason low and medium storage units can be applied to stabilize the AC frequency. The technical potential of electricity storage to stabilize grid frequency, improving the dynamic performance of the grid and supply quick quantities of active or reactive power demand is addressed in several studies [58][60].

Load following are units which can operate in real-time for a period ranging from tens of minutes up to hours.

5.2.4 *Reserves: spinning, non spinning, secondary and tertiary reserve.*

The TSO operates the high voltage grid and is responsible for the country's security of supply through the Regulating (or balance) Power Market. Through this platform the TSO keeps the balance between total generation and consumption of power in the overall system, in real time. This is done by means of the spinning as well as non-spinning (or supplemental) reserve. Spinning reserve is the unused capacity, which can be activated if required by the TSO [45]. Non-spinning reserve instead, is an extra capacity that, in a normal situation, is not connected to the system but can be brought online if require by the TSO, in a short time.

In interconnected systems this reserve can come be supplied by the import from adjacent systems but in isolated systems fast response generators are needed. In order to keep the balance between production and consumption, already injected power can also be withdrawn if required by the TSO.

All the energy storage technologies are suited for this application. In isolated system the use of power storage can play a key role in maintaining the grid stability. Due to its fast response to changes in net power consumption and demand, hydrogen storage are very suitable candidates for this application.

5.2.5 *Capacity Market*

Some grid operators are already experimenting capacity markets with the main objective of fostering investments in power plants which are becoming more and more uncertain with the market penetration of renewable energy.

In this market, power plants are paid for capacity, i.e. the power they will be asked to provide at some point in the future. Examples of capacity markets are found in the US, in the UK (from 2014) and Italy (from 2017). I US and Italy there is an auction every year in which the capacity for the next three years is secured by the TSO.

In exchange for the auction capacity premium (EUR/MW per year) power units are obligated to keep their capacity available on the day-ahead and infra-day markets.

This is clearly an opportunity for potential electricity storage operators as well as an insurance for final customers against risk-pricing.

5.3 TECHNOLOGY SCOPING

In order to provide reliable cost and performance data for the simulation, a techno-economic overview of current-day commercially available electrolyzers, compressors and fuel cells is here given. The most up-to-date literature has been reviewed and companies have also been involved in the data collection through the publicly available information (websites, technical sheets) and through specific interviews.

Europe has set a target of 1 GW production capacity from fuel cells by 2015 as well as 0,4-1,8 million hydrogen vehicles sold per year in 2020 [28]. Japan's Ministry of Economy has now set a target of 5 million hydrogen fuel cell vehicles and 10 million kW of power generation by stationary fuel cells by the year 2020 [24]. Therefore, technology development and cost improvement, due to a larger scale commercialization needs to be considered for having an overall picture. For this reason, besides having the latest research results, a technology perspective is of great interest. In the simulation, this goes under the 2025 scenarios.

Technology	2006	2020-2025	2050
EU portable fuel cells sold per year	-	250 M	-
EU fuel cell vehicle sold per year	-	0,4-1,8 M	-
EU stationary fuel cells CHP sold per year	-	2-4 GW	-
Global fleet of fuel cell vehicles	-	-	700 M

Table 9: Hydrogen and fuel cells development scenario by International Energy Agency, 2006. From Edwards et al.[28].

5.3.1 *Electrolysers*

Electrolytic hydrogen production has been object of study for over 100 years. The produced hydrogen was then used for industrial, commercial or military purposes. However, between the other methods (e.g. methane reformation), water electrolysis has got high production costs [50]. The main expense is due to the electricity consumption needed to break the water molecules. These molecules are weakly bounded by the so-called hydrogen bounds. An electrolyser plant consist in the electrolyser(s) stack and the balance of plant (BoP).

Electricity is applied on two electrodes immerse in a liquid containing mobile ions (electrolyte). Because of electric attraction positive ions are attracted by the negative electrode (cathode) and the negative ions are attracted by the positive electrode (anode). Two reactions take place, the so-called reduction (at the cathode) and oxidation (at the anode). Result of the reaction are oxygen and hydrogen molecules. In lab condition 1,23 V are required to break the atomic bounds, this is called the equilibrium voltage of water. However much higher voltage is needed in industrial electrolysis process because of non optimal conditions of pressure, space between electrodes, bubbles and voltage waveform [50].

The chemical reaction is:

$$\begin{aligned} 2H_2O + 2e^- &\rightarrow H_2 + 2OH^- && \text{anode} \\ 4OH^- &\rightarrow O2 + 2H_2O + 4e^- && \text{cathode} \\ 2H_2O &\rightarrow 2H_2 + O_2 && \text{total reaction} \end{aligned} \tag{3}$$

There there are two main commercialized types of low temperature electrolyzers: the polymer electrolyte membrane (PEM) and the alkaline electrolysis (AEC's). PEM technology is newer than the more established AEC. A third type, solid oxide, is still only in research stages. Chemical reaction in AEC's and PEM occurs at temperature which is usually less than 80°C.

Alkaline electrolyzers are today most efficient at around 50°C but PEM electrolysis has a great advantage: its ability to operate at high current densities [19]. This can result in reduced operational costs, especially for systems that are asked to follow a dynamic production pattern. In fact PEM can provide the maximum efficiency when sudden spikes in energy input would otherwise result in uncaptured energy.

Since in the model the electrolysers production depends on the spot market price, PEM electrolysers are selected. This is also the most interesting case in terms of technology development. The recent work by Colella et al.[23] was taken as a guideline for cost and performance parameters and it is used with the permission of the authors.

An investment cost of EUR 690 per kW-e is taken for the present scenario and EUR 330 per kW-e for the 2025 scenario. O&M cost is assumed to be EUR 19 per hour of operation, decreasing to EUR 7 per hour in 2025. PEM electrolysers electric efficiency is today 73% and heat efficiency 15%. These values moves to 79% and 15%, respectively, in year 2025.

Capital cost of a complete PEM electrolysis unit, composed by stack and BoP, is reported in Table 10.

Basis Year	2014	2025
Total cost (EUR/kWh)	690	330
Stacks	41%	38%
BoP Total	59%	62%
Hydrogen Gas Management System-Cathode system side	10%	6%
Oxygen Gas Management System-Anode system side	5%	2%
Water Delivery Management System	6%	5%
Thermal Management System	5%	5%
Power Electronics	20%	26%
Controls & Sensors	3%	6%
Mechanical Balance of Plant, cables, valves ...	5%	5%
Other	1%	2%
Assembly Labor	4%	5%

Table 10: Basic Parameters of the PEM electrolyser direct capital cost and cost components. Data from Colella et al.[23].

5.3.2 *Hydrogen Compressor and Storing*

Hydrogen can be stored outdoors for stationary uses, under-earth and in hydrogen fuelled vehicles. Storage principle is fairly simple, requiring just a pressurized container and a compressor, but the main problem is caused by the volume required. In fact, hydrogen has got a lower volumetric energy density then other fuels (but higher mass energy density). With equal volumes, hydrogen contain less energy than, e.g. methane. 1 kg of hydrogen at atmospheric pressure and ambient temperature spread over 11 m3. High-pressure compression is therefore needed.

Hydrogen can be pressed into storage mainly through piston or diaphragm compressors. Diaphragm compressors are more indicated for explosive gas, since compression occurs by means of a flexible membrane, instead of an intake element, and this is the only part of the compressor which come in touch with pumped gas. A three-stage diaphragm compressor is currently used to compress hydrogen gas to 410 bar for use in a fueling station built in Phoenix, Arizona by the Arizona Public Service company. For this study two companies were interviewed and asked specific cost evaluations: RIX Industries (US) and Ventos Compressors (Italy).

The estimated investment is EUR 220.000 for a diaphragm compressor of 200 Nm3/h capacity, 30 bar inlet pressure and 500 bar outlet pressure. On the base of average 4.000 operating hours, an O&M costs of 5 EUR per hour was estimated. Compressor efficiency is 92%. These numbers are a synthesis of the views of the two companies. In line with the other technological improvements analyzed in the study, a cost reduction of at least 20% is assumed for the 2025 scenario. These numbers can be referenced against specific company viewpoints.

After the compression, hydrogen needs a safe place were to be stored: gas cylinder are used for quantities under 15.000 Nm3, otherwise spherical tanks [44] or under-earth storage which is preferred, instead, when dealing with greater quantities and long storage periods. In literature there is a lack of clarity about the standard pressure which can be reached by those pressurized containers. Jelicic and Zollino[44] writes about 207 bar for gas cylinders, but recent researches have field tested hydrogen tanks at 400 bar [36] [70]. Future hydrogen refueling stations are planned to store at the high pressure of 400 bar. This storage pressure is applied in this study.

When calculating the amount of energy stored into a pressurized hydrogen storage, the compressibility factor, Z, has to be applied. This factor modifies the ideal gas law

$$PV = nRT \tag{4}$$

to account for real gas behaviour. Specifically the factor Z is defined as

$$Z = \frac{PV}{nRT} \tag{5}$$

so that Equation 4 becomes

$$\frac{PV}{n} = ZRT \tag{6}$$

Z it is equal to 1 in the case of ideal gases, per definition. For real gases it is a propriety of the specific gas and varies with temperature and pressure. Z generally increases with increasing pressure and decreases with increasing temperature. This means that the higher the pressure, the harder is to keep on compressing the gas. For instance, applying the hydrogen compressibility factor of 1,272 (0°C and 400 bar), it is obtained that, cateris paribus

$$\frac{V_1}{V_2} = \frac{Z_1 P_2}{Z_2 P_1} = 310 \tag{7}$$

There are several examples of already working under-hearth hydrogen storage. Since 1971 the municipality of Kiel (Germany) uses this method for coal gas storage (about 65% composed by H2). Also Gaz de France, has taken advantage of under-earth refinery gas storage in Baynes (France) and the Imperial Chemical Industries store hydrogen in salt mine in Teesside (England). Sicily has got a historical coal mine activity and, maybe, feasible sites could be found for implementing this storage option. However, this kind of assessment was out of the goal of the study.

In line with other studies made by EMD International in which biogas storage was analyzed, the estimated cost for the storage is EUR 100 per MWh.

5.3.3 *Fuel Cells*

A fuel cell system converts hydrogen (or another fuel containing hydrogen) and an oxidant (usually oxygen from air) into electricity, through a low-temperature electrochemical process [28]. There are several kinds of fuel cells, but they all share the same basic structure of two electrodes (anode and cathode), a solid or liquid electrolyte (or a membrane) separating the electrodes, an hydrogen-rich fuel and an oxygen-rich fuel fed into the electrodes. Electrolytes enable transport of ions from anode to cathode while excess electrons are free to flow through an external circuit providing electrical power [28]. A fuel cell system can be considered as to be formed by several sub-systems:

Fuel cell stack. It can contain several fuel cells, typically about 100. The fuel cell itself is a low voltage device, with output of about 1 V. The fuel cell is an electrochemical engine which turns the chemical potential energy of the fuel into electricity [10] .

Electrolyte, fuel and oxidant. The electrolyte determines the way the electricity production process takes place and the needed fuel. An oxidant is then needed for the reaction to take place. Oxygen is usually used for this, being economically available in air [10]. Fuel cells are usually classified by the electrolyte they use (proton exchange membrane, alkaline, direct methanol, phosphoric acid, molten carbonate, solid oxide).

Heat and power management and conditioning. By-products of the reaction are simply water and heat. An hot water tank can be placed to store the heat coming from the system. In the study it is assumed that the whole produced heat can be virtually recovered. The fuel cell produces DC power which needs to be converted through a DC/AC converter. Also the power needs to be adjusted in the power management sub-system to meet the load requirements for voltage and power quality.

Instruments and control. Sensor, actuators, processors and LCD touch screen can be installed to control the operating parameters. These might also be valid to monitor the so-called parasitic load, e.g. the electricity needed for powering fans, blowers or compressors.

