Evaluation of a potential reintroduction of nuclear energy in Italy to accelerate the energy transition

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Abstract

Nuclear energy was adopted in Italy in the past to deal with the insufficient fossil fuels on the national territory. After a public vote subsequent to the Chernobyl accident, Italy abandoned the use of nuclear energy and nowadays adopts a mix of fossil fuels and renewable energy sources for electricity production. However, the urging environmental pollution and climate change issues are forcing Italy to realize a so-called "energy transition" towards a more sustainable energy production and consumption system. In this framework, following the examples of other countries, it could be re-evaluated the adoption of nuclear to reduce the consumption of fossil fuels. In the present paper, it is presented an overview of the nuclear energy history in Italy and the current and projected electricity demand and supply. Then, with reference to the Italian framework and policies, the main advantages and disadvantages of a hypothetical reintroduction of nuclear energy are presented. The analysis shows that the adoption of nuclear energy would bring several advantages in terms of lower emissions, higher security of supply and enabling of possible other technologies; the main disadvantages are related to the opposing public opinion and the nuclear waste management.

Keywords: Nuclear energy; Italian energy mix; Energy demand and supply; Energy sources; Energy transition

1 Introduction

Environmental pollution and climate change are challenging and urging issues. Several organizations are emphasizing the need to reduce the pollutant and Green House Gases (GHG) emissions to limit the effects on the environment and people (IEA, 2019), (IPCC, 2011), (United Nations, 2016). The energy sector is one of the most relevant in terms of emissions. In this framework, the energy demand is rising (Enescu et al., 2019) due to the increase of the worldwide population and the economic growth of several countries.

Therefore, there is the need of an "energy transition" towards a more sustainable energy system. A system is sustainable if it can survive or persist for a time scale consistent with its spatial scale or, in other words, if it can persist in a nominal state at least as long as it is naturally expected (Costanza and Patten, 1995). The three pillars of sustainability are economy, environment and society and all these aspects should be adequately considered.

An energy transition occurred in 1700 with the shift from biomass to fossil fuels (Solomon and Krishna, 2011). Another energy transition, more related to the consumption, could be identified at the beginning of 1900 with the massive electrification of several countries. Energy transitions could also be classified by source (from biomass to coal, then oil and finally gas) or technology (from steam engine to internal combustion engine and then to electric motor). Now another energy transition is required to increase the sustainability of the energy sector. While the previous transitions were very slow, this transition should be much faster (Solomon and Krishna, 2011) but it is proceeding quite slowly (Di Giulio, 2020).

At the beginning of the new millennium, "Renewables" Energy Sources (RES) were considered the solution to cope with the energy demand and reduce emissions. Several countries invested huge amount of resources on RES, through financial support based on the capacity and energy produced. Now, the limits of this policy are emerging, in particular the increased energy cost and the lack of significant reduction of pollutant and GHG emissions (Bethge, 2020).

Also nuclear energy has the potential to reduce the dependency on fossil fuel and the emissions. Nuclear fission started to be adopted for civil purposes after 1953, with the "Atoms for Peace" program, and at that time and during the Oil Crisis in the '70 it was seen as a possible source of almost unlimited energy (Bradshaw et al., 2011), (Bornschein et al., 2013). However, the support to nuclear energy has been significantly reduced following the three major nuclear accidents: Three-Miles Island (1979), Chernobyl (1986) and Fukushima-Daiichi (2011). In Italy the use of nuclear power was abandoned after a public vote in 1987.

The current environmental situation is forcing several organizations (e.g. IEA, IPCC, UN), to reconsider the use of nuclear energy as a low-carbon technology. In addition, some nations are showing the advantages of having nuclear in their energy mix, alongside with RES. Conversely, other industrialized countries are still largely dependent on fossil fuels, and this does not allow a significant reduction of the emissions.

The Italian public opinion is still opposing nuclear energy. However, the urging climate issues may force to reconsider it, as a low-carbon energy source. The present paper exposes the main advantages and disadvantages of a possible reintroduction of nuclear energy in Italy.

2 Historical overview of nuclear energy in Italy

The relationship between nuclear energy and Italy has always been thigh. The group of "Via Panisperna", led by Enrico Fermi, conducted pioneering researches in the '30 in nuclear science. Then Fermi moved to the US where he became fundamental for the exploitation of nuclear energy. Indeed, Fermi directed the team that realized the first human-made self-sustaining nuclear chain reaction (1942).

With the Atoms For Peace program, Italy embraced the use of nuclear energy for civil purposes (Bini and Londero, 2017). This was due to the lack of large fossil fuel resources on the national territory; therefore, the use of nuclear energy was considered the best option to increase the country energy independence.

At the beginning of the '60 three Nuclear Power Plants (NPP) were built in Italy: a Gas-graphite Magnox reactor (155 MWe), a dual-cycle Boiling Water Rector (BWR) (160 MWe) and a Pressurized Water Reactor (PWR) (260 MWe). In 1964-1965, Italy was the third nation worldwide for installed nuclear capacity. Trino PWR was the most powerful NPP worldwide between 1964 and 1966 and held the record for the longest full-power operation period (322 days). A fourth NPP, a BWR with around 860 MWe, was built in the '70.

The Chernobyl accident caused a strong opposition of the public against nuclear energy. In 1987, Italians voted on three questions against nuclear energy. Even if the questions were not explicitly whether to abandon nuclear energy or not (but related to the localization process for NPP and the participation of Italian companies on projects abroad) for political reasons it was decided to abandon the use of nuclear energy. At that moment, three units were still in operation, two BWRs (982 MWe each) were under construction and the executive plan of two PWRs (950 MWe each) was approved. The PWRs were based on the PUN (*Progetto Unificato Nucleare*) and eight additional units were planned in different sites (DIR-PUN, 1986).

At the beginning of the new millennium, considering environmental, economic and security aspects, the nuclear energy option came back in the political debate. A new public vote was scheduled for June 2011, but the occurrence of the Fukushima-Daiichi accident on March 2011 contributed to convince the large majority to vote against nuclear energy.

