This study proposes an investigation of costs of different energy sources: a comparison will be made between nuclear energy, and two among the so called “renewable” energies, wind and solar power.

Nuclear energy is the energy released by the nucleus of an atom as the result of nuclear fission, nuclear fusion, or radioactive decay[1].

Nuclear power is a significant contributor to world electricity, and its role as a major source of energy supply has been undergoing a steady re-evaluation[2].

This type of energy allows to reduce green-house gas emissions and make states energetically independent. In recent years there has been a resurgence of interest in developing nuclear power as a result on volatile fossil fuel prices, concerns about the security of energy supplies, and global climate change, which is now under debate after the recent Fukushima accident;

The cost of electricity generation plants consists of three major components[3]:

- capital or construction costs
- operation and maintenance
- fuel cost.

Nuclear power also includes a fourth major components: back end one costs, those related to the decommissioning of the plant at the end of its operating life and disposal of the radioactive waste.

Given that the only fuel cost can create electricity cost volatility, atomic energy is said to be immune to fuel volatility relative to gas-fired station. For instance, a doubling in the price of uranium, would cause only a 5% increase in the total cost of generation, while the same increase in natural gas price would result in a 65% increase.

Thus, nuclear power allows to keep prices stable and predictable.

There are currently two Generation III+ reactors in constructions in France and in Finland. An international working group is researching on the development of

[1] The free dictionary website

[2] John F. Ahearne, Prospects for Nuclear Energy, *Energy Economics*, 2010

[3] World Nuclear Association, Economics of Nuclear Power, cit., p. 2, 2011

Generation IV plants, with an amazing optimization, in terms of economy and safety. They are supposed to be on-line in 2050.

As said before, nuclear is meant to be one of the promising energy sources for the next few decades, dealing with environmental issues and the uncertainty of fossil fuel supply. However , nuclear energy has some vulnerable points in the view of social acceptance [4]due to the history of its development and tremendous accidents such as Chernobyl and the recent Fukushima.

Some Korean researcher showed that, if an adequate information is provided to the public, the social value of nuclear would increase approximately 68.5%[5].

Social acceptance management is important as well as nuclear energy innovation.

Solar energy, despite being the most abundant energy resource on earth , it provides for only the 0.1% of total global electricity generation[6].

However, it is expanding very rapidly due to effective supporting policies and recent dramatic cost reductions. Photovoltaic is now an almost commercially available technology, with a significant potential for long-term growth in nearly all world regions.

This major increase was linked to the rapid growth of the German and Italian markets. With 7.4 GW installed in just one year[7], Germany, the most mature market today, the country continues to dominate the solar power market world-wide[8].

Italy installed 2.3 GW, starting to exploit some of the potential of its huge solar resources. Other countries also saw significant growth, such as the Czech Republic which rose to 1.5 GW in 2010.

Total system costs, which represent the most important barrier to solar power deployment today[9], are sensitive to economies of scale and can vary substantially depending on the type of application. Typical key prices in 2008 in leading market

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[4] A. Adamantiades, I. Kessides, Nuclear power for sustainable development, cit., p. 5152

[5] Eunju Jun and others, Measuring the social value of nuclear energy using contingent valuation methodology, *Energy Policy*, p. 1475

[6] International Energy Agency, Solar energy, Technology Roadmap, p. 5, Paris, 2010

[7] Data of 2010

[8] Data of 2010

[9] P. Denholm, R.M. Margolis, Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems, *Energy Policy* 35 (2007),2855

countries ranged from USD 4000/kW for utility scale[10], multi-megawatt applications, to USD 6000 /kW for small-scale applications in the residential sector.

Associated levelized electricity generation costs from PV systems[11] depend heavily on three factors:

- the amount of yearly sunlight irradiation
- the capacity factor
- the discount rate

Solar power systems do not have moving parts, so variable costs such as operating and maintenance (O&M) costs are relatively small, estimated at around 1% of capital investment per year[12].

There are some limits in the large scale deployment of solar energy.

The limited flexibility of base load generators, produces increasingly large amounts of unusable PV generation[13].

In theory, this technology would have the technical potential to supply all of the electricity demand in a big area, and to virtually eliminate carbon emissions from the electric power sector.