According to energinet.dk energy technology catalog [31] an investment cost of EUR 5.000 per kW is considered for year 2014, reduced to EUR 1.200 per kW in year 2025. After having analyzed a multitude of market available units, the commercial Ballard ClearGen hydrogen fuel cell [11] was considered for performance parameters. Electric efficiency of 54% and heat efficiency of 36% are used as input for the model. Performance improvement moves efficiencies to 57% and 37%, respectively, as from the energinet.dk point of view [31], in year 2025.

It has to be noticed that values that different view points can be found for the technology improvement. It was decided to consider the energinet.dk catalog because that was the most recent analysis in literature. This is however more conservative than the Edwards et al. estimation that, in year 2008, estimated a price for PEMFC of EUR 400 per kW-e in 2025 (40 in 2050) and of a price for high-temperature fuel cells of EUR 800 per kW-e in 2025 (200 in 2050) [28].

5.4 HYDROGEN STORAGE INVESTMENT

Table 11 shows a summary of the investment costs explained in the techno-economic scoping study of Section 5.3. Project and planning costs are taken from [23] and are here considered to cover the whole project planning and preparation costs. In this study investment and

Base Year		2014	2025
Electrolyser	Investment (EUR/kW)	690	330
	Main replacements interval (years)	7	10
	Main replacements cost (% investment)	15%	15%
Compressor	Investment (EUR)	220.000	176.000
	Replace interval of major components	spread as O&M	
Storage	Investment (EUR/Nm3)	100	100
Fuel Cells	Investment (EUR/kW-e)	5.000	1.200
Site preparation		443.912	195.573
Project and Design		37.000	37.000

Table 11: Investment costs for the implemented energy storage system in the 2014 and 2025 scenario.

operation of a decentralized hydrogen-based electricity storage are simulated. The main grid application is to shave the peaks in electricity demand of the island of Sicily. For this reason, providing an energy grid-service the storage can be virtually located in every point of the island's grid, which is well connected to the high-voltage lines. This represents an hybrid solution between the capacity and energy congestion prevention service (Figure 15 on page 47). The simulated storage is a medium-term unit which is able to provide electricity for some hours, shaving daily peaks.

With different purposes, the storage could be operated by different stakeholders: a DSO, aiming to increase renewable energy depth of penetration, a power generator applying price arbitrage to avoid curtailment and firm RE outputs, or an operator in the transmission grid, aiming to improve grid stability by preventing zonal bottlenecks.

All of this aspects will be analyzed in Chapter 6 on the facing page and Chapter 7 on page 77, representing the core of this study.

6 OPERATIONAL BUSINESS OPTIMIZATION AND STORAGE SIZING

This Chapter reports the economic analyses and the obtained results. The storage operates on the day-ahead electricity market. Both the national and the zonal price of Sicily have been studied in order to understand the economic possibilities of the Italian market and to provide the storage with the optimal operation strategy which is derived in Section 6.3 on page 65. The operation strategy is the central element of the model described in Section 6.2 on page 61 which is designed by means of the modelling software energyPRO. After having found the optimal operating mode, an investment analysis is implemented to size the hydrogen store. Investment NPV is studied in Section 6.4 on page 71 and Section 6.5 on page 73 concludes with the sensitivity analysis.

6.1 DAY-AHEAD PRICE

Market trends are studied through the most recent IPEX annual report [34] and the most updated market data collected in the IPEX spot market and Terna (TSO) webpages. Main indicators show that in the recent years, despite an increasing natural gas price (the most used fuel) the electricity price is slowly decreasing, mainly because of the overcapacity situation of the Italian electricity system. This is caused by a decrease in energy demand (which has reached a historical low) and an increase in RE penetration, today representing 11% of the national electricity production. Comparing to 2011, market contraction (-4% spot market volume exchange) and RE growth (+30% capacity installed) also led to another consequence: a decreasing electricity production from old power plants. This resulted in two environmental successes: -8% market share for combined cycle production and -11% natural gas used for electricity production, from year 2011 to year 2012 [8].

According to the goal of the study, the national PUN price (price for every Italian day-ahead market buyer) and the Sicilian zonal price (selling price for producers in Sicily) are considered. Firstly the *hourly variability* is analysed, secondly the yearly *price volatility* is evaluated and finally the price increase due to the Sicilian bottleneck (*zonal variation*) is estimated. The Sicilian spot price is from now referred as SIC.

6.1.1 *Hourly Variability*

Decreasing demand and increasing share of wind and solar power are making day and night prices converging. In 77 days the average night price was higher than the average day price, in 2012 [34]. Most of these days have been between April and September, when PV production increases. Figure 16 shows the price fluctuations in the last two years and Figure 17 reports the RE penetration since 2008. The storage is expected to buy at the cheapest PUN hours, from 00:00 to 07:00 and from 12:00 to 16:00, and sell at the most expensive SIC hours, from 08:00 to 11:00 and form 17:00 to 00:00, with an average price difference of EUR 61,54 per MWh, staying to the 2013 spot prices.

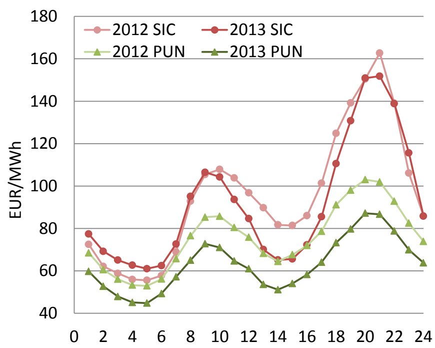


Figure 16: Hourly average price for the PUN and the Sicily zonal price.

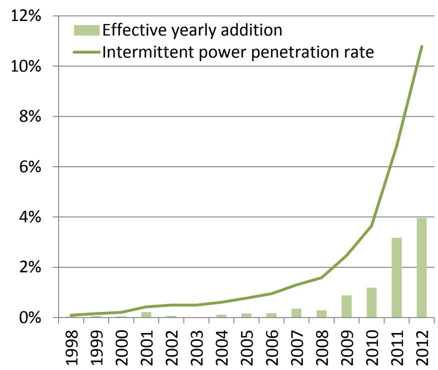


Figure 17: Renewable energy penetration from year 2008. Data from [34].

6.1.2 *Price Volatility*

Price variation is now considered in relation to the average price assumed by electricity in the spot market, both in the PUN and the SIC. Figure 5 on page 12 shows that the spread between these values is being slightly incrementing between 2012 and 2013, meaning that current policies are far to solve the Sicily day-ahead market problems. Interesting for the study is to look into the potential lowest buying price (PUN) and highest selling price (SIC) hours. These numbers are shown in Figure 16 (average values) and Figure 18 on page 60 (actual 2013 values with a 1% aggregation). These numbers clearly show that there is a great potential of price arbitrage between those two market.

Table 12 shows spot market volatility. Peak hours are defined as weekdays from 8.00 to 20.00 [5].

Year	Average spot price	Average peak	Average off-peak	Peak/off-peak spot price (%)
PUN (EUR/MWh)				
2012	75,48	81,44	71,70	1,14
2013	62,99	71,56	57,57	1,24
SIC (EUR/MWh)				
2012	95,28	109,39	86,34	1,27
2013	92,00	102,92	85,10	1,21

Table 12: Annual spot price volatility in the IPEX. PUN and Sicily zonal price reported. Elaboration from GME website.

6.1.3 *Zonal variation*

Besides the already mentioned non optimal energy mix and high price of natural gas, there is another cause for the Italian spot market price to be the highest one in Europe: the limitation in transmission capacity between the mainland and the two major islands, Sardinia and Sicily. According to the principle explained in Section 1.2 on page 5, the market is divided in different zones to overcome system bottlenecks when needed. This results in an annual average spot market price in Sicily which is EUR 30 per MWh higher than the PUN in year 2013 (Figure 5 on page 12).

In 2013 the spot market price has reached EUR 0 per MWh in 89 hours in the South zone, that was the cheapest one, 91 hours in Sicily and 53 hours in Sardinia [34]. However the PUN reached EUR 0 per MWh only in 2 hours. In 2013 the only net exporters of the system were the South and Sicily market zone, due to the grid layout and to their fast RE growth.

For the purpose of this study, it is worth mentioning that in none of the hours in which Sicilian day-ahead price went to zero, the zonal RE actually met the whole demand. However, to reduce starting and stopping costs, some fossil fueled power plants had to bet EUR 0 per MWh in these hours. It is also important to notice that Sicily and the South zones simultaneously had a price of EUR 0 per MWh in 35 hours. This is due to the same weather conditions rather then a real connectivity between the two zones.

Table 13 shows the frequency of interconnection bottlenecks between the Italian market zones. These numbers underline the complete system isolation of the Sicily spot market.

Zone	NORTH	CNOR	CSOU	SOUTH	SARD	SICI
NORTH	100	67	59	53	37	5
CNOR	86	100	88	82	60	10
CSOU	79	92	100	93	52	12
SOUTH	70	82	89	100	49	13
SARD	56	66	62	56	100	8
SICI	25	30	32	33	23	100

Table 13: Percentage of hours in which two zones share the same wholesale price in year 2012. Data from GME[34]

When Sicily is the only congested zone (4.771 hours in 2012, 5.183 hours in 2013), the gap between PUN and the spot price of the non congested zones says how much money consumers in these zones transfer to Sicily, uniquely because of grid congestion between the island and the mainland. This calculation was undertaken showing an average PUN increase of EUR 1,89 per MWh in 2012 and EUR 2,82 per MWh in 2013. Multiplying this number by the volume of electricity bought on the spot market in that hours it is obtained a total extra expense of EUR 459 million in 2013 and EUR 308 million in 2012.

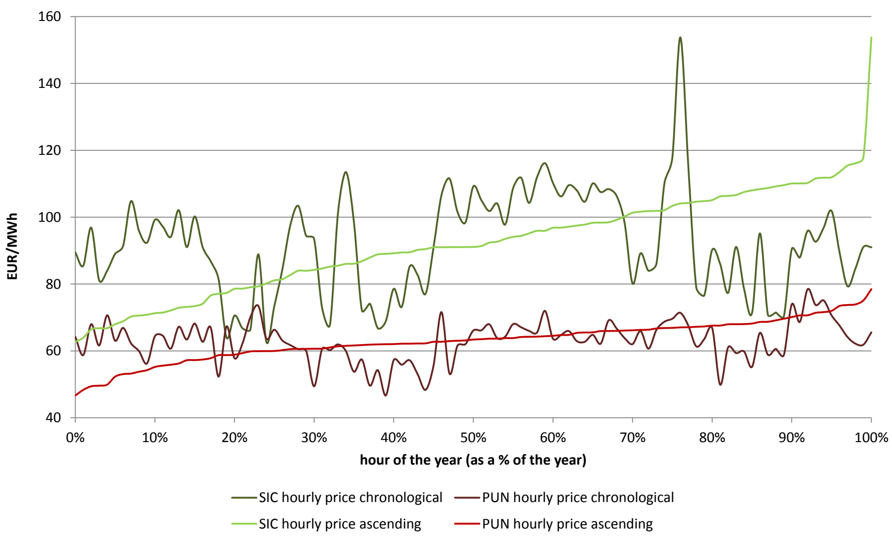


Figure 18: National and Sicily day-ahead price evolution in year 2013. Data elaborated from GME[1].

6.2 MODEL DESCRIPTION

For the analyses an existing optimization tool, energyPRO, is applied to design and optimize the hydrogen-based electricity storage system. The software, which is described in Section 3.3 on page 30, is syncronized with MS Excel import/export, to facilitate joined financial considerations.

The storage is formed by a charging unit, electrolyser and compressor, a storage unit, pressurized hydrogen tanks and a discharging unit, the fuel cell. An operation strategy is designed to optimized the time-shifting property of the storage which applies price arbitrage on the Italian day-ahead market. The storage is located in Sicily and, staying to the Italian spot market rule, it buys at the national average PUN and it sells at the Sicily zonal price.