3 Energy demand and supply in Italy

3.1 Overview of the actual energy demand and supply

In 2017, Italy registered a gross domestic energy consumption of 159.5 Mtep and a final energy consumption of 113.3 Mtep (Terna, 2019), considering the energy product provided to industry, transport, agriculture and services sectors. Figure 1 shows the weight of each energy source on the final energy consumption.

In 2017, electricity covered more than 22% of the final energy consumption. Despite in the last years the demand of electricity slightly reduced as a consequence to the economic crisis of 2008 and energy efficiency improvements, the share of electricity on the final energy consumption is increasing. This is due to a higher electrification of some sectors, such as electric vehicles, the increase energy demand for air conditioning, etc. The installed electric capacity in 2017 was about 112 GW (Terna, 2019). Figure 2 displays the amount of installed capacity for the different technologies.

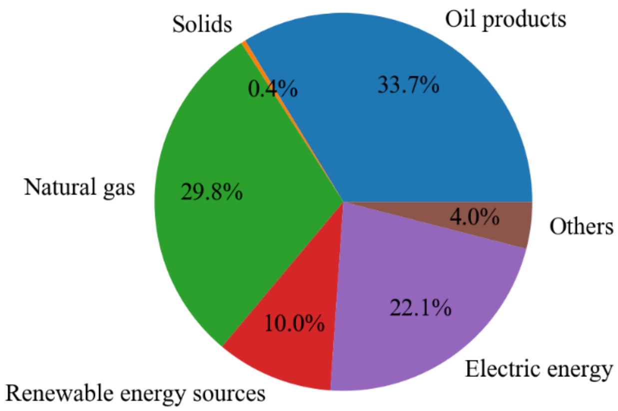

Figure 1 Final energy consumption

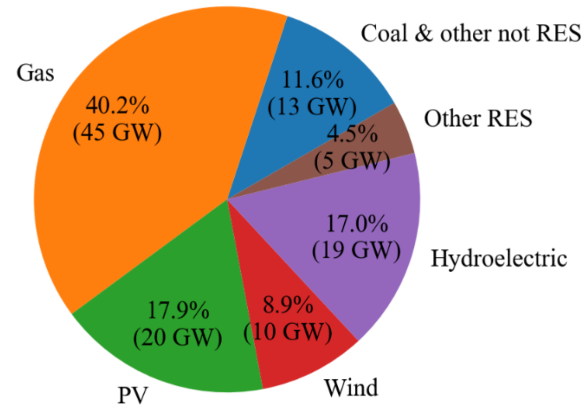

Figure 2 Installed electric capacity by source

Considering the thermoelectric sector, in the 2000s there was a capacity increase of 10 GW with a gradual switch from oil to natural gas, which now covers almost the 73% of the total thermoelectric capacity. Despite that from 2025 there should be the phase out of coal, it is still relevant with a capacity of 7.9 GW. The increase of natural gas is related to the replacement of traditional plants with Combined Cycle Gas Turbine having a high conversion efficiency (Terna, 2019).

Regarding RES, starting from 2009 there was a significant increase of wind and photovoltaic (PV), with the latter that now is the first source in terms of capacity, even higher than hydroelectric, which has always been massively exploited in Italy and that remained almost constant in the last period.

In 2017, the total electricity consumption was 332 TWh, with the 88.6% (294 TWh) covered by domestic production and the 11.4% (38 TWh) covered by net import from foreign countries (Terna, 2019). Figure 3 shows the amount of electricity produced by the different technologies.

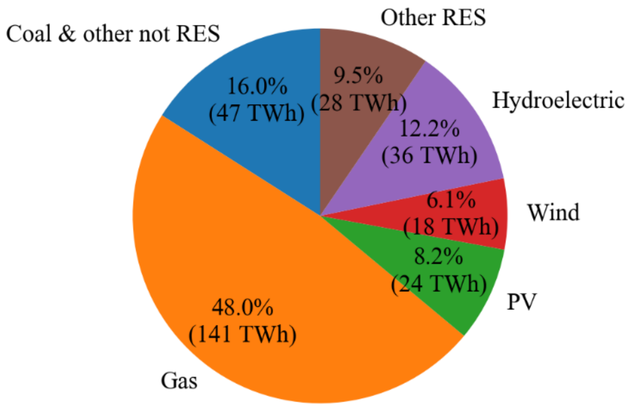

Figure 3 Electricity production by source

The electricity production in Italy is still strongly dependent on the thermoelectric sector (64% of the total generation). Concerning RES, the energy production is more than doubled in the last decade, thanks to the relevant increase in PV. Nevertheless, a reduction in the energy production has been recorded in the last 3 years, mainly because of a drop in the hydroelectric sector. This is mainly related to a reduction of the rainfall and therefore of the hydroelectric production and, starting from 2000, to a reduction of -72.6% in the production from the pumped-storage hydropower (PSH). This is due to the reduction of the differential pricing of electricity between day and night. In fact, usually the production from PSH is convenient if the sale price is 1.4 times the purchase price (Terna, 2019).

The capacity of coal and wind are quite close but the energy production from coal is considerably larger: this is related to the different Utilization Factor (UF) of each technology. For the same reason, despite the solar capacity is about 1.5 times larger than coal one, the total production from solar is about half of the production from coal. Table 1 reports the UF in 2017 in Italy for the different technologies.

Table 1 2017 UF for energy source in Italy according to actual capacity and production

	Coal & other not RES	**Gas**	**Solar**	**Wind**	**Hydroelectric**	**Other RES**
UF	41.3%	35.8%	13.7%	20.5%	21.6%	63.9%

For RES the UF is related mainly to the availability of the energy source while for coal and natural gas the UF is more related to the balance between the demand and supply of electricity. Considering hydroelectric power and PSH, the UF is also related to technological aspects since this source can be used to regulate frequency and voltage of the grid. Finally, the amount of electricity imported is high, covering 11.4% of the total consumption in 2017, mainly from France and Switzerland.

