# Cogeneration: an Option to Facilitate Load Following in Small Modular Reactors

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# Abstract

Nuclear Power Plants (NPPs) have been historically deployed to cover the base-load of the electricity demand. Nowadays some NPPs might perform daily load cycling operation (i.e. load following) between 50% and 100% of their rated power. With respect to the insertion of control rods or comparable action to reduce the nuclear power generation, a more efficient alternative might be the “Load Following by Cogeneration”, i.e. diverting the excess of power, respect to the electricity demand, to an auxiliary system. A suitable cogeneration system needs:

1. To have a demand of electricity and/or heat in the region of 500 MWt – 1 GWt;
2. To meet a significant market demand;
3. To have access to adequate input to process;
4. To be flexible: cogeneration might operate at full load during the night when the request (of) for electricity is low, and be turned off during the daytime.

From the economic standpoint, it is essential that the investment in the auxiliary system is profitable. This paper provides a techno-economic assessment of systems suitable for coupling with a NPP for load following. The results show that district heating, desalination and hydrogen might be technically and economically feasible.

**Keywords:** Small Modular Reactors; Cogeneration; Load Following; Economics; Nuclear Power; Feasibility Study.

**Highlights**

- Nuclear Power Plants are usually deployed to cover the base-load
- Load following will be more and more common in the future
- Reduce the nuclear power generation is economically inefficient
- The excess of power can be used to cogenerate valuable products
- District heating, desalination and hydrogen production are realistic options

# 1 Introduction

The increasing penetration of variable renewable energy and Nuclear Power Plants (NPPs) in several developed and developing countries is forcing NPPs to follow the energy demand i.e. to operate at variable power output (NEA - OECD 2011). As a consequence, NPPs vendors and utilities have studied the capability of the plants to work in the so-called 'Load Following' (LF) mode by temporarily reducing the power output and consequently the overall electric energy produced. As explained later, reducing the power in the primary circuit is not ideal, while the cogeneration, in some scenarios, might be more economically convenient. The goals of this papers are: to analyse the requirements of cogeneration options for LF with NPPs; to review of the most significant results in this field; to point out the most interesting systems for future studies.

## 1.1 The need of Load Following with Nuclear Power Plants

Historically, NPPs have been mainly seen as a baseload source of energy. This is the most economical and technically straightforward mode of operation: power changes are limited to frequency regulation for grid stability purposes and shutdowns for safety purposes. Still nowadays, the majority of NPPs are used for the baseload and operate at a fixed power level. However there is an increasing number of countries such as France and Germany, where this situation has changed, and NPPs are forced to work in the LF mode (NEA - OECD 2011). For instance, in France, the share of nuclear power in the national electric portfolio is so relevant (about 75%), that particularly during the night-time there is a surplus of production (WNA 2016).

Although France is an exception several countries that present shares above 50%, (Belgium, Hungary, Slovakia and Ukraine) face similar problems(NEI 2016). Furthermore, even in countries not having a very high penetration of nuclear power (e.g. South Korea), the LF can be imposed in specific regions with several NPP. NPP would also be required to LF when a large proportion of power portfolio is constituted by large-scale deployment of intermittent sources of energy like photovoltaic or wind (e.g. in Germany) (NEA - OECD 2011). Since most of the renewable power plants (i.e. wind farms) are not dispatchable, other plants have to reduce their power level to avoid an excess of supply compared to the electric power demand (NEA - OECD 2011). This situation is forcing the utilities to implement or improve the flexibility of their NPPs and to adapt the electricity supply to daily or seasonal variations of the power demand i.e. to do the LF.

The requirements for a NPP to perform LF are specified in (NEA - OECD 2011) and mainly consist in:

- The capability to operate between 50% and 100% of the nominal reactor power;
- The output variation rate, at least, equal to 3% of nominal power per minute;
- Capability to perform at least the following number of load variation: two per day, 5 per week, 200 per year.

Modern NPPs, like the PWRs operating in France, are designed to have a large manoeuvring capability: for instance, the European Pressurised Reactor (EPR) can perform LF between 25% and 100 % of nominal power ($P_N$), and supports power variation speeds up to 5% $P_N$ per minute (UK-EPR 2012). Several French NPPs follow a variable load program, with one or two large power changes per day. This can be made in different ways, mainly:

- For PWRs: by inserting the control rods (made of neutron absorbers);
- For BWRs: by changing the coolant flow rate (by mean of recirculation pumps), or with the control rods.