EnergyPRO is specifically used for two optimization analyses: an *operational optimization* to find the optimal operation strategy of the storage and an *investment optimization* which, having fixed all the other parameters, optimizes the hydrogen storage size.

Following the method applied in the recent simulations by Colella et al. [23] two basic scenarios have been analysed: the current scenario, with base year 2014, and the future scenario, with base year 2025, in which performance and economical parameters are improved assuming technology development.

The model is outlined in Figure 19. This Section now explains technical and economical assumptions and constraints adopted in the analyses.

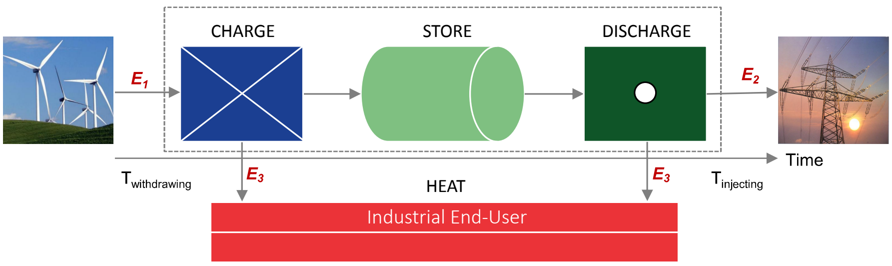


Figure 19: Schematic representation of the energy system that shows electricity conversion into hydrogen (charge), hydrogen storage (store) and hydrogen re-electrification (discharge). Heat recover for an industrial end-user is also represented.

6.2.1 *Assumptions*

The value of the 20-year cash flow generated by the hydrogen-based electricity storage investment is evaluated in Section 6.4 and is composed by:

- Initial investment at base year
- Replacement cost of major components
- Yearly net operating income (EBIT) resulting from the energyPRO model, which is actualized using the assumed 2% yearly inflation

The EBIT is, in turn, the result of the operating costs and revenues related to the storage operation. These are revenues from the produced heat, from the injected electricity and from the incentives, and costs for the withdrawn electricity and the O&M of the energy units. The assumed values are reported in Table 14. Heat value is assumed to

Value	2014	2025
Heat value (EUR/MWh-heat)	80	
Green Certificates (EUR/MWh-heat)	84,34	
Electricity buy	2013 PUN spot price	
Electricity sell	2013 Sicily spot price	
Electrolysers O&M (EUR/h)	19	7
Compressors O&M (EUR/h)	5	5
Fuel Cells O&M (EUR/MWh-e)	25	7

Table 14: Operational economic assumptions of the modelled energy system.

be equal to EUR 80 per MWh-heat. This is in line with the Italian district heating average price [42] and also consistent with an estimated consumer cost for 1 MWh-heat, for individual electricity heat pumps and gas-fired boilers. This estimation was made according to AEEG[8] resulting in an average cost of EUR 47,44 per MWh-heat for the cheapest electricity heat pumps, and EUR 83,22 per MWh-heat for the natural gas-fired individual boiler, VAT excluded. However in this calculation was only considered the retail fuels cost (EUR 18,98 per MWh-e for electricity and cEUR 83,01 per Sm3 for natural gas) and not maintenance costs which would also lie on the consumer economy.

It might not be necessarily feasible to be able to buy electricity in the spot market and sell heat without paying any tax. In fact in this way, the State would loose the consumer tax coming from either natural gas or electricity consumption to produce heat. However, in line with the district heating general case, it is assumed that the final consumer will pay heat taxes. In Italy this is a 10% subsidized VAT. It is also generally assumed that the heat produced is entirely used. This is realistic if the system is connected to a district heating network, for instance close to an industrial site requiring process heat or an hospital. The system could also be completed with a thermal store, but this is not part of this study. Being the hydrogen storage located in a warm climate zone, the possibility of a heat absorber to enable a process of district cooling might be worth considerations.

According to this considerations one of the implemented scenarios includes the historical Italian incentives for district heating, generally called Green Certificates (GC). This incentives scheme, which awards the plant operator with one certificate (EUR 84,43) every MWh-heat produced, is no longer existing due to budget overrun. Another incentives scheme is now running and is applied to high-efficiency CHP, the White Certificates for energy efficiency. White Certificates today pay around EUR 120 per saved TOE. Applying the due multiplicative factors, the two incentive schemes, in this study, are mostly equivalent. To make things easier, the Green Certificates scheme is applied.

Unit	Parameter	2014	2025
Electrolyser	Type	PEM	
	Input (kWe)	3.413	3.144
	Output (kW-hydrogen)	2.491	2.484
	Output (kWh)	512	456
Compressor	Type	Diaphragm	
	Inlet pressure (bar)	30	70
	Outlet pressure (bar)	400	
	Efficiency	92%	
Storage	Type	Pressurized Tanks	
	Pressure (bar)	500	
Fuel Cell	Type	PEMFC	
	Input (kW-hydrogen)	3.704	3.509
	Output (kW-e)	2.000	2.000
	Output (kW-heat)	720	730

Table 15: Technical assumptions of the modelled energy system.

Assumed O&M costs of fuel cells and electrolysers result from a scoping analysis, largely based on previous investigations by Colella et al. and energinet.dk [23][31] in which several companies were interviewed about the current as well as future technology performances and costs. Costs of compressors and pressurized tanks were instead obtained trough specific interviews made for this study. Interviewed companies agreed that compressors require to be expensively maintained after an average period of 5.000 hours due to diaphragm damage but, for simplification, this cost was converted into a hourly cost.

Entrance fee of EUR 7.500 and fix yearly fee of EUR 10.000 have to be paid to operate in the IPEX. According to the current market rule, the analysed storage units are exempted from the operating fee, being under the threshold of 0,02 TWh per month exchanged [1].

Technical assumptions are the result of the already mentioned technology scoping of Section 5.4 and summarized in Table 15.

6.2.2 *Constraints*

Major constraint in the storage operation is a dependency rule for electrolysers and fuel cell, requiring non-simultaneous operation. Beside being a legally uncertain behavior, this option is considered socio-economically absurd and therefore neglected. This operation dependency from other units is needed because of:

- a non perfect match between electrolyser input and fuel cell output capacities
- a high value of heat, tending to decrease the operation strategy dependency from the electricity spot price
- the Italian day-ahead market structure in which the storage buys and sells in two different markets

The second important constraint is that, in order to distribute the storage benefit throughout the year, the model is forced to be empty at the starting hour of every month.

6.2.3 *Scenarios*

As already introduced in Section 3.5 on page 32 the model is firstly run for 4 basic scenarios which are named: 2014, 2014-GC, 2025 and 2025-GC.

The number, 2014 or 2025, indicates the considered year of techo-economic development of the hydrogen-based electricity storage. The GC suffix instead, indicates whether the Green Certificates (incentives for district heating) are applied (2014-GC and 2025-GC) or not (2014 and 2025).

6.3 OPERATION STRATEGY

The optimal operation strategy is calculated in Excel and later inserted into the energyPRO model. Calculations are based on efficiencies and operating costs and benefits outlined in Table 15 and in 14 on page 62. The idea on the base of this calculations is to evaluate the cost and the value of 1 MWh of hydrogen at 400 bar, as of now 1 MWh-hydrogen400, in relation to the fluctuating spot market price. Those two quantities, changing in time with a time frame of 1 hour, represent the priority of production of, respectively, electrolysers and fuel cells. The two priority functions are not in relation with each other. They just indicate, in each hour, the priority scale of buying (electrolysers priority function) or selling (fuel cells priority function) electricity. Once they are imported in the energyPRO model, the energy units produce as for the algorithm explained in Section 3.3. At the end of this Chapter, a nomenclature helps the reader follow the reported formulae.

6.3.1 *Cost of compressed hydrogen (COH)*

COH is defined as the production cost of 1 MWh-hydrogen400, staying to the techno-economic assumption addressed above. It consists of four components: the cost of buying electricity

$$C_{ee} = -\frac{1}{\eta_c \eta_{el}} SP_{buy}(h) \tag{8}$$

the O&M cost of electrolysers and compressor

$$O\&M = -\left(\frac{1}{\eta_c \eta_{el}} \frac{O\&M_{el}}{C_e} + V_H \frac{O\&M_c}{C_c}\right) \tag{9}$$

the revenue from selling the recovered heat from the electrolysis

$$R_{heat} = \frac{\eta_{hel}}{\eta_c \eta_{el}} H_{sell} \tag{10}$$

and the revenue from incentives that in our incentivized scenario are the Italian Green Certificates for district heating, defined as it follows (this revenue might go to zero or be defined differently in other scenarios)

$$R_{GC} = \frac{1}{\eta_c} GC. \tag{11}$$

The sum of these costs and revenues is finally obtained

$$\begin{aligned} COH(SP_{buy}(h)) = \frac{1}{\eta_c \eta_{el}} \Big(\eta_{hel} H_{sell} - SP_{buy}(h) \\ - \frac{O\&M_{el}}{C_e}\Big) - V_H \frac{O\&M_c}{C_c}. \end{aligned} \tag{12}$$

Having fixed the other parameters, it can be obtained the linear dependency of the production cost of 1 MWh-hydrogen400 on the purchase spot price. The final formula is now derived for the 2014 incentivized scenario. To obtain Equation 16, Equation 12 is firstly evaluated in two hours h, for instance the two hours in which there is the cheapest and most expensive SP_{buy} price

$$COH(SP_{buy}) = \begin{cases} 19 & \text{if } SP_{buy} = 0; \\ -208 & \text{if } SP_{buy} = 152; \end{cases} \tag{13}$$

the wanted relation is described in Equation 14 in its general linear form. Slope (m) and y-intercept (q) can then be evaluated

$$COH(SP_{buy}(h)) = \frac{\Delta y}{\Delta x} SP_{buy}(h) + q \tag{14}$$

$$m = \frac{\Delta y}{\Delta x} = -\frac{227}{152} \qquad q = COH(0) = 19 \tag{15}$$

from the above evaluated parameters m and q, the explicit form of Equation 14 is found, representing the priority of dispatch, hour by hour, of the electrolysers.

$$El_{priority}(h) = COH(SP_{buy}(h)) = -\frac{227}{152} SP_{buy}(h) + 19. \tag{16}$$

6.3.2 *Value of compressed hydrogen (VOH)*

Similarly to COH in the case of the electrolysers, economic value of 1 MWh-hydrogen400 (VOH) is the key element to describe the linear relation between the zonal selling spot price, SP_{sell}, and the priority of dispatch of the fuel cells $FC_{priority}$. Equation 25, which describes VOH in relation on the spot price, is now derived starting from its components.

In the modelled energy system, hydrogen is used in the fuel cell to produce electricity and heat. Electricity is injected into the grid and pays the zonal spot price of Sicily. Revenue from selling electricity is described as

$$R_{ee} = \eta_{fc} SP_{sell}(h) \tag{17}$$

similarly, the revenue from the sold heat, recovered from the fuel cells, is

$$R_{heat} = \eta_{hfc} H_{sell} \tag{18}$$

and the maintenance cost of the fuel cell device is defined as

$$O\&M = \eta_{fc} O\&M_{fc} \tag{19}$$

finally, in the incentivezed scenario presented in this study, the Italian Green Certificates for district heating are applied, defined, for the heat provided by the fuel cells, as

$$R_{GC} = \eta_{hfc} GC. \tag{20}$$

These equations result in the final definition of VOH

$$VOH(SP_{sell}(h)) = \eta_{fc}\left(SP_{sell} - O\&M_{fc}\right) + \eta_{hfc}(H_{sell} + GC). \tag{21}$$

$VOH(SP_{sell}(h))$ is then evaluated in two actual SP_{sell} situations. This is here done for the highest and lowest SP_{sell} price

$$VOH(SP_{sell}) = \begin{cases} 46 & \text{if } SP_{sell} = 0; \\ 165 & \text{if } SP_{sell} = 222; \end{cases} \tag{22}$$

The wanted relation is described in Equation 23 in its general linear form. Slope (m) and y-intercept (q) can then be evaluated.

$$VOH(SP_{sell}(h)) = \frac{\Delta y}{\Delta x} SP_{sell}(h) + q \tag{23}$$

$$m = \frac{\Delta y}{\Delta x} = \frac{120}{222} \qquad q = VOH(0) = 46 \tag{24}$$

From the above evaluated parameters m and q, the explicit form of Equation 23 is found, representing the priority of dispatch, hour by hour, of the fuel cells

$$Fc_{priority}(h) = VOH(SP_{sell}(h)) = \frac{120}{222} SP_{sell}(h) + 46. \tag{25}$$

Operation strategies are used as inputs in the energyPRO model. Since the hydrogen-based storage is buying and selling electricity in two different markets for over 8.000 hours (Table 13) a problem could arise in situation in which it is economically beneficial to buy and sell electricity in the same hour. As previously explained in Section 6.2.2 a constraint to the model does not allow this operating situation.