3.2 Overview of the projected energy demand and supply

In 2019, Terna, the Italian transmission system operator, presented three scenarios to forecast the future trends of energy demand and supply up to 2040 (Terna, 2019):

- Business-As-Usual (BAU): it is based on the actual trend and is characterized by technological switch mechanism of the type technology-driven based on economic merit (i.e. a better technology is adopted only when it is economically convenient);
- Centralized (CEN): it is characterized by technological switch mechanism of the type technology-pull (i.e. the diffusion of new technologies is subject to the achievements of specific targets). The scenario is based on a sustained economic growth aimed to reach the 2030 targets shown in the *Clean energy for all Europeans* (European Union, 2019);
- Decentralized (DEC): it also reaches the 2030 targets of the *Clean energy for all Europeans.* In the DEC scenario it is expected a greater development of decentralized generation systems (like PV together with small-scale electrochemical storage system) and a higher electrification of the final energy consumption (e.g. electric heat pumps).

Figure 4 shows the forecasts of the capacity. In all the scenarios, the total capacity is expected to grow, with an increase of more than +50% in 2040 for the DEC scenario. The PV is the source with the higher growth; wind capacity is expected to almost double by 2040 in all the scenarios while hydroelectric remains almost constant. The increase of RES capacity requires more flexibility in the electric grid management; thus, in all the scenarios there is the need to maintain the capacity of programmable thermoelectric plants at least equal to 50 GW. Also in the scenario with the higher RES capacity (DEC in 2040), 28.9% of the total capacity will be covered by thermoelectric plant.

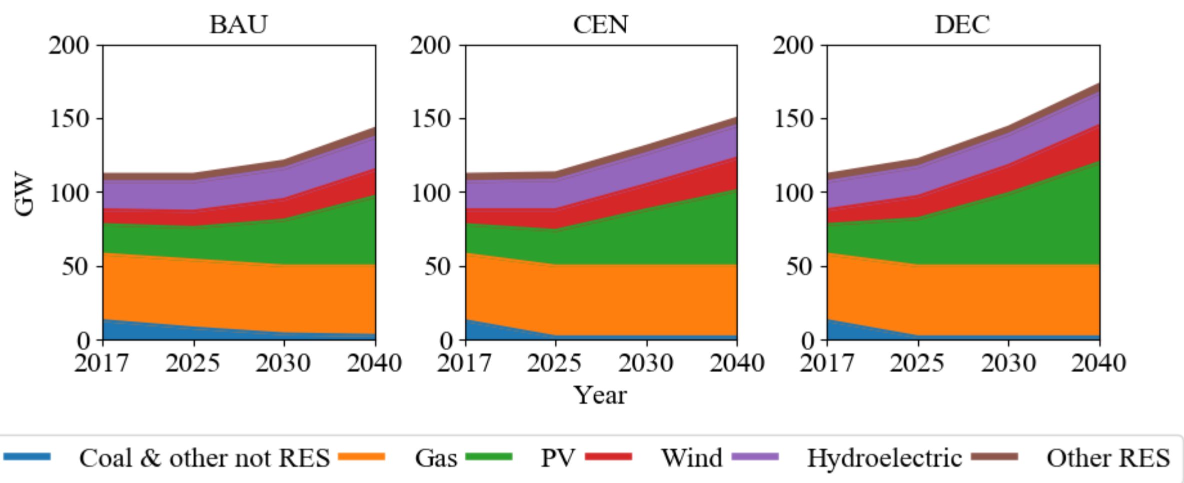

Figure 4 Forecasted installed capacity for the three scenarios considered (Terna, 2019)

Figure 5 shows the evolution of the electricity generation for the different scenarios. In the BAU scenario, thermoelectric remains the main energy source covering more than 50% of the production. The production from RES increases but it is not sufficient to reach the targets expected by 2040. Concerning CEN and DEC scenarios, the production from gas is almost constant, with a slight increase in 2025 due to the phase out of coal (Terna, 2019).

For all the scenarios, the hydroelectric production is expected to double despite the capacity remains almost constant. For the other RES, the availability of the sources is responsible for the difference between the capacity and the energy production: for this reason in DEC scenario, by 2040 more than 40% of the electric capacity is covered by PV but the production is about 25%.

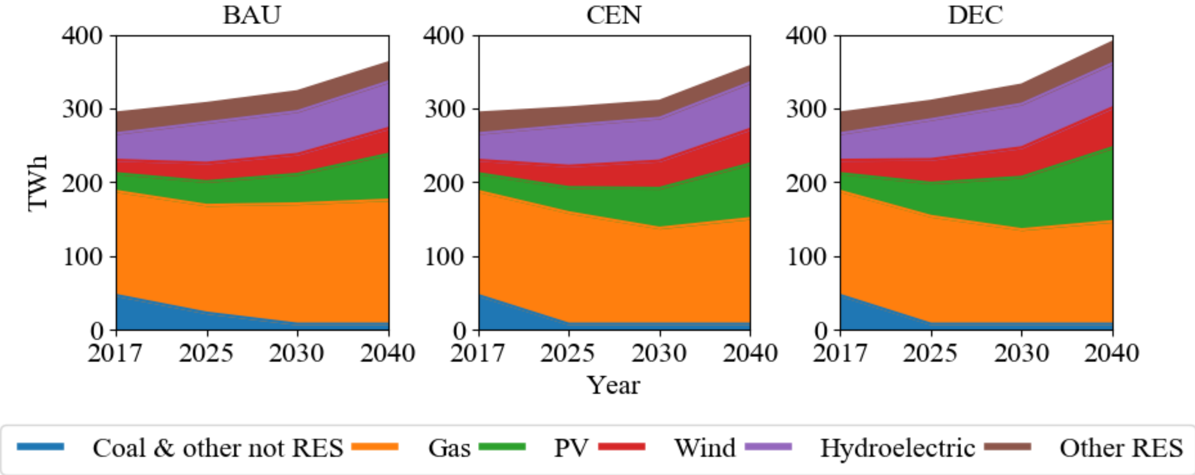

Figure 5 Forecasted electricity generation for the three scenarios considered (Terna, 2019)

3.3 Relevant issues

In Italy the electricity sector is strongly dependent on coal and natural gas, even if a great effort has been done to increase RES. In all the scenarios an increase of the electricity consumption is expected. Natural gas plays a crucial role in the energy balance with respect to the targets. In the BAU scenario the production from gas increases also if the capacity remains constant. In the CEN and DEC scenarios, the production from thermoelectric is respectively almost constant and reduced; to reach the *Clean energy for all Europeans* targets, it is expected a gradual switch from natural gas to biomethane and the adoption of carbon capture system. The DEC scenario is the one that shows the higher share of production from RES: however, the massive adoption of not programmable RES and the switch from concentrated utility-scale systems to decentralized systems require great investments to develop flexible electric grids.