All these methods induce a decrease of the reactivity into the core, i.e. a variation of the thermonuclear power production. This introduces thermomechanical stresses in the reactor fuel and components. Even though this problem can be mitigated by modern NPPs designs (NEA - OECD 2011), the NPP still essentially remains under-utilized, since a reduction of the production represents a loss of revenues without any significant variable cost reduction. Indeed, differently from gas power plants, there is no relevant cost saving in decreasing the electricity production, because:

- Capital cost is a sunk fixed cost;
- O&M costs (e.g. staff) are fixed costs, independent of the power rate;
- Nuclear fuel accounts only for about 10%-15% of generation costs and there is a not linear relationship between power produced and “fuel usage”.

Thus, the economic consequences of LF are mainly related to a reduction in revenue with substantially unvaried costs. This causes an increase in capital costs incidence on the unit power output.

## 1.2 The key idea: Load following by cogeneration

The key idea of the 'LF by Cogeneration' is to meet electricity market requirements and avoid an economic penalty at the same time. This is achieved by operating the NPP at its nominal power all the time, leaving the primary circuit conditions unchanged. During the high load/high price hours (day) the nuclear power is fully converted into electricity to the grid, while during hours of low demand/low price (night) the excess power can be directed to an external system (e.g. a desalination plant) producing valuable by-products (e.g. fresh water). The coupling is particularly virtuous for those systems that require large amounts of energy in terms of heat or electricity and whose main cost of production is represented by the energy supply. Cogeneration based on heat supply are preferable since the heat-to-electricity conversion is avoided with related efficiency losses. Small Modular Reactors (SMRs) are ideal for this kind of application (Locatelli et al. 2015) as discussed also in sections 2.1.

Reasonably, it should be distinguished between pre-programmed LF and dynamic LF. In case of pre-programmed LF, utilities know the ammount of electricity to produce each hour. This information come from historical data about electricty consumption during the nights or the week-ends and are reflected in the “day-ahed electricity market” or comparable mecanisms. Alternativelly NPP dynamically LF or adjust its power output according to the change of power produced by not dispachable renewables, e.g. wind farms. The application of cogeneration with dynamically LF is more challenging than the programmed LF (generally applied in all NPPs). This paper investigates pre-programmed LF, while dynamic LF is an enviseged future development.

# 2 Methodological consideration

## 2.1 Criteria for selecting the Nuclear Power Plant

### 2.1.1 Introduction to Small Modular Reactors

NPPs can have different sizes. Small sized reactors are defined as those with electric power inferior to 300 MWe while medium-sized reactors are those with electric power in the range 300 - 700 MWe (IAEA 2007b). More recently the IAEA defined small modular reactors (SMR) *"as advanced reactors that produce electric power up to 300 MW(e), designed to be built in factories and shipped to utilities for installation as demand arises."* (IAEA 2016). Several SMRs design, detailed in (IAEA 2014) and (IAEA 2016), are currently at different stages of development around the globe. Considering SMRs (Ingersoll 2009) provides a good summary of their innovative features; *"reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics".*

Several papers discuss how SMR can be economically competitive with Large Reactors (LR), in certain scenarios and contexts. In particular, SMR might balance the "diseconomy of scale" with the "economy of multiples". (Carelli et al. 2007) analyse specific factors, such as grid characteristics, construction time, financial exposure, modularization, learning, which distinguish SMR from LR in the evaluation of the capital cost. When these factors are taken into account, the capital cost might not be a discriminant between the two technologies. (Boarin et al. 2012) provide a full economic analysis reaching the same conclusions for a large plant vs. SMR plant comparison; (Locatelli & Mancini 2011a) offer a portfolio level analysis of large versus SMR plants. (Locatelli & Mancini 2011b) discuss the effects of "non-financial parameters," such as electric grid vulnerability, public acceptance, the risk associated with the project, on the evaluation of the best reactor size for investment in the nuclear sector. For many of these parameters, the authors show many benefits of SMR respect to LR. One of the key SMR advantages is the possibility to turn a large investment into a scalar and modular one. The construction of a single large reactor of GWe scale is a very risky single investment decision (Locatelli & Mancini 2012b; Brookes & Locatelli 2015; Locatelli et al. 2016) while the construction of four SMR with a fractional capacity can be a safer option from a financial perspective. Conversely, the Nuclear Safety Regulation plays a key role that might potentially undermine the business case (Sainati et al. 2015). Therefore, a holistic assessment is needed to select the best type of nuclear reactor (Locatelli & Mancini 2012a) or base load technology (Locatelli & Mancini 2010). An overview of the techno-economic aspects of the so-called Generation IV reactor is provided in (Locatelli et al. 2013).