Results

Graphical representations of the two priority functions of electrolysers (Equation 16) and fuel cells (Equation 25) are shown in Figure 20 in relation to the variables PUN(h) and SIC(h) in the first week of February 2013. Priority functions are not in competition because the units are producing different outputs. EnergyPRO uses the priority functions to make the unit working in the most prioritized hours, i.e. the lowest valued ones.

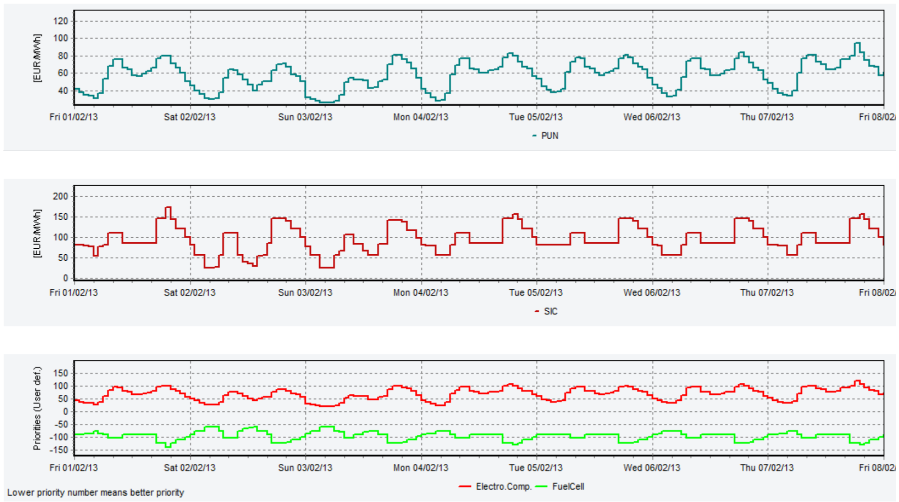


Figure 20: Spot market prices (PUN and Sicily zonal price) and priority functions for the operation of electrolyser and fuel cells. In the shown priority functions, Green Certificates for district heating are applied.

The resulting production graphs of the same storage in the same first week of February are shown in Figure 21 (2014-GC scenario) and Figure 22 (2014 scenario) for the 3 MW input/2 MW output storage, with a 20 MWh storage energy content, which resulted to be the optimal size, as later shown in the following Section 6.4.

Economic results of this part of the analysis are a comprehensive calculation of the net operating income. This was made for different volumes of available pressurized tanks (Figure 24) in order to find the optimal one. Table 23 on page 70 summarizes selected operating indicators and payments of 1-year operation of the 20 MWh electricity storage.

Results of the operational optimization are later used in the investment evaluation in Section 6.4 to calculate investment NPV, IRR and payback period.

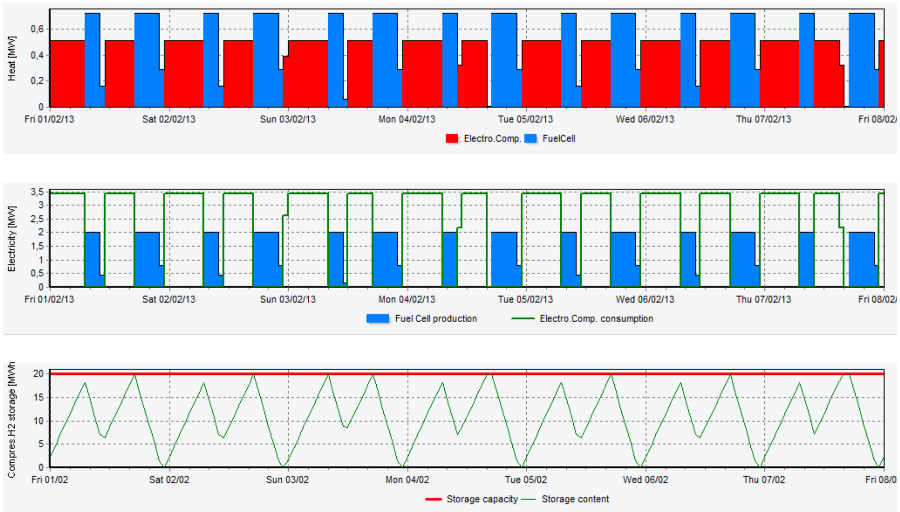


Figure 21: Electricity consumption and production of the hydrogen-based electricity storage system. Heat production and hydrogen storage content are also shown. First week of February. 2014-GC scenario with a hydrogen400 storage of 20 MWh, 3MW input/2 MW output. It can be noticed that the district heating incentives would make it convenient for the storage to work 24/7.

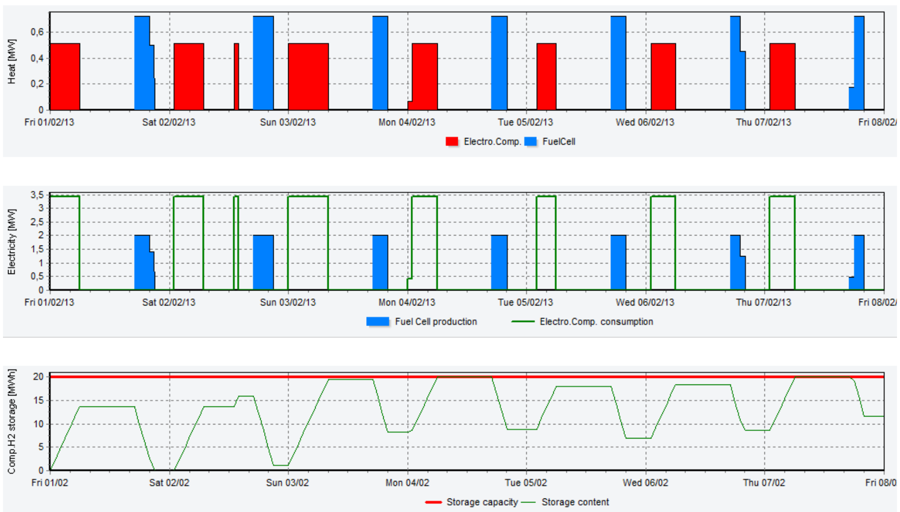


Figure 22: Electricity consumption and production of the hydrogen-based electricity storage system. Heat production and hydrogen storage content are also shown. First week of February. 2014 scenario with a hydrogen400 storage of 20 MWh, 3MW input/2 MW output.

Yearly parameters	with GC	without GC
Electricity production (MWh)	6.091	3.016
Electricity consumption (MWh)	16.873	8.355
Heat production fuel cells (MWh)	2.193	1.086
Heat production elect.compr. (MWh)	2.531	1.253
Hours of operation elect.compr.	5.028	2.532
Hours of operation fuel cells	3.307	1.620
Average sell price (MWh-e)	127,31	148,23
Average buy price (MWh-e)	53,10	43,30
Revenues		
Spot market electricity (EUR)	775.539	447.121
Sale of heat (EUR)	377.952	187.142
Green Certificates (EUR)	398.456	0
Expenditures		
O&M electrolyser (EUR)	152.298	47.728
O&M compressor (EUR)	25.290	12.560
O&M fuel Cells (EUR)	152.298	75.410
Spot market electricity (EUR)	896.066	361.755
Operation income	382.186	136.806

Figure 23: Operating balance in the 2014 and 2014-GC scenarios. Storage: 3 MW input/2 MW output, 20 MWh content. Calculation results from energyPRO. Spot market fees and planned maintenance costs later added when the overall investment is evaluated.

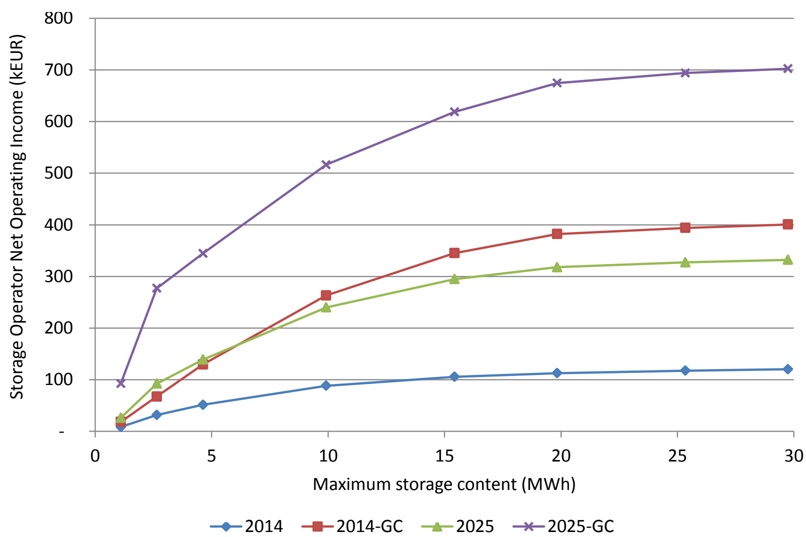


Figure 24: Yearly net operating income of the simulated storage units.

6.4 storage sizing and investment evaluation

Three parameters are selected to evaluate the feasibility and the value of investing in hydrogen-based electricity storage in Sicily: the net present value (NPV), the internal rate of return (IRR) and the discounted payback period. To calculate those values the investment cost of Section 5.4 is used together with the assumptions of Table 16.

Real Discount Rate	2,5%
Inflation	2,0%
Lifetime of the investment (years)	20

Table 16: Economic assumption for the investment evaluation. A real discount date of 2,5% is equal to an approximate nominal discount rate of 4,5%.

The NPV compares the initial cost of the project to the total value of the future cash flow and is calculated through

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{(benefits - costs)_t}{(1+r)^t} \tag{26}$$

The IRR is the discount rate which makes the NPV of the whole cash flow equal to zero. Finally the discounted payback time is the number of years needed to get a positive accumulated balance from the investment. Costs and revenues are actualized taking into account discount rate and inflation. The investment is entirely paid at base year.

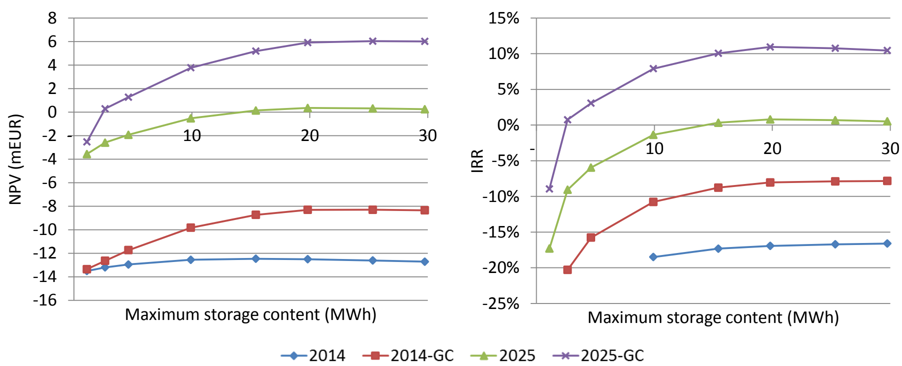


Figure 25: IRR and NPV calculated for the hydrogen-based storage investment in Sicily. Operating cash flow is optimized with price arbitrage on the Italian day-ahead market (prices for the analysed year 2013). The project is currently unfeasible (best NPV of EUR -8 m) but, staying to the assumptions, it will be in 2025 (best NPV over EUR 6 m). IRR confirms that the optimal storage size is 20 MWh.