The achievement of the emission targets requires a wide diffusion of high efficiency technologies (e.g. heat pumps, etc.). However, a not negligible issue is that, regardless of the considered scenario, the cost of electricity it is expected to increase.

4 Advantages and disadvantages of nuclear energy in the Italian framework

From the previous analysis emerges that a large share of a programmable and dispatchable energy source will be required for backing up the growing RES. In all scenarios this source is gas that, even if cleaner than coal, releases emissions; additionally, the majority of natural gas is imported with a strong dependence on foreign countries. The only large, dispatchable and carbon-free source is nuclear. The present section shows the advantages and disadvantages of nuclear energy, with a focus on the Italian framework.

4.1 Advantages

4.1.1 Emissions

Nuclear releases very low emissions, considering both the construction and operation of NPP. Many studies analyzed causal links between nuclear energy consumption and CO_2 emissions finding that increasing nuclear consumption could actually decrease CO_2 emissions, while there seems to be no such a strong correlation between RES and CO_2 emissions (Kojo and Wolde-Rufael, 2010), (Hiroki et al., 2010), (Jungho, 2015).

Italy is significantly affected by the emissions issue, both considering air pollution by Particulate Matter (PM) and possible effects of climate change. For instance, in 2018 an unusually violent storm irreparably destroyed forests in the northeast. In 2019, Venice got the highest flooding since 1966. Pianura Padana, the most industrialized and populated area of Italy, is also one of the most polluted areas of Europe (Squizzato et al., 2013), (Bigi et al., 2014), (Finardi et a., 2014). Turin and Milan are the most polluted cities in Europe and experience increase in the incidence of pollution-related diseases and mortality (Migliaretti et al., 2007), (Giovannini et al., 2010), (Santus et al, 2012), (Bono et al., 2016). Recently it has been highlighted a possible relationship between the spreading of the COVID-19 infection in the north of Italy and the PM10 present in the air (Setti et al., 2020).

Italy alone could not solve the problem of climate change, since it accounts for less than 1% of the total GHG emissions worldwide (Croshaw, 2015), (Muntean et al., 2018), (Fracciascia et al., 2019). Nevertheless, reducing the emissions would certainly decrease the air pollution observed in the northern regions and in other large cities. Table 2 lists the pollutant emissions for some energy sources over their entire life-cycle (Rashad and Hammad, 2000). Nuclear shows emissions lower than coal, as expected, but also than solar, since the production of PV panels is a polluting operation (Fthenakis et al., 2011).

Table 2 Pollutant emissions for some energy sources (Rashad and Hammad, 2000)

Emissions [kg/GWh]	Wind	Solar (PV)	Coal	Nuclear
CO2	$7.5 \cdot 10^4$	$2.79 \cdot 10^5$	$1.26 \cdot 10^6$	$3 \cdot 10^4$
SO2	10.9-23.5	300-380	704-709	33-50
NO_X	16.0-34.2	300-380	717-721	64-96
Dust	2.0-4.3	60-80	150	6-8

In life-cycle assessments, emissions coming from both the fuel cycle (extraction, processing, transportation and usage) and the plant cycle (design, construction, operation and dismantling) should be considered. In the nuclear sector, the plant decommissioning and the spent fuel/waste management are accounted in the life-cycle assessments. Fossil plants do not require particular actions on their wastes, as they are mainly released in the atmosphere. RES require a huge amount of material for the structures (e.g. wind turbines) and for the chemicals (e.g. PV) that need to be produced and disposed. For instance, Fthenakis et al. 2011 state that for the 3.5 MW Tucson Electric Power (PV) around 164 tons of material per MW was necessary. Similar studies show that wind turbines up to 3 MW need more than 1000 tons of material each (Crawford, 2009), (Martinez et al. 2009a), (Martinez et al. 2009b). Conversely, a 1500 MWe ESBWR (Economic Simplified Boiling-Water Reactor) needs about 5100 tons of steel and 105000 m^3 of concrete (Peterson et al., 2005). The amount of material adopted is approximately 200 kg/MWe, at least three orders of magnitude lower than the two examples of RES mentioned.

Because of these differences among fossils, nuclear and RES, emissions analysis over the whole life-cycle of a plant is more effective than just the ones during operation. Several studies showed that nuclear is significantly less polluting than fossil fuel and solar, being comparable to wind (Rashad and Hammad, 2000), (IPCC, 2011).

Figure 6 shows the minimum, maximum and median lifecycle GHG emissions for different sources. Biomass has a negative minimum due to the CO_2 absorbed by the plants during their growing. Natural gas, oil and coal present the highest emissions. Nuclear has a median value comparable to Concentrated Solar Power (CSP), wind and hydro, even lower than PV.

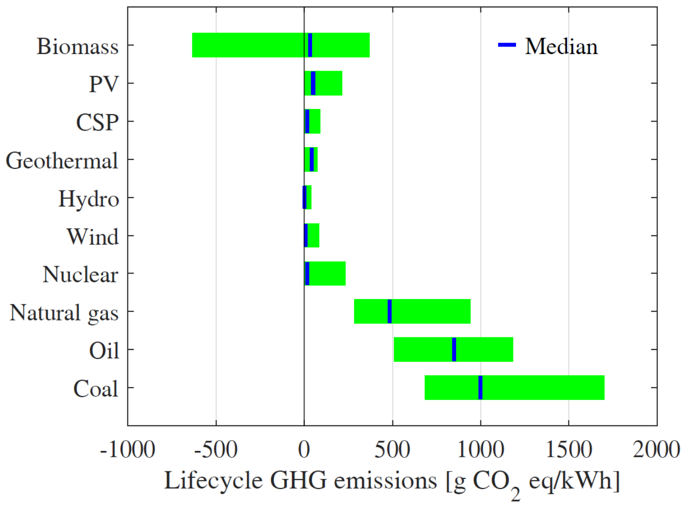

Figure 6 Lifecycle GHG emissions by energy source (IPCC, 2011)

4.1.2 Energy density

Nuclear reactions allow energy density of nuclear fuel to achieve overwhelming values with respect to fuels based on chemical reactions. Table 3 lists the energy densities of some sources.