The intermittency of solar energy, however, presents critical challenges in integrating large-scale PV into the electricity grid. This intermittency ultimately may limit the potential contribution of PV to the electricity sector.

Unlike conventional generators, intermittent sources of electricity cannot respond to the variation in normal consumer demand patterns[14]. Rapid fluctuations in output can impose burdens on generators and limit their use.

Although the ability to integrate fluctuating sources is improving[15], there is a somewhat absolute limit to the economic integration of renewable energy sources

[10] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, p.62, Paris.

[11] A separate chapter will be dedicated to the levelized costs f electricty

[12] International Energy Agency, Solar energy, Technology Roadmap, cit., p. 7

[13] P. Denholm, R.M. Margolis, Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems, cit.,2855

[14] P. Denholm, R.M. Margolis, Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems, cit.,2855

[15] International Energy Agency, Solar energy, Technology Roadmap, cit., p. 30

such as solar PV, based on the fundamental mismatch of supply and demand. Only so much solar power can be integrated into an electric power system before the supply of energy exceeds the demand.

Wind power, although more competitive than solar, suffers the same limits.

Wind energy, like other power technologies based on renewable resources, is widely available throughout the world and can contribute to reduce energy import dependence, entailing no fuel price risk or constraints[16].

To give an idea of the diffusion of wind energy, in 2008, it provided for nearly 20% of electricity consumption in Denmark, more than 11% in Portugal and Spain, 9% in Ireland and nearly 7% in Germany, over 4% of all European Union electricity, and nearly 2% in the United States[17].

In 2008, more than 27 GW of capacity were installed in more than 50 countries, bringing global capacity onshore and offshore to 121 GW[18].

In contrast to the situation on land, deployment offshore is at an early stage.

This technology extracts energy from the wind by means of a horizontal rotor, upwind of the tower, with three blades; today's offshore wind turbines are essentially marine versions of land turbines with, for example, enhanced corrosion protection[19].

A turbine lifetime is ranging between 20 and 25 years[20].

An important difference between wind power and conventional electricity generation is that wind power output varies as the wind rises and falls. Thus wind power is dependent on climate issue as well as solar power.

The key elements that determine the basic costs of wind energy are:

- Upfront investment costs, mainly the turbines
- The costs of wind turbine installation
- The cost of capital, i.e. the discount rate
- Operation and maintenance (O&M) costs
- Other project development and planning costs

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[16] International Energy Agency, Wind energy, Technology Roadmap, cit., p. 6, 2010
[17] International Energy Agency, Wind energy, Technology Roadmap, cit., p. 8, 2010
[18] International Energy Agency, Wind energy, Technology Roadmap, cit., p. 8, 2010
[19] International Energy Agency, Wind energy, Technology Roadmap, cit., p. 9, 2010
[20] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p.43

– Turbine lifetime
– Electricity production, the resource base and energy losses[21].

Approximately 75% of the total cost of energy for a wind turbine is related to upfront costs, such as the cost of the turbine, foundation, electrical equipment, grid-connection and so on. All those costs which are considered to be fixed[22].
Obviously, fluctuating fuel costs have no impact on power generation costs. Thus a wind turbine is capital-intensive compared to conventional fossil fuel technologies such as a natural gas power plant, where as much as 40-70% of costs are related to fuel and O&M.

After having presented main features of nuclear energy, solar and wind power, the analysis of economic aspects of these sources will be presented, as well as their competitiveness.

The notion of levelised cost of electricity is a fundamental tool to compare the costs of different technologies over their economic life[23]. Comparing it with a different economic area, it would correspond to the financial cost of producing a certain amount of electricity, assuming the certainty of production costs and electricity stability. It is an average cost of producing electricity including capital, finance, owner's costs on site, fuel and operation over a plant's lifetime, with provision for decommissioning and waste disposal[24]. Therefore, the discount rate used in the calculation of LCOE reflects the return on capital for an investor.
without any specific market risks[25].
Given that, on the contrary, specific market and technology risks do exist, a gap between the results found by the formula below and the actual cost of an investor operating in real electricity markets must verify. Uncertainties and risks are not completely foreseeable. Some structural determinants, such as non-storability of

[21] The European Wind Energy Association, The Economics of Wind Energy, cit., p. 29
[22] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p.40
[23] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 34
[24] World Nuclear Association, *The Economics of Nuclear Power*, p. 5, 2011
[25] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 34

electricity, peaks and variability of daily electricity demand or eventually seasonal variations, spot prices allow prices to fluctuate[26]. Even though there are some strong assumptions in the construction model of this unit for electricity costs comparison, it must be specify that LCOE remains the most transparent consensus measure of generating costs, and is widely used tool used in modeling and policy discussion[27].