Results

Operation income are used in the investment evaluation to find the optimal storage energy content and to later analyse the variables relations through feasibility analysis. Although the operation income of Figure 23 the scenarios 2014 and 2014-GC show an unfeasible investment with negative NPV and IRR (Figure 25). This means that, staying to the current techno-economic development, the investment in hydrogen-based electricity storage does not even become economically feasible with the incentives scheme of the Green Certificates for district heating.

The NPV gets positive with the 15 MWh storage in the 2025 scenario and with the 3 MWh storage in the 2025-GC scenario (Figure 25). NPV and discounted payback period show that, with the modelled layout, the 20 MWh storage is the optimally sized one (Table 17). In the 2025 (and 2025-GC) scenarios, the 20 MWh storage has an IRR of 5,4% (16%) and a discounted payback period of 11 (5) years. Table 17 shows the NPV for storage of increasing energy content for the 2025 and 2025-GC scenarios. A storage of 20 MWh compressed hydrogen content maximizes the NPV in the 2025 scenario and minimizes the discounted payback period (PB) in both the 2025 and 2025-GC scenarios. This storage size is also the one maximizing the IRR for the 2025, 2025-GC and 2014-GC scenario and is therefore selected for the sensitivity analysis which is reported in Section 6.5.

Hydrogen Store		Total Investment	NPV 20 years (mEUR)		Discounted PB (yr)	
(Nm3)	(MWh)	(mEUR)	2025	2025-GC	2025	2025-GC
370	1	3,883	-3,571	-2,537	-	-
880	3	3,934	-2,593	0,288	-	18,20
1.540	5	4,000	-1,930	1,275	-	14,20
3.300	10	4,176	-0,531	3,775	-	9,16
5.140	15	4,360	0,140	5,188	20,14	7,70
6.610	20	4,507	0,352	5,913	18,13	7,33
8.440	25	4,690	0,313	6,032	18,28	7,41
9.910	30	4,837	0,246	6,015	18,50	7,54

Table 17: Comparison of the economic results of the hydrogen-based storage (2 MW-e discharging power, 3 MWE-e input). Technology development year 2025, with (scenario 2025-GC) and without (scenario 2025) Green Certificates. The optimal storage of 20 MWh is underlined.

6.5 sensitivity analysis

Results of the sensitivity analysis are here shown in terms of NPV fluctuations. The four basic scenarios are the ones introduced in Table 7 on page 32, with techno-economic parameters as from Table 14 on page 62, Table 15 on page 63 and Table 16 on page 71.

Firstly, sensitivity to the energy price variation is shown and, secondly, an in-depth sensitivity study on the techno-economic development of the fuel cells is undertaken.

Sensitivity analysis is only conducted for the optimal storage configuration with fuel cell capacity of 2 MW, electrolysers capacity of 1.500 kg/day and storage content of 20 MWh.

6.5.1 *Energy price variations*

Heat price is the most uncertain value and the impact of its variation on the overall 20-year investment is here discussed together with the impact of a change in spot market price.

When considering a 60% decrease in heat price this also represents, approximately, the economy of a scenario in which only 60% of the heat is sold to the initially assumed price. Having assumed that the whole produced heat is used and paid by the end-user, this is an important analysis. Despite the great impact of the heat price on the 20-year investment, not even a 60% heat price increase would make the investment feasible in the 2014 and 2014-GC scenarios (full and dotted red lines Figure 26). Even in the 2025 scenarios, incentives are crucial to keep the investment safe against heat price changes (Figure 27).

The storage buys electricity at the PUN buy price and sells electricity at the zonal Sicily price. Those two price are proportionally changed to test the effect of a spot market fluctuation on the investment economy. 2014 and 2014-GC scenarios are always negative and the higher the price, the more negative the investment NPV (full and dotted green lines Figure 26). 2025 and 2025 scenarios instead are more interesting to be analysed. In this case the storage shows a substantial independence from spot price fluctuation (buy and sell effect balance each other) with a small improvement in the 2025 scenario (full green line Figure 27).

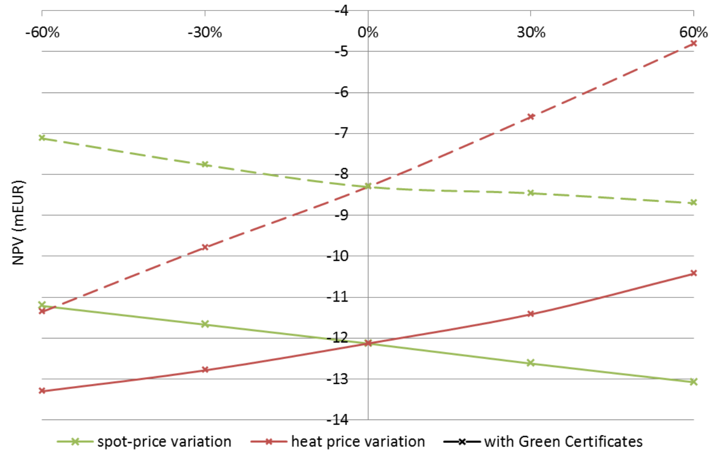


Figure 26: Impact of variation of electricity and heat price on NPV for the 2014 and 2014-GC scenarios.

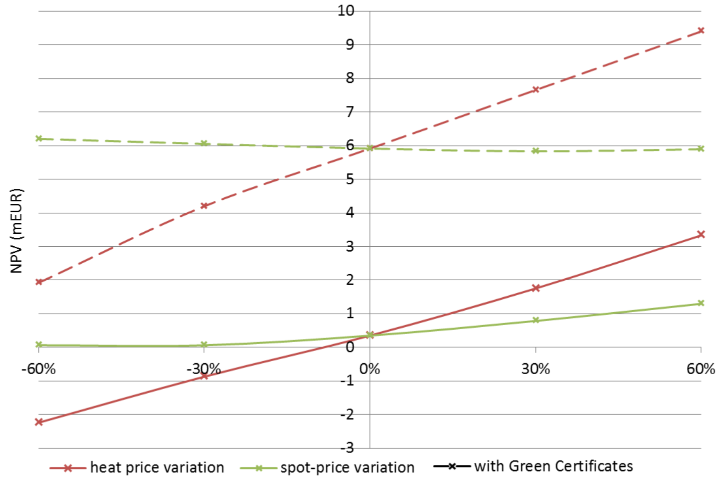


Figure 27: Impact of variation of electricity and heat price on NPV for the 2025 and 2025-GC scenarios.

6.5.2 *Fuel cells size and cost*

Fuel cells are here considered to analyse two aspects. Firstly, a change from the cost found in the report by energinet.dk[31] is considered, since this parameter is expected to have a great impact on the outputs, and its evolution is hard to predict.

Secondly, the impact of a change in the applied fuel cell size is also analysed. This analysis its interesting to understand how far from the optimal fuel cell size is the assumed storage system of 2 MW discharging, 3 MW charging and 20 MWh energy content.

Since a change is size most likely entails also a change in investment cost, the analysis is undertaken in three different perpectives: the first one studies NPV change by changing only the fuel cells price (blue lines Figure 28), the second one studies the NPV change by changing only the fuel cells size (red lines Figure 28) and the third one studies the NPV change by assuming proportionality between size and price change(green lines Figure 28). The analyses are only undertaken for the 2025 techno-economic development with (dotted lines) and without (full lines) district heating incentives.

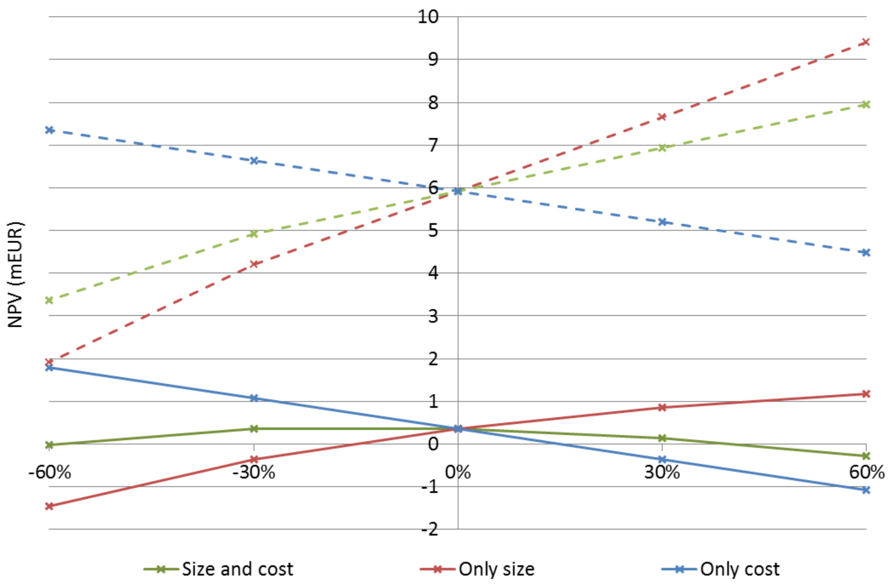


Figure 28: Impact of variation of fuel cells investment cost and size on NPV for the 2025 and 2025-GC (dotted lines) scenarios.

The NPV of the 2025 scenario gets negative with a fuel cells price increase of 15% (full blue line Figure 28). As expected, an increase in size without an increase in cost would make the economy of the investment better. However, this is clearly not the most probable prospect.

It seems more reasonable the situation in which an increase in size coincides with an increase in investment cost. In this case the utilised fuel cell of 2 MW-e results to be the optimal one in the 2025 scenario (full green line Figure 28).

Discussion

The sensitivity analysis has confirmed a bad economy for the investments simulated in the 2014 scenarios. This means that these projects, which are often first-of-a-kind experiments must be incentivized, not only through an incentive scheme awarding the storage operation, but also with fiscal support and capital grant, to reduce the initial investment. These forms of support are today used in countries like Finland, Germany and Netherlands to support high-efficiency CHPs

[35][22]. In the current situation, investments in hydrogen-based electricity storage will be probably only experimented by supported research projects, exactly as it is actually already happening [3][2].

NOMENCLATURE

COH	cost of hydrogen (EUR/MWh-hydrogen400)
η_c	compressor efficiency
η_{el}	electrolyser hydrogen production efficiency
η_{hel}	electrolyser heat efficiency
$SP_{buy}(h)$	spot price buy (EUR/MWh)
H_{sell}	heat price (EUR/MWh-heat)
GC	Green Certificates (EUR/MWh-heat)
$O\&M_{el}$	electrolyser operation and maintenance cost (EUR/h)
$O\&M_c$	compressor operation and maintenance cost (EUR/Nm3)
C_e	electrolyser capacity (KW-e)
C_c	compressor capacity (Nm3/h)
V_H	hydrogen volume inpunt in compressor (Nm3)
VOH(h)	value of hydrogen (EUR/MWh-hydrogen400)
η_{fc}	fuel cell electric efficiency
η_{hfc}	fuel cell heat efficiency
$SP_{sell}(h)$	spot price sell (EUR/MWh)
$O\&M_{fc}$	operation and maintenance cost for fuel cell (EUR/MWh-e)
H_{sell}	heat selling price (EUR/MWh-heat)

7 GRID SERVICE EVALUATION

In the previous Chapter the hydrogen-based storage has been firstly economically optimized in its operation strategy (operational optimization). Secondly, fixing electrolyser (charging) and fuel cells (discharging) capacity, the optimal size of the hydrogen stocking unit was found (investment optimization). The operational optimization is based on the spot price at which the storage operator can buy and sell electricity, applying price arbitrage.