Table 3 Energy density of some energy sources (Hore-Lacy, 2006)

Fuel	**Uranium**	**Wood**	**Crude oil**	**Natural gas**	**Diesel**	**Coal**
Energy density [MJ/kg]	3900000	16	44	55	45	24

Of particular interest are natural gas and coal, having large shares in the Italian electricity production, and uranium. Nuclear requires orders of magnitude less fuel to produce the same amount of energy than gas and coal. The higher energy density can be directly translated in minor volumes of fuel to be mined and transported and less wastes.

For RES, it can be considered the energy density in terms of land footprint. A 1000 MWe nuclear or fossil power plant occupies approximately 1-4 km^2 of land; this is one-to-two orders of magnitude lower than RES. In fact, solar requires around 20-50 km^2 of land for the PV panels, while windfarms need roughly 50-150 km^2 for the same capacity (Rashad and Hammad, 2000). Considering the Italian situation this has a significant impact. Almost all the national territory, with the exception of the mountain regions, is already heavily exploited by agriculture and industry, and a massive installation of solar farms will create issues of land usage. Considering onshore windfarms, similar issues are present, while for offshore installations, the large majority of the coastal areas is exploited for tourisms or comprises protected natural resources (Falcucci et al., 2007).

4.1.3 Dispatchability

Dispatchability is the capability of an energy source to be exploited when needed, considering the demand, which varies throughout the day and seasonally. In a heavily industrialized country, such as Italy, it is necessary to produce electricity 24/7. Several structures cannot afford losing electricity (e.g. industries, hospitals etc.) because of the risk of loss of income or population health issues.

Currently, nuclear is the only viable carbon-free option to substitute fossils fuels as backup for RES. It can provide electricity regardless of external factors like time of the day, position of the site or weather. NPP unavailability is rare and usually caused by scheduled refueling and outages. RES, because of their intrinsic dependence on external factors, are somehow random producers of electricity. This could cause instability of the grid and the need of large-scale energy storage. However, over a certain amount of RES penetration, large energy storage seems to be not cost-effective, in particular in deregulated markets (Denholm et al., 2010), (Fertig and Apt, 2011), (Figueiredo et al., 2006).

Countries that adopted nuclear as baseload show significantly lower emissions than other large industrialized nations (MIT, 2018). There are also few countries with a significant share of their baseload from RES, but the instances are limited to low populated countries that are geographically favored for hydroelectric and geothermal production. Nonetheless, this is not the case of the most of industrialized countries. Italy already takes advantage of hydroelectric and geothermal, but it is also forced to rely on coal, gas and to purchase energy from abroad.

Researchers are attempting to solve the problem of low UF of RES. A partial solution is the adoption of energy storage systems, such as mechanical storage (Chesnokov et al., 1999), thermal storage (Sharma et al., 2009), electrochemical (Yang et al., 2011) and chemical storage (Aho et al., 2012). Nevertheless, such promising technologies show some downsides. Firstly, storage systems are in general low efficient (Kaldellis et al., 2007), (Gatta et al., 2015); most of them rely on mature technologies, meaning that future efficiency increase by technical improvements can only be marginal. Secondly, energy storages require a huge amount of additional materials for the construction of the system and are in general not compact. The amount of materials, low efficiency and use of rare materials bring to a low economic competitiveness and high life-cycle emissions on large scale.

Recalling the future scenarios, natural gas is the main backup for the high penetration of RES. Nuclear could be a precious alternative since it provides both low-emission and high availability. If historically nuclear has been considered mainly a baseload source, the new Small Modular Reactors (SMR) can be used also for load-following (MIT, 2018). This makes nuclear complementary with intermittent RES.

4.1.4 Fuel availability and security of supply

Every energy source is almost useless if the related resources are not sufficiently abundant to sustain the current and projected energy demand. While RES have an availability not related to the fuel, nuclear and fossil future is strictly driven by the amount of available reserves.

Table 4 shows the current reserves-to-production (R/P) ratio of fossil fuels (BP, 2019); the R/P is an indication of the duration of a source, considering a constant production and a fixed reserve. Oil and natural gas should be available for around 50 years, while coal for around 132 years. This is only a rough estimation since the extraction of a source is not constant and new reserves may be discovered or become exploitable for technical or economic reasons.

Table 4 Reserves-to-production (R/P) ratio of fossil fuels (BP, 2019)

Fuel	R/P ratio
Oil	50.0
Natural gas	50.9
Coal	132.0

Considering the electricity consumption of 1999, world is expected to terminate uranium in 308 years (Price and Blaise, 2002). At 2017, 6.1 Mton of Uranium were considered recoverable at less than 130 US$/kgU with additional 1.8 Mton recoverable at less than 260 US$/kgU (OECD/NEA and IAEA, 2018). 20 Mton of Estimated Additional Resources (EAR) are inferred, from geomorphology analysis. In addition, unconventional resources, such as uranium in seawater (Tsouris, 2017), would rise the availability up to 8350 years (Price and Blaise, 2002).

Moreover, there are other possibilities to increase nuclear fuel resources such as spent fuel reprocessing, fast breeder reactors, thorium-uranium fuel cycle. The exploitation of these technologies would increase the availability of nuclear fuel up to 250000 years (Price and Blaise, 2002).