The calculation of the LCOE is based on the equivalence of the present value of the sum of discounted revenues and the present value of the sum of discounted costs.

Therefore, if the electricity price results equal to le levelised average lifetime costs, an investor would precisely break even on the project.

There are some important assumptions to have this equivalence:

- the interest rate "r" used for discounting both costs and revenues is stable over the period of the production, meaning that it does not vary during the project lifetime.
- the electricity price, indicate as "P electricity" is stable too, and does not change during the lifetime of the project.
- all output once produced, is immediately sold at that price
- variables are 'real' so net of inflation.

The results presented by the study below will depend on a 5-10% interest rate.

LCOE is equal to the price of electricity found in the following equation:

$$P_{electricity} = \Sigma_t ((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t) * (1 + r)^{-t}) / (\Sigma_t (Electricity_t * (1+ r)^{-t}))$$[28].

[26] For these reasons, LCOE calculation and results are very closer to the real cost of investment in electricity production in regulated monopoly electricity markets with loans guarantees and regulated prices rather than to the real costs of an investment in competitive electricity markets with all the uncertainties described above at the same time.

[27] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 33

[28] The different variables in the equation are[28]:

- $Electricity_t$: the amount of electricity produced in year "t" ;

Results show that:

- overnight costs for the new nuclear power plants under consideration in the OECD area, vary substantially across the countries, ranging from as low as 1556 USD/kWe[29] in Korea[30], to as high as 5863 USD/kWe in Switzerland, with a mean of 4055 USD/kWe[31].
  Reported load factor is on average 85%[32].
- the data for wind show a very wide range, with overnight costs ranging from 1821 USD/KWe in France to 3716 USD/KWe Switzerland. Reported load factors range from 20% to 41%.
- the range of overnight costs for the offshore wind projects is from 2540 USD/KWe to 5554 USD/KWe. Load factors range from 34% to 43%.
- for solar power, capacities range from 0.002 MWe, for roof panels, to 20 MWe for industrial usage; load factors range from 9.7% in the Netherlands to 24.9% in France[33]. Overnight costs exhibit a range from as low as 3067 USD/KWe for a utility-scale solar photovoltaic farm in Canada to 7381 USD/KWe in the Czech Republic.

- $P_{electricity}$: the constant price of electricity;
- $(1+r)^{-t}$: the discount factor for year "t"
- $Investment_t$: investment costs in year "t"
- $O\&M_t$: operations and maintenance costs in year "t"
- $Fuel_t$: fuel costs in year "t"
- $Carbon_t$: carbon costs in year "t"
- $Decommissioning_t$: decommissioning costs in year "t"

[29] Kilowatt of electric capacity

[30] noting the generally low construction costs in that country, as well as its recent experience in building new reactors

[31] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 50

[32] The load factor is an important performance indicator measuring the ratio of net electrical energy produced during the lifetime of the plant to the maximum possible electricity that could be produced at continuous operation

[33] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 56

At 5% discount rate nuclear is comfortably cheaper than coal and gas in all countries. At 10% discount rate, nuclear is still cheaper than coal in all but the three EU countries[34].

Also, investment cost becomes a much greater proportion of power cost than with 5% discount. At a 10% discount rate, coal is sometimes cheaper than nuclear, like in Belgium and in the Netherlands. Only in the United States, on-shore wind seems to be cheaper than nuclear.

The results of LCOE shows that renewable energies are not yet competitive with respect to traditional sources and the atomic energy.

Large hydroelectric, biogas, and on-shore wind are sporadically as efficient as nuclear power.

On-shore wind is for sure the cheapest energy source among all the renewable types. Its technology needs some improvements but is already well-performing.

It would be attractive to make the off-shore wind turbines cheaper, because they have a much higher capacity.

Unfortunately, they are, nowadays, one of the most expensive technology in the industry.