### 2.1.2 Rationale for selecting Small Modular Reactors

Among all the SMR, two examples (whose technical data are available in the scientific literature) have been chosen, representing respectively the PWR and the Very High-Temperature Gas-Cooled Reactors (VHTGR) categories: IRIS (Carelli 2004; Carelli 2009) and GTHTR300 (Yan et al. 2003). The VHTGR reactor has been *resized*, in order to make the economic assessment over the same power output, so that the two reactors can provide the same *electric* energy to the grid over one year, or the same *thermal* power to the auxiliary plant, as can be seen in Table 1 (Shropshire 2011; Yan et al. 2003).

| | PWR | VHTGR | UNIT |
|---|---|---|---|
| Thermodynamic efficiency | 33.5% | 46% | - |
| 1 SMR nominal Electric Power | 335 | 335[1] | MWe |
| Number of SMRs | 4 | 4 | - |
| NPP nominal Electric Power | 1,340 | 1,340 | MWe |
| NPP *electric* equivalent available power during the Night | 670 | 670 | MWe |
| NPP *thermal* equivalent available power during the Night | 2,000 | 1,456 | MWth |
| Capacity factor | 95% | 95% | - |
| Theoretical Annual Electric Energy produced | 11,151 | 11,151 | GWh el |

**Table 1 Nuclear Power Plants technical characteristics**

As explained in (Locatelli et al. 2015) a key advantage of adopting multiple SMR instead of a single LR is the intrinsic modularity of an SMR site. In particular, it is possible to operate all the primary circuits of the SMR fleet at full capacity and switch the whole thermal power of some of them or use the electricity produced for the cogeneration of suitable by-products. Therefore, the LF strategy is realized at the site level, by diverting 100% of the electricity produced or 100% of the thermal power generated by some SMR units, to different cogeneration purposes and let the remaining units produce power for the electricity market. Either in the case of full electricity conversion or in the case of full cogeneration operation mode, the efficiency would be maximized by-design: SMR could run at full nominal power

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[1] Resized, in order to make the calculations with the same electric power output.

and maximum conversion efficiency and cogeneration plant size could be optimized for the thermal power rate.

Considering four IRIS units, the power rates at site level would be approximately 0%, 25%, 50%, 75% and 100%; these steps are suitable for the general LF requirement by a baseload plant. Gas plants could provide the fine matching with the electricity market demand, as usual. By using SMR smaller than 335 MWe size, the possible power rates steps of the nuclear power station could be smoother. Even if IRIS plants does not house multi reactors in the same reactor building the concept still apply. For the sake of the reasoning let's compare a site with four "independent IRIS SMR of 335 MWe" vs. a site of same total power (1340 MWe) represented by a single LR. If, during the night, the power need to be reduced by about 50%, two IRIS can be disconnected from the grid and used for the cogeneration of other products, while the two remaining will continue to produce electricity, at full power rate and maximum efficiency. In case of a 1340 MWe the 50% power reduction will cause some components (including pumps and turbine) to work outside the most efficient operating conditions, with lower efficiency of the cogeneration process. Therefore, when operating in LF mode, the four IRIS would be more efficient that a single stand-alone LR, at plant level. The detailed analysis considering the coupling with a desalination plant is presented in (Locatelli et al. 2015).

## 2.2 Criteria for selecting cogeneration systems

The challenge for the 'LF by cogeneration' strategy is to find an external system whose characteristics allow the coupling with a NPP. In particular there are both economical and technical criteria for selecting the cogeneration system. From the economical perspective the main criterion is that the investment profitability of the NPP-cogeneration combined facility, i.e. has a "Net Present Value" above zero. Along with this essential criterion there are a number of other criteria that need to satisfy the scrutiny of investors, such as the "pay back time", the "value at risk", the "uncertainty of costs and revenues" etc. All the economic performance includes the capital cost of the facility, the operation cost (including the opportunity cost related to the electricity) and the revenue(s). These parameters are "market specific" for, instance in case of a desalination plant the value of the fresh water (and therefore the overall investment) would be different if the plant is located in the UK or

Sweden (two countries with abundant low cost fresh water) or a country with a desert climate and very limited fresh water. In this paper the investment appraisal has the character of a “feasibility study” highlighting scenarios that might be relevant for a future detailed analysis and ruling out scenarios that are not worthy of future investigations.