Natural gas is the largest source adopted in Italy for electricity generation and more than 92.6% of the gas is imported (Snam and Terna, 2019). Therefore, the dependency on foreign countries is very high, posing the issue of the security of supply (Helm, 2002). In Italy this issue has been addresses by diversifying the suppliers, e.g. through imports by Liquefied Natural Gas (LNG) carrier ships, but not diversifying the energy source. This results in a strong dependency on foreign countries and on the global natural gas market cost variations (Cosmi et al., 2009). The adoption of nuclear energy would decrease the natural gas imports, with an increase of the national energy security.

4.1.5 Safety

Despite the fear of nuclear energy raised in Italy after Chernobyl, statistics show that safety is actually an advantage of nuclear power. Nuclear holds the lowest severe accident frequencies and death-to-unit energy ratio in the energy field. Frequency of accidents able to irreparably damage the plant and/or harm the population has been evaluated between 10^{-6} and 10^{-4} events per reactor per year (Petrangeli, 2006).

The WASH-1400 compared the frequency of some man-made and natural events, and the related fatalities, to NPP (USNRC, 1975). Dying because of an accident in 100 NPP has a probability comparable to die because of a meteorite. Dying because of other natural catastrophes like earthquakes and hurricanes is 10 thousand to 100 thousand times more likely.

The deadliest accident in the civil nuclear energy sector (Chernobyl) accounts for tens of fatalities directly attributed to the accident (Takamura et al., 2012). In addition, Cardis and Hatch (Cardis and Hatch, 2011) state that twenty-five year after the Chernobyl accident it is documented that children exposed to radioiodine from Chernobyl fallout have a sizeable dose-related increase in thyroid cancer. Moreover, there have been highlighted increases in incidence and mortality from non-thyroid cancers and non-cancer endpoints. Other NPP severe accidents, even if with core degradation (i.e. Three Miles Island and Fukushima-Daiichi), did not cause any directly related death. However, major accidents, despite being very rare, have a huge economic impact. While deaths per unit energy are very low, a nuclear sever accident is more expensive than other ones.

Fossil fuels account for the highest death rate per energy produced. Deadly and polluting accidents have been recorded at any stage of the energy cycle, such as Benxihu Coal Mining Explosion 1942, Exxon Valdez Oil Spill 1989, etc. Also RES caused the death of thousands of people. For example, between 1896 and 2014 more than 180 hydropower dams' failures and accidents have been recorded, causing several fatalities (Kalinina et al., 2018). In Italy a terrible accident at the Vajont dam in 1963 caused the death of about 2000 people (Guzzetti, 2000). Figure 7 shows the mortality of some energy production technologies over the entire life-cycle (Brook et al., 2014).

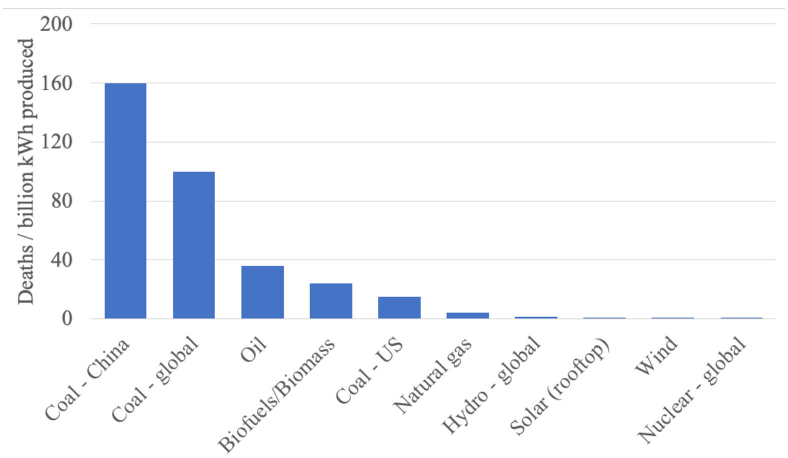

Figure 7 Mortality of various energy production technologies (data from (Brook et al., 2014))

4.1.6 Economy

The construction cost of NPP can be one of the most relevant disadvantages, as discussed afterwards. However, the adoption of nuclear energy in Italy would bring also significant economic benefits. Firstly, the cost of electricity imports from foreign countries would be reduced or cancelled. Similarly, also the amount of fossil fuels imported (mainly natural gas) would be reduced together with its costs. There are also some hidden costs of electricity generation; a relevant one is the sanitary-related cost due to the illness caused by air pollution such as lung cancer (Molinier et al., 2006). The reduction of air pollution, especially in northern regions of Italy, would lead to a decrease of such indirect costs.

4.1.7 Additional applications

Studies show that the pollution problem in northern Italy is caused mainly by house-heating in the winter season (Pizzalunga et al., 2013), industry and transport sectors. Nuclear could help reducing emissions in these sectors.

Since nuclear relies on a thermodynamic cycle to generate electricity, the excess of thermal energy could be applied for house heating in District Heating Networks (DHN). DHN are being used in several cities like Turin, relying on fossil fuel power plants. For economic reasons, DHN can be adopted only in large cities (Guelpa et al. 2017). For smaller cities and isolated houses, since nuclear provides carbon-free abundant electricity, heat pumps (Hepbasli and Kalinci, 2009) could substitute the natural gas boilers.

In the transport sector, once the energy mix is mostly carbon free, it becomes meaningful to incentivize the adoption of electric cars in the city centers. At present, such politics would not be particularly advantageous since the pollution and GHG emissions would be only moved from the city center to the power plants.

Waste heat from NPP could also be used for process heat in industries. Another innovative application is the production of hydrogen (Elder and Allen, 2009), but this would be attractive only if there will be an increasing demand of hydrogen for automotive propulsion (Akansu et al., 2004) or for hydrogen blending in the natural gas pipeline network (Melaina et al., 2013).

4.2 Disadvantages

4.2.1 Costs

Nuclear is a capital-intensive business, since the initial investment could account for about 80% of the electricity cost. The other 20% is due to fuel (5%) and operation and maintenance (15%) (MIT, 2018). Table 5 lists the typical costs of common energy production facilities, divided in capital costs and operating cost (Blumsack, 2020). The difference between the upper and the lower bound of the nuclear capital cost is quite large. This is due to the different construction cost of new NPP in the various countries, which is related to the NPP design, workforce cost, standardization, industrial know-how, etc.