Afterwards, the sensitivity test allows a cost driver analysis :

- the economics of nuclear energy are largely dependent on total investment costs, which are determined by both construction cost and the discount rate.
- at a 5% discount rate, the key driver of the LCOE of nuclear power is construction costs, while at 10%, discount rates have a larger impact on the LCOE than any other parameter[35]
- a reduction in lead time also has a significant impact on total costs, in particular at a 10% discount rate due to increased interest during construction
- nuclear fuel has a minor impact
- the levelised costs of electricity produced with onshore wind and solar photovoltaic technologies exhibit a very high sensitivity to load factor variations, and to a lesser extent to construction costs, at any discount rate

[34] World Nuclear Association, *The Economics of Nuclear Power*, cit, p. 7, 2011

[35] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 107

- construction cost is the second most important parameter affecting the competitiveness of renewable plants[36]
- given the short construction times and relatively modest up-front investment compared to other generation plants, all the interests paid represents a relatively minor cost component and, despite the high capital-cost ratio, lead times become the least important cost driver for these technologies at both discount rates.

It has been showed that nuclear power, although expensive at the beginning, is already a self-sustaining source of energy, while many renewable energies, such as solar and off-shore wind are not yet competitive in free-markets. If the social, health and environmental costs of fossil fuels were also taken into account[37], the economics of nuclear power would consequently outstand its "rivals".

Furthermore, nuclear energy is a large scale base load technology, with an average capacity per reactor of 800/1000 MWe, while renewable energies are not, yet.

Wind and solar power cannot serve for base load demand because their operating mechanisms severely depend on climate issue.

Consequently a first question may arise: " Are renewable energies the real competitors of nuclear energy? "

So far, it emerges that they are not.

From an economic perspective, nuclear energy is much more similar to gas and coal energy, rather than to wind and solar power. Gas plants operate from a minimum cost of USD 57.75/ MWh in Russia, (with except for China which is far below the standard costs for both nuclear and gas) to a maximum level of USD 105/MWh (USA, Switzerland) or USD 119/ MWh (Japan).

Instead, electricity from coal is produced at a minimum cost of USD 70-85/MWh in Germany and at a higher level in some sites in Czech Republic or Belgium[38].

[36] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 111

[37] Denholm Paul, Margolis Robert. *Evaluating the limits of solar photovoltaic in traditional electric power system*, 2007. Energy Policy,35, p. 2855

[38] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 60

Although nuclear and renewable sources share the same cost structure, wind and solar LCOE is today too far from the cost of nuclear. This is due especially to the high load factor variation and the short operating lifetime of the plants.
The main research question of the Thesis has been whether nuclear is needed in Italy or not.
Italy largely depends on sources not produced in house, gas (40.3%), oil (42%) and coal (9.4%), which lead to a dramatic dependence on suppliers.
The country produces small volumes of natural gas and oil but the majority of fossil fuels are imported[39]. Dependence on imports is widely increasing and accounts for almost 90% of TPES.

Concerning electricity production, Italy utilizes mainly oil, gas and coal, practically all imported[40]. In 2009, gross electricity generation in Italy was 290 billion kWh. Of this, 146 billion kWh (50%) was from gas-fired generation; 43 billion kWh (15%) from coal; 28 billion kWh (10%) from oil; and 51.7 billion kWh (18%) hydro.

Most of the renewable energy production is represented by hydropower and geothermal. We are using potential of this type already at their maximum.
Solar is nowadays increasing over the total amount of electricity produced and can be widely exploited as well as wind power.
The levelised cost of electricity of on-shore wind is higher than the average G8 and Europe countries, ranging from a 145.50 USD/MWh at a 5% discount rate, to 229.97 USD/MWh, at a 10% discount rate.
This high level is mainly due to a higher investment cost, which include both the overnight cost and the implied interest during the construction.
Germany, France, Canada and the United States, produce electricity from on-shore wind turbine in a more efficient way[41]:

- France: USD 90.20/MWh – USD 121.97/MWh
- Germany: USD 105.81/MWh – USD 142.96/MWh

[39] International Energy Agency, Energy policies of IEA countries: Italy Review, p. 16, Paris, 2009
[40] S. Esposto, The possible role of nuclear Energy in Italy, p. 1584, *Energy Policy*, 2008
[41] International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity*, cit., p. 62

- USA: USD 48.39/MWh – USD 70.47/MWh
- Canada: USD 99.42/MWh – USD 139.23/MWh

As explained earlier on, solar power is largely the most expensive source, among the so called renewable sources; this gap is even more dramatic in Italy, where, although the solar industry is experiencing a fast growth, it cannot survive without public incentives.