Regarding technical criteria it is worth to distinguish electric and non-electric applications. In case of electrical application the NPP always supplies the electricity to the grid and the auxiliary plant itself is connected to the grid. This is called in the literature “virtual power plant” (Pudjianto et al. 2007; Masuch et al. 2012) and it is a concept applicable also to the nuclear sector (Fridolfsson & Tangerås 2015). The coupling of a NPP with an electrical application is the most simple, because:

- it does not require modifications of the NPP design since no changes of the thermodynamic cycle are involved: the electricity is “split into two paths” in the grid *outside* of the NPP;
- no close proximity between the cogeneration facilities and the NPP is necessary, since electricity, differently than heat, can travel reasonably longer distances with relatively small losses;
- if the cogenerating facilities is outside the nuclear site, there are not relevant licensing constraints.

Essentially *every* system requiring electricity could be coupled with a NPPs, if:

- its power demand is large enough (670 MWe, i.e. the half of 1,340 MWe, which is the nominal power of 2 PWR SMR modules);
- it is flexible enough to work at full power during the night and be switched off (or operated at a much lower load, consuming less electricity) during the day.

Systems using thermal energy are more demanding. The technical criteria are:

- requiring a large thermal power supply (about 2,000 MWth, i.e. approximately 3 times the excess electric power, due to the characteristic conversion efficiency of a LWR, or an equivalent combination of electrical and thermal);
- requiring relatively low-temperature heat (except for the coupling with an VHTGR, but currently the large majority of NPPs worldwide are PWR and BWR) :
- do not having a relevant thermal inertia;
- allowing daily load variations, with rather fast dynamics.

Cogeneration therefore should not be a continuous process, but a "batch" type production and the last two characteristics are essential for the flexibility required by the LF operation. The analysis performed in this study answers to the following questions on the auxiliary system:

1. What is the suitable size (in terms of power input) of the system?
2. Would it be technically feasible to build a system needing 670 MWe equivalents (that is the *excess power* during the night)?
3. Is there enough input material for the cogeneration system?
4. Would it be enough demand for the by-product?

These represent the preliminary requirement for a cogeneration system; if these requirements are not met, any further technical /economical analysis is not developed.

As previously analyzed, the actual daily power output profile for a NPP varies case by case, and strongly depends on the local power supply and demand structure. The analysis is based on the following hypothesis:

- the electric power required by the grid is equal to the nominal power during the day (8.00 am to 12.00 pm), and to the 50% of the nominal power during the night (0.00 am to 8.00 am). This means that the available power for the auxiliary plant will be 670 MWe (or, in case of thermal application: 2000 MWt with the PWR, 1196 MWt with the VHTGR) for 8 hours;
- all the 365 days of the year are considered identical in terms of energy required by the grid;
- NPP availability is 95% (5% is lost for refueling and maintenance).

Although a few commercial NPPs worldwide provide energy to non-electrical applications, nuclear energy is primarily used only for base-load electricity production. Of the nominally 440 commercial nuclear plants operational world-wide, 59 units in 9 different countries (Bulgaria, Czech Republic, Hungary, India, Romania, Russia, Slovakia, Switzerland, Ukraine) are being used for district heating/process heat and 12 units in 3 countries (India, Japan, Pakistan) are being used for water desalination (IAEA 2008). To date, no commercial NPP has been used to provide process heat directly to industrial applications such as oil refining or chemical production (D. Ingersoll et al. 2014). For the purpose of this work, and following a brainstorming with experts, candidate systems for cogeneration with nuclear power are the following:

- Seawater desalination plant;
- Gasoline production plant;
- Oil Sand extraction facility;
- Algae – Biofuel production plant;
- District heating;
- Diesel-like fuel production from waste plastic pyrolysis;
- Waste wood palletisation plant;
- Hydrogen production from water splitting plant.

# 3 Results of the assessment of candidate systems

## 3.1 Seawater Desalination

Along with pollution and depletion of hydrocarbon resources, water scarcity is one of the most serious global challenges of our time. NPP can make a substantial contribution to the challenge of providing fresh water to everybody by supplying energy to desalination plants (IAEA 2007a). Desalination has proven its reliability to deliver large quantities of fresh water from the sea during the last 30 years. The sea is the unlimited source to create new fresh water through desalination. Currently, about 2.3 billion people live in water-stressed areas and among them 1.7 billion live in water-scarce areas, where the water availability per person is less than 1000 $m^3$/year (IAEA 2007a).