Table 5 Capital and operating costs of some common energy production technologies

Technology	**Capital Cost [$/kW]**	**Operating Cost [$/kWh]**
Coal-fired	500 - 1,000	0.02 - 0.04
Natural gas	400 - 800	0.04 - 0.10
Coal gasification combined-cycle	1,000 - 1,500	0.04 - 0.08
Natural gas combined-cycle	600 - 1,200	0.04 - 0.10
Wind turbine (includes offshore wind)	1,200 - 5,000	Less than 0.01
Nuclear	1,200 - 5,000	0.02 - 0.05
Photovoltaic	More than 4,500	Less than 0.01
Hydroelectric	1,200 - 5,000	Less than 0.01

Although nuclear is not competitive with fossil fuels for the capital costs, it is economically competitive with RES. However, the current concerns regarding climate change are leading to the implementations of carbon taxes. MIT experts evaluated the likely relative cost of energy activities with and without the implementation of carbon costs (MIT, 2018). Since climate change and pollution cause increasingly issues, carbon taxes are likely to rise, increasing nuclear competitiveness over fossils.

Due to the high capital cost of NPP, political stability is fundamental to attract investors. No company would risk a high investment without insurance on energy policies stability over periods comparable to the plant pay-back time. This is a critical point for Italy since the average duration of a government is around 1.1 years. If Italy will ever consider again the nuclear option it must ensure a stable decision, not influenced by the current governing parties' ideas.

A possibility to mitigate the economic risk is the adoption of SMRs. In fact, even if SMRs may seem disadvantageous from an economy of scale, their modular construction allows to defer the construction cost (Boarin and Ricotti, 2014).

4.2.2 Wastes

Nuclear energy produces waste, as all energy sources. However, nuclear fuel produces a relatively small amount of radioactive waste, which must be managed safely to safeguard human health and the environment. Safety is based on redundancy and complementarity; multi-barrier system, involving both geological barriers and engineered barriers, are adopted to isolate the waste from the biosphere (Ojovan and Lee, 2014).

Other radioactive wastes are produced by radioactive materials adopted in medicine, agriculture, research, manufacturing, and minerals exploration (World Nuclear Association, 2020). Minimization, characterization, processing, storage and transport activities are preliminary steps before the final disposal, as defined by the International Atomic Energy Agency (IAEA, 2003). The final disposal consists in placing and monitoring radioactive waste in a repository for a long control period.

IAEA suggests a classification of the radioactive waste based on radioactivity and half-life (IAEA, 2009). The Italian radioactive waste classification is organized in five categories: Very Short Lived Waste (VSLW), Very Low Level Waste (VLLW), Low Level Waste (LLW), Intermediate Level Waste (ILW), High Level Waste (HLW). Table 6 shows the Italian radioactive waste classification with the condition and origin for each category and the option for the final disposal (Legislative Decree n° 45/2014; Italian Government, 2015).

Table 6 Italian radioactive waste classification and its disposal

<table>
<tr><th>Category</th><th colspan="2">Condition and origin</th><th>Final disposal</th></tr>
<tr><td>VSLW</td><td colspan="2">$T_{1/2} < 100$ days generated by medical application and research</td><td rowspan="2">Temporary storage (art. 33 Legislative Decree n° 230/1995) and disposal in compliance with the provisions of the Legislative Decree n° 152/2006</td></tr>
<tr><td rowspan="2">VLLW</td><td rowspan="2">Radioactivity < 100 Bq/g (with α-emitters contribute < 10 Bq/g). This waste considers materials coming from safety activity of maintenance and from decom-missioning activities of nuclear installations.</td><td>Achievement in $T \leq 10$ years of the condition</td></tr>
<tr><td>Not achievement in $T \leq 10$ years of the condition</td><td rowspan="3">Surface, or small depth, disposal facilities with engineered barriers (National Repository according to Legislative Decree n° 31/2010)</td></tr>
<tr><td>LLW</td><td colspan="2">• short-lived radionuclides ≤ 5 MBq/g
• ^{59}Ni-$^{63}Ni \leq 40$ kBq/g
• Long-lived radionuclides ≤ 400 Bq/g
• This waste derives by the nuclear installations.</td></tr>
<tr><td rowspan="2">ILW</td><td rowspan="2">• short-lived radionuclides >5 MBq/g
• ^{59}Ni-$^{63}Ni > 40$ kBq/g
• Long-lived radionuclides >400 Bq/g
• No heat production.
• This waste is generated by decommissioning of plants related to nuclear fuel cycle and by research laboratories.</td><td>Alpha-emitting radionuclides ≤400 Bq/g and beta-gamma emitters in concentrations which meet the radiation protection objectives established for the surface disposal facility.</td></tr>
<tr><td>Radionuclides in concentrations which do not comply with the radiation protection objectives established by the surface disposal facility.</td><td rowspan="2">Temporary storage facility of the National Repository (Legislative Decree n° 31/2010) waiting for the geological disposal.</td></tr>
<tr><td>HLW</td><td colspan="2">Heat production or high concentrations of long-lived radionuclides, or both such characteristics.</td></tr>
</table>

In Italy radioactive wastes are stored at the production sites, while the wastes from industrial, R&D and medical sectors are stored in temporary facilities. Spent nuclear fuel was transferred to France and the UK for reprocessing, and it will return as vitrified waste by 2025. The European directives impose the realization of final repositories in each country that produce radioactive waste from each kind of application.

Sogin, the Italian State-owned company responsible for the decommissioning of Italian NPP and the management of radioactive wastes, is working to site, build and operate the national near-surface repository to host LLW and ILW definitively, and to temporary store HLW until its final disposal in a deep geological formation. The repository requires a long period to be completed; respecting the time schedule for its realization it will be operative around 2030, while the vitrified waste will return by 2025. Two scenarios are under evaluation: new agreements to postpone the return of wastes, or the improvement or construction of new repositories in the existing nuclear sites to temporary store them (Testoni et al., 2019).