Beside being economically beneficial for the storage operator, this operation mode is also expected to be beneficial for the overall grid of Sicily. Buying in low price time frames and selling in high price time frames the storage fulfills the task of shaving zonal demand's peaks, absorbing electricity in hours of high RE penetration (low spot price) and helping the island grid from the inside in hours at risk of expensive transmission congestion (high spot price).

These benefits are expected by virtue of data based observation made on the analysed year 2013. The structure of the Italian day-ahead price is reported in Section 4.2 on page 35 and the time-shifting properties of electricity storage is explained in Section 5.2.2 on page 48. The basic idea of the relations between spot price, RE share and market competition is shown in Figure 29.

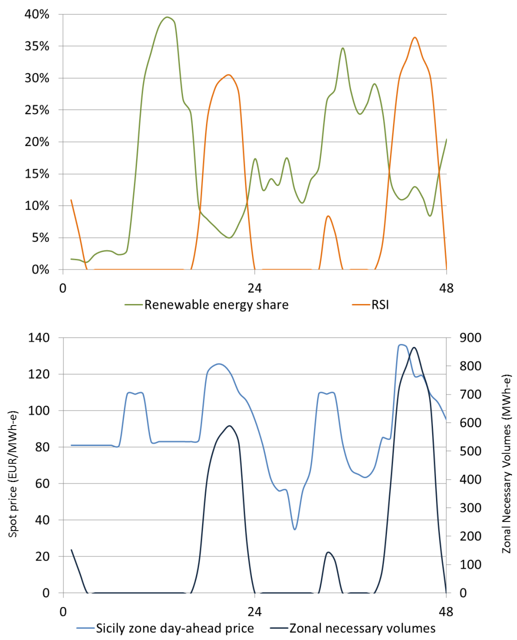


Figure 29: Spot market price in relation to RE share, volumes sold with no competition and RSI. Sicily zone, 1st and 2nd of January 2013. It can be seen that in abundance of RE the RSI, which goes to 0, indicates a situation of higher market competition, resulting in a lower zonal price. Elaboration from GME[1].

This Chapter now shows the analyses which aimed to confirm this expected matching between the operational economic optimization (price arbitrage) and the wanted grid support applications of the hydrogen-based electricity storage: support to the intermittent RE production, prevention of transmission bottleneck and decrease in market power of pivotal operators.

These analyses was only undertaken for the 3 MW input/2 MW output, 20 MWh storage and the 2014 scenario (current technology development without district heating incentives).

Support in increasing RE depth of penetration is tested in Section 7.1 where several future scenarios of RE share are considered.

As it was already commented before, Sicily spot market was separated from the other zones for 88% of the hours in year 2013. This makes it hard to evaluate a relation between the storage operation and the presence of bottlenecks and therefore only general trends are shown in Section 7.2.

Section 7.3 finally shows an in-depth calculation which, by means of the RSI, demonstrates the potential help which could come from energy storage, in decreasing market power of dominant operator, the main grid problem in Sicily.

7.1 RENEWABLE ENERGY SUPPORT

The importance of electricity storage units is increased by their application to support a greater exploitation of variable RE [67]. When more RE feeds the grid, daily load profile is more variable and uncertain. From a price arbitrage perspective this results in a greater advantage from price differentials. From a grid perspective, higher peaks have to be shaved off, to limit expensive capacity-reserve needs [67].

In literature, supporting the integration of variable RE is usually considered a specific storage application [67], and so it is in this study (Figure 15 on page 47). Still, it tends to be a combination of other applications. For this reason, the potential in RE support of a storage operating in price arbitrage is here analyzed.

The link between the zonal spot price of electricity and generation variability in Italy, year 2013, is illustrated in Figure 12 on page 38.

Results

Figure 30 shows a relevant example of a week in which RE peaks correspond to the storage charging hours on Wednesday, Thursday, Saturday and Sunday. In the same week, every day, the storage sells electricity in the spot market straight after the RE peak.

This trend is analysed on a seasonal base, obtaining Figure 31. Every hour of the simulated year 2013 is firstly classified to be above or under the seasonal average production from intermittent RE (wind and solar). After this, hours in which electrolysers (charging) and fuel cells (discharging) are working are also classified.

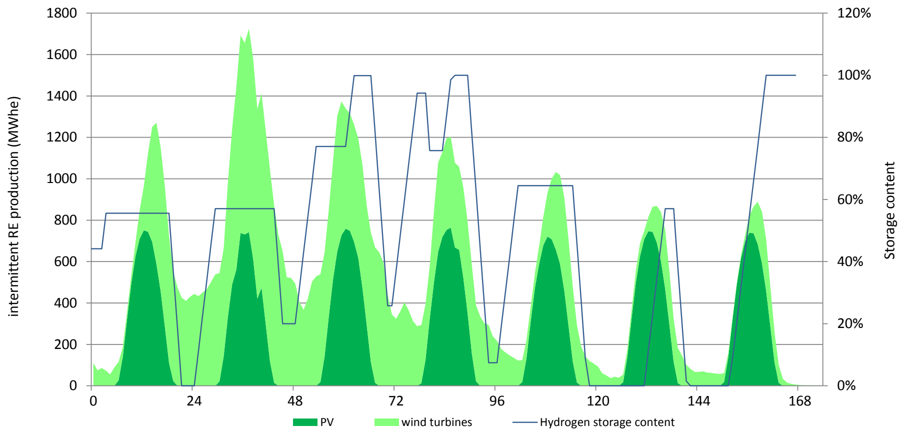


Figure 30: Intermittent RE production and hydrogen storage content. Simulated week 10th - 17th of June 2013. Storage: 20 MWh content, 3 MW input/2 MW output. 2014 scenario.

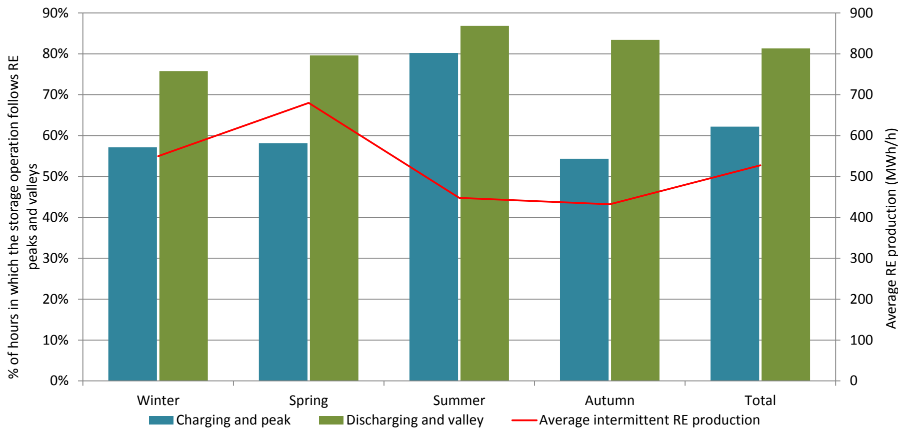


Figure 31: 62% of the hours in which the storage is charging are RE peaks and 81% of the hours in which is discharging are RE valleys. Simulation year 2013. Storage: 20 MWh content, 3 MW input/2 MW output. 2014 scenario, price arbitrage operation.

Finally, matching between storage content and RE peaks is found coupling charging hours with RE peaks and discharging hours with RE valleys. It results that 62% of the charging hours correspond to a peak in RE and 81% of the discharging hours correspond to a valley (Figure 31). The best match between the peak/valley pattern and the storage charging/discharging scheduling is found in the summer. Here, a theoretical 80% of the stored electricity is shifted from hours of peak in RE production to hours of lack of RE.

The average hourly renewable share of spot market demand was equal to 30%, in Sicily in 2013. Staying to the 2013 demand and production profile, a large RE penetration would result in green energy overproduction as shown in Table 18.

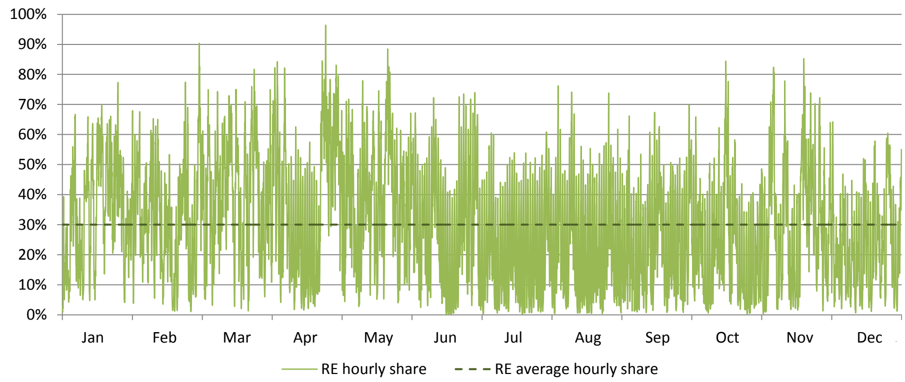


Figure 32: Intermittent RE zonal hourly share in Sicily over the analysed year 2013.

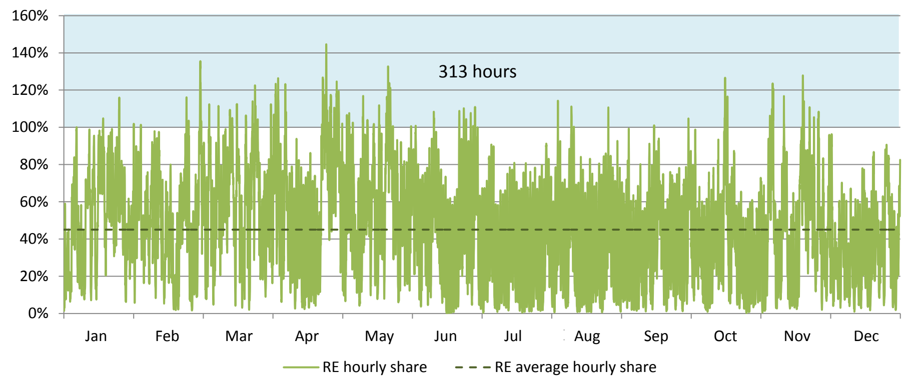


Figure 33: Intermittent RE zonal hourly share in Sicily over 1 year with a 50% increase comparing to the 2013 actual hourly share.

intermittent RE average hourly share (%)	over production hours
30% (2013 situation)	0
38% (current +25%)	36
45% (current +50%)	313
53% (current +75%)	885
60% (current +100%)	1.511
75% (current +150%)	2.866

Table 18: RE (wind and solar) overproduction resulting from increased average of hourly RE shares. Year 2013 is analysed as base year for the hourly demand distribution and intermittent RE actual production 2013.

7.2 ZONAL BOTTLENECK PREVENTION

In 2013, Sicily was in a situation of zonal transmission bottleneck in 88% of the hours of the year. In this hours the interconnection between the island and the South zone reached its utilization limit. This situation was introduced in Section 1.2.1 on page 6 and detailed in Table 1 on page 8.

A minimum cost of about EUR 1,67 per MWh, weighting on the electricity bills of Italian consumers, was estimated in Table 8, in every hour with transmission congestion in Sicily. At current status, interconnections allow a 100 MW flow toward the island (300 MW if extra units are committed) and a 250 MW (weekdays 8-23) or 100 MW (rest of the hours) flow from the island (respectively 600 MW and 150 MW if extra units are committed)[48].

As explained in Table 1 on page 8 the transmission grid can be congested in import (Sicily zonal price > South zonal price) or export (Sicily zonal price < South zonal price). In order to help congestion prevention the storage should be discharging in hours of bottlenecks in import, and charging in hours of bottlenecks in export.