Its levelised cost of electricity ranges from a low level of USD 410.36/MWh, to a high level of USD 615.98/MWh.

In others country, even though solar is not a cheap generation, the LCOE is under our level:

- France: USD 286.62/MWh – USD 388.14/MWh
- Germany: USD 304.59/MWh – USD 439.77/MWh[42]
- USA: USD 215.45/MWh – USD 332.78/MWh
- Canada: USD 227.37/MWh – USD 341.72/MWh[43]

Electricity production from solar power is more expensive in Italy than elsewhere because of a high cost of investment that producers have to face.

This means that the industry must be sustained by subsidies as long as prices fall.

The wind energy industry is much more competitive than the solar one, although we have a greater potential of sun.

Our main issue is that we cannot substitute fossil fuels completely with renewable energy sources.

To give an example of the infrastructure needed, for covering the whole national electricity energy demand, 0.8% of the Italian soil should be covered by photovoltaic systems, a total surface of 2410 km^2.

There are two different strategies to increase the penetration of intermittent energy source inside a grid, from a 10–20% penetration up to a theoretical 50%, without affecting its stability: load shifting and energy storage[44].

[42] Data refer to an ' open-space' solar irradiation, which costs less than a roof installation

[43] Data refer to industrial installation

The economic and technical constraints became harder to overcome with the present technology. Moreover, the penetration percentage is linked to the flexibility of the overall electricity production, and the introduction of intermittent renewable energies with shares more than 20% would deeply transform the existing system.

The storage solution is the most interesting but is also the most limited one from a technical point of view. Electricity storage is not considered for large systems due to the limits of battery systems[45].

A possible scenario mixing wind and PV for increasing the share of electricity produced by renewable energy is possible, and must be considered for the future.

Nonetheless, renewable sources has got fundamental limits to a large scale implementation.

Wind and solar technology, at the current state of technology, has got some main limits:

- limited coincidence between electricity generation and normal demand[46][47]
- high flexibility factor
- prohibitive costs due to an overall immaturity of the sector
- they cannot serve as base load technology

The amount of usable photovoltaic and wind energy is largely determined by the flexibility of the existing electric power system to vary load.

System flexibility is defined as the fraction below annual peak to which a conventional generation fleet may reduce output[48].

Researchers suggest that when the load drop below the 30% of the annual peak, wholesale electricity prices often drop below the actual variable costs of producing electricity[49].

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[44] P. Denholm, R.M. Margolis Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies, *Energy Policy* (2007), 4424

[45] . Esposto, The possible role of nuclear Energy in Italy, cit., p. 1585

[46] P. Denholm, R.M. Margolis, Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems, cit.,2855

[47] For solar power, there is considerable coincidence between solar insolation and normal demand in the summer, there is less coincidence during other months

[48] P. Denholm, R.M. Margolis, Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems, cit.,2856

This would imply that generators are willing to sell electricity at a loss in order to keep plants running.

Italian energy mix is definitely unbalanced toward expensive or polluting sources.

I would like to suggest main reasons to rethink properly the nuclear option.

First of all, there is an economic purpose.

G8 and others European countries, have lower electricity price[50], both for the household use and the even more important industrial use; the levelised cost of electricity is lower for nuclear than for others base load electricity sources.

Secondly, there is strategic purpose which can be explained by:

- economic diversification of the energy sector
- creation of a new industry.

Moreover, there is the need to diversify our suppliers.

Nuclear energy can substitute the base load energy production in the Italian system[51].

In the end, the need to avoid climate change and the need to replace traditional crude oil as the basis of our transport system[52].

Radical changes in our energy system will be required to meet these challenges, which may require tight coupling of different energy sources: nuclear, fossil, and renewable.

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[49] P. Denholm, R.M. Margolis Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies, cit., p. 4425

[50] As demonstrated in chapter 3 and 4.

[51] S. Esposto, The possible role of nuclear Energy in Italy, cit., p. 1586

[52] C.W. Forsberg, Sustainability by combining nuclear, fossil and renewable Energy sources, cit., p 192

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