Figure 8 shows the wastes produced in Italy until 31/12/2015 for the energetic and non-energetic sources and Figure 9 shows the estimated wastes that will be produced in the next 40 years (Chiaravalli F., 2019). The produced and estimated radioactive waste are almost 40% of non-energetic waste and almost 60% of energetic waste. The VLLW and LLW will represent about the 80% of the total radioactive wastes, while ILW and HLW the 20%.

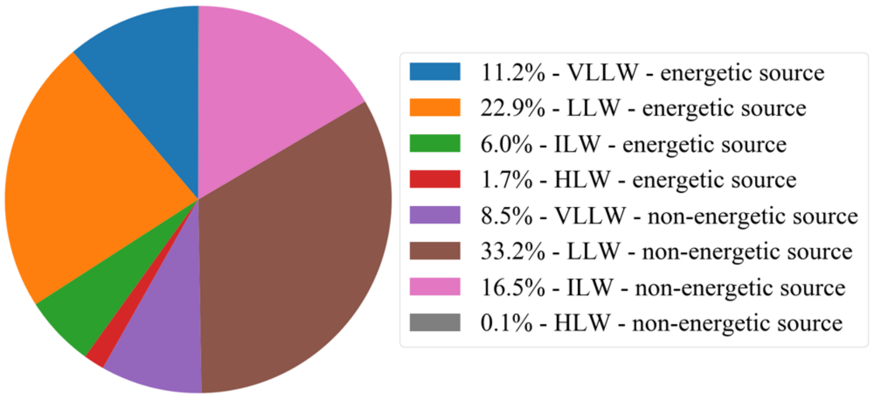

Figure 8 Classification of produced radioactive waste in Italy until 31/12/2015

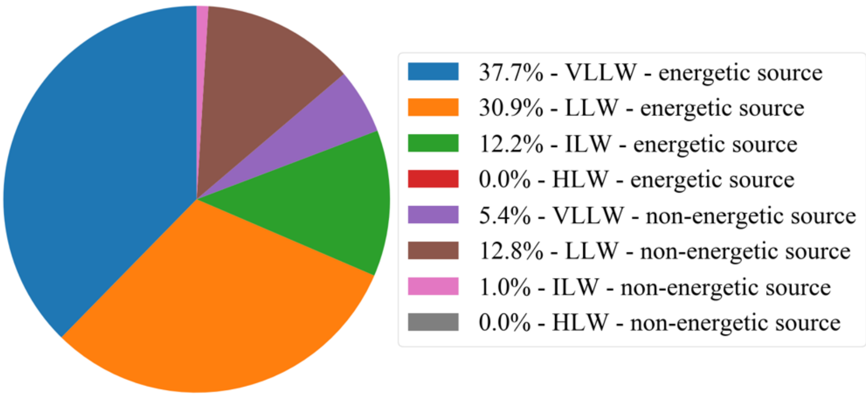

Figure 9 Classification of estimated radioactive waste that will be produced in the next 40 years in Italy

All minerals and raw materials naturally contain radionuclides. For most human activities, the levels of exposure are not significantly greater than the background levels. However, certain activities, such as burning coal, producing fertilizers, etc. can result in enhanced exposures that may need to be regulated. In particular, burning coal releases radioactive impurities that were previously trapped in the solid fuel. Due to the huge amount of fuel required, a coal power plant can release more radioactivity than a NPP (Zucchetti et al., 2018). This is avoided if emission reduction technology (e.g. scrubbers, filters) are adopted. Therefore, not only nuclear but also other activities produce radioactive wastes and must be regulated.

4.2.3 Proliferation

Nuclear proliferation is the risk of spreading of nuclear materials that can be used for the construction of nuclear weapons. The proliferation risk can be considered almost null for Italy for several reasons: it is very unlikely that Italy would construct fuel enrichment and reprocessing facility, but it would be more convenient for technical and economic reasons to purchase nuclear fuel from foreign vendors. Moreover, Italy is a member of European Union, UN, NATO and other international organizations and it does not have any military nuclear ambitions. Finally, Italy is not located in a critical geographical position where terrorists group could easily target nuclear installations to obtain nuclear materials.

4.2.4 Public acceptance

Public acceptance is the greatest barrier against the reintroduction of nuclear energy in Italy. After the Chernobyl and Fukushima-Daiichi accidents there was a strong anti-nuclear campaign, which resulted in a perceived nuclear-related risk higher than the actual one (Sjorberg, 2000). In Italy the effects were the two votes against nuclear energy in 1987 and 2011.

However, the majority of the public does not know that Italy can be considered still in the nuclear sector from several points of view: R&D in research centers and universities, industrial activities for the export, management of nuclear waste from the old NPP and other sectors, proximity to foreign NPP close to the Italian border.

5 Conclusions

Environmental pollution and climate change require an energy transition towards a more sustainable energy system. Italy is investing in RES and in the transition from coal to natural gas. However, the dependency on fossil fuels is still large and it is not projected to drastically reduce. This poses issues also considering the security of supply and economics, due to the lack of large fossil fuel reserves in the Italian territory.

Nuclear could play an important role to accelerate the energy transition and decarbonize the energy sector together with RES. Considering the Italian framework, the adoption of nuclear energy would bring several advantages (low emissions, dispatchability, security of supply, etc.).

The main criticalities are the management of nuclear wastes and the public perception of nuclear energy. Two preliminary actions that would be fundamental to think about a possible reintroduction of nuclear energy in Italy are an acceleration in the construction of the final waste repository and a more effective communication of the advantages of nuclear energy to the public. Concerning the first action, European directives impose the realization of a national repository, thus the Italian government together with Sogin must work in this direction. For the public, after the Chernobyl and Fukushima-Daiichi accidents the perception of nuclear risk resulted higher than the actual one. Few efforts were dedicated to the communication with the people of the real risks and potentiality of nuclear energy. An informative public campaign, which explains the real risks of nuclear energy and compares the advantages and disadvantages of each energy sources, should be organized.

Due to the high capital cost of NPP, a stable Italian energy policy should be defined and implemented by the government in the case of a reintroduction of nuclear energy. In addition, the adoption of innovative reactors, may reduce the investment risk for the construction of new NPP.

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