Results

The reference scenario shows 7.964 hours in which Sicily interconnection with the mainland were congested in 2013, i.e. the 88% of the hours. 85% of the hours were import bottleneck, while the remaining 15% were either export bottleneck or export with no congestion. The implemented model made the storage work in 1.902 of those hours of which 1.682 (the 98%) are congested hours.

With a great majority of bottleneck hours in export, it is quite reasonable to foreseen that the storage most likely discharges in this type of critical hours. Instead, data about the hours in which the storage is charging are much more interesting. Figure 34 shows that, 22% of the charging hours are hours of export (of which most have export congestion). In those hours the storage is most likely giving an extra escape valve to the RE flowing out of Sicily.

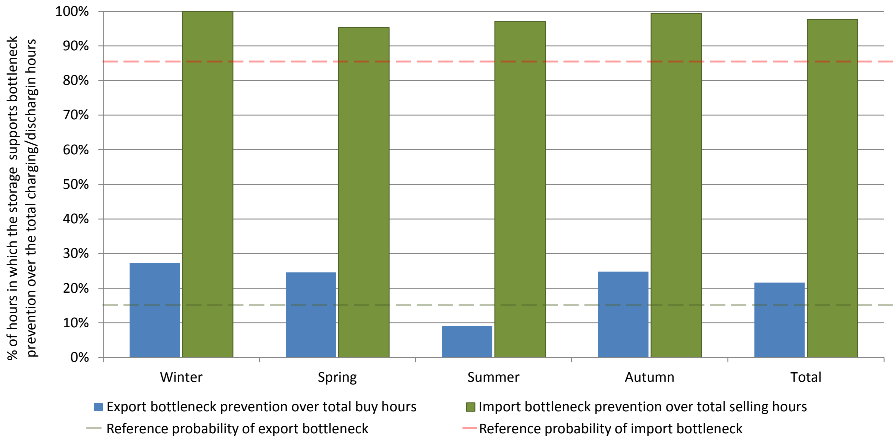


Figure 34: In 98% of the hours in which the storage is discharging is helping prevent zonal transmission congestion in import. In 22% of the hours in which is charging is helping prevent zonal transmission congestion in export. 2014 scenario: 3 MW input/2MW output, 20 MWh content, techno-economic development base year 2014, price arbitrage operation without incentives.

7.3 DECREASING MARKET POWER OF PIVOTAL SUPPLIER

A pivotal operator is a supplier whose volumes are strictly necessary to meet the electricity demand

As introduced in Section 3.2.1 on page 28, the IPEX regularly publishes the supply of electricity that is sold by pivotal operator in every hour h and every market zone mz, $N_{mz,h}$. In literature, a pivotal supplier is defined as a supplier whose volumes are strictly necessary to meet the demand on a given market zone. $N_{mz,h}$ is therefore the amount of electricity that is sold, in a certain hour h, with no competition. In a certain market zone mz with I operator $N_{mz,h}$ is defined as

$$N_{mz,h} = \sum_{j=1}^{I} n_{mz,h,j} \tag{27}$$

where $n_{mz,h,j}$ is the volume sold by the single operator j which is necessary to meet the electricity demand. $n_{mz,h,j}$ is defined, in that specific hour and zone, as

$$n_{mz,h,j} = \begin{cases} V_{mz,h} - \sum_{i \neq j} S_{mz,h}(i) & \text{if } V_{mz,h} > \sum_{i \neq j} S_{mz,h}(i); \\ 0 & \text{if } V_{mz,h} \leqslant \sum_{i \neq j} S_{mz,h}(i); \end{cases} \tag{28}$$

where $V_{mz,h}$ is the zonal demand and $\sum_{i \neq j} S_{mz,h}(i)$ the total volumes offered by competitors. Non pivotal suppliers give a contribution $n_{mz,h,j}$ equal to zero, while a pivotal supplier gives a positive contribution, equal to the amount of MWh sold with no competition, also called necessary volumes.

The RSI index was originally developed by the California Independent System Operator. In this study a corollary of the Californian RSI is used. It measures the ex-post residuality and it is a criterion for the level of competition of the market:

$$RSI_{mz,h} = \frac{\sum_{j=1}^{I} (V_{mz,h} - \sum_{j \neq i} S_{mz,h}(i))}{V_{mz,h}}. \quad (29)$$

Representing the percentage of volumes sold without competition, RSI ranges between 1 and 0. RSI equal to 0 shows a good market with a proper level of competition. RSI going up to 0,5 shows the presence of one or more pivotal operators that are in condition to exercise their market power. Finally, having an RSI close to 1 shows a situation of complete mono- (if there is only one pivotal operator) or oligo-polistic (if there are more) market.

Results

In 2013, 2.021,348 TWh of electricity were sold without competition (14% of the annual demand) is Sicily. The storage operation of the 2014 scenario (3MW input/2 MW output, 20 MWh content) lowers down this number to 2.020,442 TWh, meaning that the storage moves 906 MWh of electricity (45 complete charge-discharge cycles) from hours of competition to hours of non-competition. This was expected to happen as a result of the price arbitrage. Details on this improvement can be obtained, and verified, by looking at the zonal RSI variation, after the storage implementation.

This analysis is undertaken considering only hours with a positive RSI, in which the storage is working (either charging or discharging). In fact the RSI numerator $N_{mz,h}$ loses, by definition, the information about how much negative the index would be, when the RSI is forced to 0 (Equation 28).

As expected, the tested 2014 scenario results in an RSI improvement ($RSI_{new} < RSI_{reference}$) in 77% of the hours in which the storage operates (RSI gets worse only in 14%) and the overall average RSI change is - 0,024%. This value was studied in detail, obtaining Table 19. It is obvious that, having fixed the storage size, the highest the RSI, the hardest is to make it varying. The relevant information in Table 19 is

$RSI_{reference}$	average change
0 - 5%	+1,94%
5 - 10%	+0,14%
10 - 20%	- 0,27%
20 - 40%	-0,26%
40 - 60%	-0,17%
60 - 80%	-0,12%
80 - 100%	-0,11%

Table 19: RSI average change from reference RSI after the 20 MWh hydrogen-based storage introduction, in the Sicily market zone. Data from the simulation of an unincentivized storage, techno-economical development year 2014.

therefore the plus/minus sign of the change. If until a reference RSI of 10% the storage produces the expected outcome of reducing the RSI for reference RSI lower than 10% the new RSI is higher, i.e. worst, than the reference one.

In the optimal situation the storage should buy from the grid only in hours of normal market competition (RSI = 0). However the positive sign in the 0-5% and 5-10% categories shows that the storage tends to withdraw electricity already in these hours, making the already non competitive RSI worse.

The impact on market competition level of a larger scale introduction of storage units operating in price arbitrage on the day-ahead market is also analysed (Figure 35). It is found that, in the assumed spot market conditions, an increasing amount of units equal in size and operation to the storage in the 2014 scenario (3MW input/2 MW output, 20 MWh content) would produce a zonal RSI improvement converging to -50%.

It is concluded that, beside being economically optimal for the storage operator, the price arbitrage strategy produces also a time-shift in electricity consumption which results in an overall improvement of the level of competiotion in the zonal spot market. An example is shown in Figure 36 where an aggregation of 20 storage units alike the simulated hydrogen-based storage (2014 scenario: 20 MWh storage, 3MW input/2 MW output, without district heating incentives, operating in price arbitrage) is considered. In 2 hours of this day the storage units transfer the electricity which is bought with a probability of 62% in an hour of peak in RE production (Figure 31) to a period in which the market would otherwise experience a situation of no competition with old, polluting, power plants as price setters. The needed assumption is that the storage is able to sell its electricity on the spot market, maybe through a priority policy.

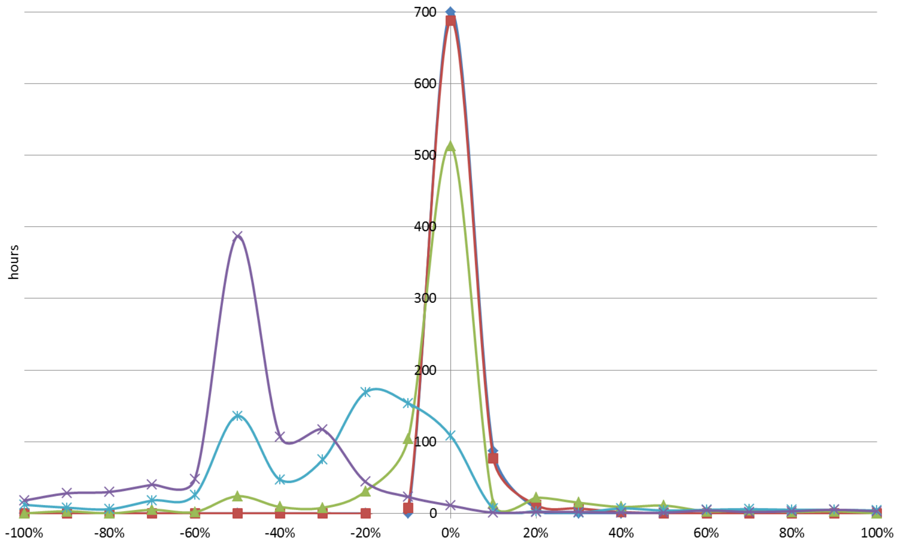


Figure 35: Impact of the storage operation on positive RSI hours. It can be seen that the result of a single unit are poorly significant from an overall zone perspective. In this case, being the capacity too low, the RSI change fluctuates around 0. However the tendency of improvement is clear when simulating the implementation of 20, 100, and 200 equally operating storage units. RSI changes here converge on -50%, indeed a higher level of competition.

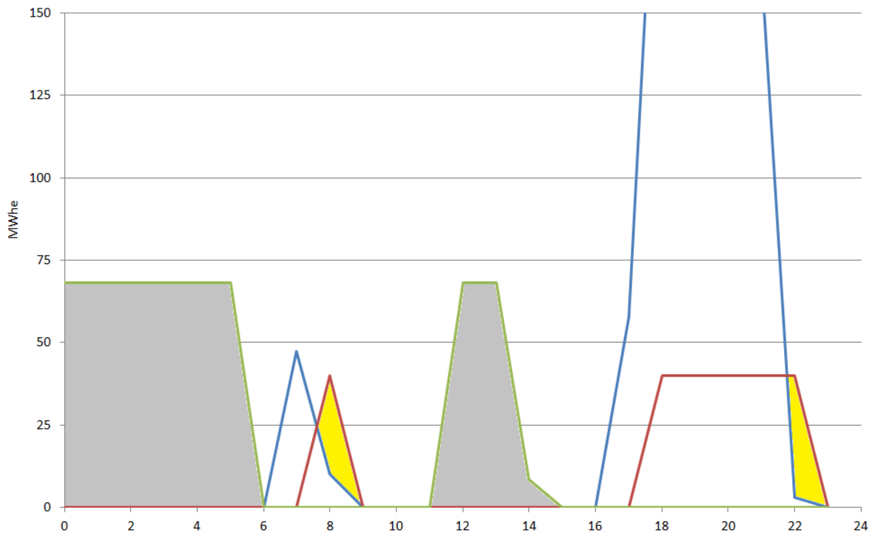


Figure 36: Yellow area is the amount of electricity that is delivered by the storage in situation in which old, price-setter, power plants can be pushed out of the market. Grey area shows instead, the withdrawn electricity in situation with no necessary volumes, most likely abundance of RE. At 8.00 and 22.00 the simulated storage supplies the volumes that, all things being equal, would make the RSI index going to 0. From 18.00 until 21.00 the storage also supplies electricity in a critical situation, providing grid support. 13th of June 2013.

$RSI_{mz,h}$	Residual supply index
$RSI_{reference}$	reference RSI before the hydrogen-storage introduction
RSI_{new}	RSI after the hydrogen-storage introduction
mz	market zone mz
h	hour h
$V_{mz,h}$	zonal demand in hour h
$\sum_{j \neq i} S_{mz,h}(i)$	total volumes offered by competitors
$N_{mz,h}$	total volumes sold with no competition in mz in hour h
$n_{mz,h,j}$	volumes sold with no competition in mz in hour h by the supplier j

8 CONCLUSIONS

The objective of this study is to determine the profitability of using hydrogen-based electricity storage technologies applying price arbitrage in the day-ahead electricity market and to analyse the grid benefits which are inherently provided by this operation strategy. As a case study the Italian spot market is taken. In the Italian electricity grid, the most problematic region is found to be the island of Sicily and here the storage is simulated. In Sicily, rivers and landscape reasons do not allow implementation of PHES storage. Due to the Italian price formulation structure (national price on the buy-side and zonal prices on the sell-side) this is also the zone which offers the best price differentials.

The simulation aims to calculate the maximum profit of the storage operating in Sicily and to understand in what extent the storage can help the zonal grid in terms of transmission bottlenecks prevention, increase of RE depth of penetration and higher market competition.

Hydrogen is an energy vector that can be used in every application in which fossil fuels are used today, including transportation and generating electricity. In increasingly renewable energy systems, hydrogen has a great potential also as an energy storage possibility. However, to become a real alternative to fossil fuel, a sustainable, economic large-scale production is required.

Commercial airplanes with hydrogen fuelled jet engines have been tested both in US and Russia. Similarly, BMW, Ford and Mazda have put their effort to develop and road-testing hydrogen powered cars ranging up to 300 km autonomy. In order to foster hydrogen cars development, networks of hydrogen-equipped filling stations are being implemented in US, Europe and Japan [24]. The so-called hydrogen highway plans to go across Europe from Oslo down to Italy. In France and Italy European projects are testing the use of hydrogen to support the renewable production in first-of-a-kind projects [3][2].

Hydrogen fuelled cars and decentralised hydrogen-based electricity storage could represent the transitional bridge to hydrogen economy [24]. The latter aspect is investigated in this thesis starting from the following research question.

Staying to the state-of-the-art research, what is the profitability of a decentralized hydrogen-based electricity storage unit and to what extent this technology can support the grid in an increasingly renewable and mostly congested power system?

In order to answer the research question three sub-questions are formulated. In the following each sub-question is answered.

What is the operation strategy which maximizes the operation income of the hydrogen-based electricity storage operating in the electricity day-ahead market?

When operating on the day-ahead market the strategy which takes advantage of the price differentials, maximizing the profit, is the price arbitrage operation. On the base of the assumed operating costs and benefits the optimal operation strategy was found in Section 6.3 on page 65. Being the hydrogen-based storage formed by a charging unit (electrolyser) and a discharging unit (fuel cells), the optimal storage operation is described by two equations, representing the priority function of the two units in linearly dependent from the spot market price. Priority functions are defined in Equation 16 and Equation 25 on page 67.

In the analysed year 2013, the calculated optimal operation strategy produces an yearly net operating income which ranges between EUR 8.000 (1MWh storage, current techno-economic technology development) and EUR 702.000 (30 MWh storage, techno-economic technology development at year 2025).

What is the optimal configuration and the profitability of the overall investment?

The investment is evaluated, in terms of NPV, IRR and discounted payback time, with a time frame of 20 years and real discount rate of 2,5%. Four basic scenarios were simulated:

2014: current techno-economical status, without incentives
2014-GC: current techno-economical status, with district heating incentives
2025: techno-economical development year 2025, without incentives
2025-GC: techno-economical development year 2025, with district heating incentives

Having previously fixed fuel cell capacity at 2 MW and electrolysers capacity at 1.500 kg/day and staying to the assumed conditions (Section 6.2.1 on page 62) the optimal configuration is found with a storage content of 20 MWh. Economic results are here shown for this specific hydrogen storage configuration.

In the current techno-economic status and according to this study's assumptions the investment is demonstrated to be economically unfeasible, even when applying district heating incentives for the recovered heat, according to the Italian Green Certificates scheme.

On the contrary, when considering the expected technology development of year 2025, the storage produces an NPV of EUR 352.000 which becomes EUR 5.913.000 when applying Green Certificates. Resulting IRR are 5% and 16%, respectively. In this situation, the investment in hydrogen-based electricity storage pays back in 11 years in the simulation without Green Certificates and in only 5 years in the simulation with Green Certificates.

These results show that the market design and its policies are fundamental in defining the feasibility of the investment and the optimal operation strategy to maximize the operating income of the plant. This is part of the reasons why sensitivity analysis was conducted.

In every sensitivity analysis the 2014 and 2014-GC scenarios are unfeasible.

On the contrary, 2025-GC shows a safe investment against every simulated sensitivity test, generating an NPV which ranges between EUR 1.921.000 and EUR 9.397.000 (Figure 28 on page 75).

Scenario 2025 is strongly dependent on both fuel cells investment cost and heat price, becoming negative with a fuel cells investment increase of 15% and with a heat price decrease of 10%.

It is concluded that in this early stage of technological diffusion different policies greatly influence the investment outcome, supporting or discouraging hydrogen diffusion. In the simulate scenario a great value was given to the by-product heat. Policies incentivizing its utilization are demonstrated to increase the profitability of hydrogen-based electricity storage.

What are the potential benefits for the overall electricity network, in terms of increasing RE depth of penetration, preventing bottleneck and increasing market competition?

The simulation clearly confirmed the expected trends. The hydrogen-based storage, whose operation was previously economically optimised in relation to the spot price, resulted to produce a positive impact on the problematic grid of the Italian island of Sicily. Results of the basic 2014 scenario are here reported.

In 62% of the hours in which the storage is charging there is a peak in RE production and in 81% of the hours in which the storage is discharging there is lack of RE (Figure 31 on page 79). In the future perspectives of greater RE penetration, the storage would support its optimal exploitation.

Since most of the hours the Sicilian grid is in a situation of transmission bottleneck in export, the storage would always give its contribution, being an additional energy supplier (discharging period), in situation in which the region in underproduction. However, the storage has also been proved to support the grid also in situation in which the Sicilian grid is in overproduction. In 22% of the hours in which the storage is charging it helps preventing congestion in export. In this case the storage can support by stocking cheap electricity.

Finally, by means of the RSI index, the impact of the hydrogen-based storage in decreasing market power of pivotal operator was analysed. Even if the above mentioned 2 MW storage is undersized to be able to notice a concrete change in market dynamics, an yearly amount of 906 MWh are moved by the storage from competitive to uncompetitive situation, reducing the zonal RSI index of 0,043%. When simulating a multitude of storage units, all operating in the same way, a convergence to halve the market power of pivotal operator is found (Figure 35 on page 85).

It is concluded that hydrogen-based electricity storage can be used for grid support purposes in highly-renewable and congested electricity systems. In those systems the operating income can be maximized applying price arbitrage, while providing, at the same time, grid support in terms of increased RE depth of penetration, higher market competition and bottleneck prevention. In line with this, if the investment economy would be more attractive, hydrogen-based storage could be the needed innovative solution to the problem of zonal bottlenecks and the consequent formation of local markets in Italy.

Perspectives for future works in this research field are finally reported.

8.1 PERSPECTIVES

In further investigations other possible grid services and their economy benefit for the storage operator have to be analysed, first of all the Ancillary Service, the regulating market and the capacity market which is working in Italy since early 2014. This options could improve the investment output, as needed.

It would be also interesting to study the economic consequences for Sicilian consumers and producers of the proposal of the Regulator to eliminate Sicily from the Italian day-ahead market price formulation.

Chapter 3 explains the theoretical background of this thesis, which is centred on the Choice Awareness theory. One of the core points of this planning theory is to compare cost and benefits of alternative options from a socio-economic point of view. By looking at the Sicily grid problems, the initial idea of this thesis was to produce a comparison between the governing strategy of increasing the transmission capacity between Sicily and the mainland and the alternative proposal to implement on-site hydrogen-based electricity storage units. However this has not been possible because of the lack of accessibility to the information related to this major work under the direction of the TSO (for instance it is not clear how many of the planned 2.000 MW are to import and to export electricity from the island).

For this reasons, the thesis has followed and completed only the first two steps of the Choice Awareness operational method (Figure 8 on page 26) that is a complete design of the technical alternative and a socioeconomic feasibility study. At this point, to initiate a real disclosure on the potential of hydrogen storage, a precise analysis of the TSO solution is needed. After this, if the hydrogen-based storage implementation results to be the socially best solution, a concrete proposal for policy measures has to be advanced in order to make it business attractive.

Another important analysis to be undertaken is an evaluation of the potential under hearth sites which coudl be suitable for compressed hydrogen storage purposes in Sicily.

Part III

APPENDIX

A

RETAIL PRICE FOR INDUSTRIAL AND RESIDENTIAL EUROPEAN CONSUMERS

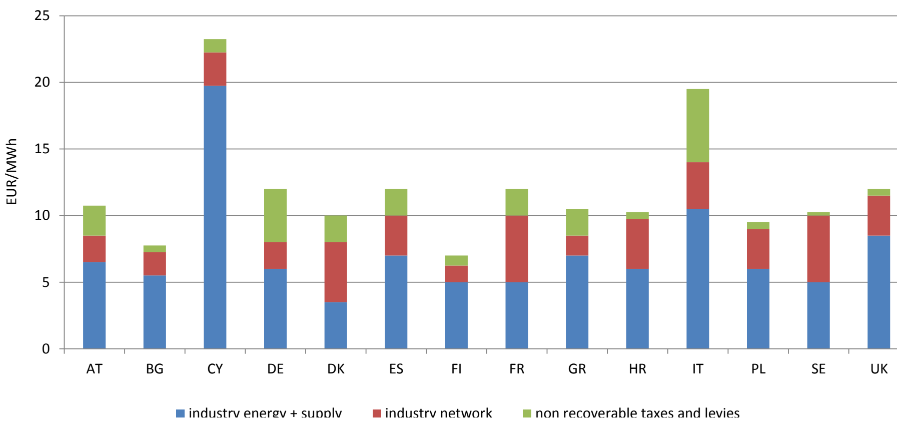


Figure 37: Industrial retail price in European countries. Data elaborated from [33].

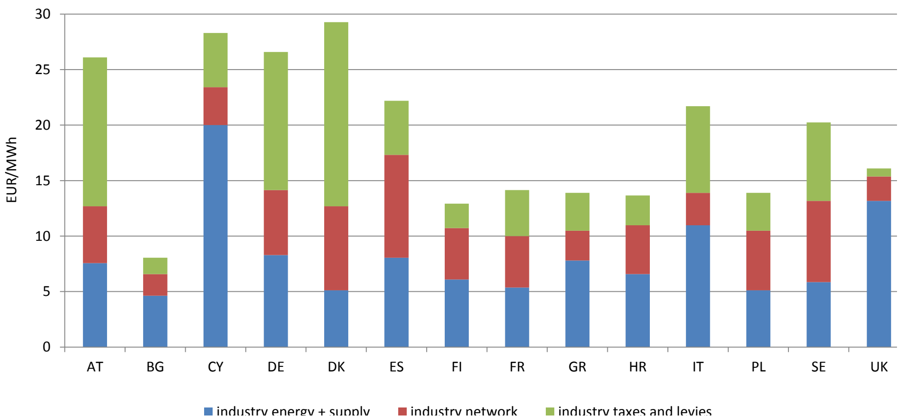


Figure 38: Household retail price in European countries. Data elaborated from [33].

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Final Version as of August 5, 2014 (`classicthesis`).

DECLARATION

This thesis presents my own original research work. Wherever contributions of others are involved, sources have been quoted and acknowledged by means of complete references.

The content of the thesis is free for everyone, but publishing must only be done with the permission of the author.

Aalborg, Denmark, August 2014

Luciano Pozzi