In some countries water desalination is very common: Qatar and Kuwait rely up to nearly 100% on desalinated water for domestic and industrial supplies, and the desalination capacity is increasing in the Middle Est and Africa (Ghaffour 2009; Ghaffour et al. 2013).

Desalination processes could be classified essentially in two groups: thermal processes and membrane processes (Locatelli et al. 2015). Thermal processes require mostly thermal energy (low-temperature steam) while membrane facilities (usually reverse osmosis) require only electricity. Nowadays, half of the total desalination investments are addressed to Seawater Reverse Osmosis (SWRO) projects, due mainly to its lower overnight construction costs and total produced water costs compared to other conventional processes (Locatelli et al. 2015). Cogeneration between a NPP and a desalination facility is a consolidated practice (Asiedu-Boateng et al. 2012; Al-Mutaz 2003; Nisan & Dardour 2007; Jung et al. 2014; Ingersoll 2009; IAEA 2007a). Over 200 reactor-years of operating experience on nuclear desalination have been accumulated worldwide (IAEA 2008).

(Locatelli et al. 2015) demonstrate that a desalination plant is flexible enough to be coupled with a NPP operating in LF mode: moreover, the required size of the considered plant has revealed to be similar to the largest plants worldwide. (D. T. Ingersoll et al. 2014) technically and economically assess the coupling between NuScale (a 45MWe PWR) and four possible water desalination plants (each of which represents a different desalination method). He concludes that although a NuScale plant coupled to a reverse osmosis desalination plant provides the most favorable economics, NuScale design features offer several flexibilities for coupling to thermal distillation plants and hybrid plant configurations.

In summary, the Seawater Desalination is a viable option for LF as long as the market value of the fresh water is high enough to justify the capital and operating cost of the desalination facility.

## 3.2 Gasoline

During refinery process, crude oil is heated and separated by evaporation into fractions by fractional distillation: the crude oil is heated and vaporized passing through a furnace, then it enters the fractioning column and begins to climb and cool down: the heavier substances condensate at higher temperatures, then fall and are collected, while the lighter continue to climb and cool.

(Alonso et al. 2014) suggest that steam process (coming from a helium cooled high-temperature nuclear reactor, PBMR) can be used to heat crude oil. They proposes to use 65 MWe (over 165 MWt) for steam production. From a technical standpoint, the process steam production is more suitable using the PBMR because the gas temperature is higher than the one coming from the Gas turbine in the Combined Cycle, which increases the thermal heat transfer providing more compact equipment for the process in the PBMR than in the combined cycle using natural gas. The results show that *(sic.) "Under an scenario of 5% discount rate and 5 US$/mmBTU and no cost for CO2 emissions, it is cheaper to produce process heat by using CCGT than the PBMR, the scenario to have the possible participation of the PBMR if the price of the gas is at least of 8 US$/mmBTU. If the previous condition is met in combination with a penalty for CO2 emissions then the HTR is a better option. Under the 10% discount rate scenario the PBMR is not competitive even if the price of the gas is 10 US$/mmBTU and the cost for emissions is 30 US$/ton of CO2. To be competitive it will be necessary that the cost for emissions will be at least of 60 US$/ton of CO2, which seems very unlikely."*

(D T Ingersoll et al. 2014) studied the feasibility of nuclear energy supply for the oil recovery and refining processes using NuScale. Results show that, based only on operating costs, a 10-module NuScale plant can be competitive with heat from fossil sources with natural gas prices as low as $5/MBtu, even with no $CO_2$ tax. The capital investment for the NuScale plant can be recovered in 25 years if the natural gas cost exceeds $9.5/MBtu without a carbon tax or $7.5/MBtu with a $40/MT $CO_2$ penalty. In summary, this option is tecnically viable, but the economic feasibility of this option is unclear and mostly linked to the cost of gas and $CO_2$ tax.

## 3.3 Shale oil Extraction

The USA have the largest and most concentrated oil shale formations in the world. The USA resources are estimated at about 2 trillion barrels of oil (Curtis et al. 2014). Oil shale contains kerogen, but no liquid oil. The process consists of heating oil shale underground to ~330°C to convert the kerogen into a light high-value oil, natural gas, and char, and then to extract these products. The required energy is enormous: in non-nuclear processes, the 25% of the product is burnt for the heating (Curtis et al. 2014).

(Curtis & Forsberg 2013; Curtis et al. 2014) suggest the use of the Nuclear Renewable Oil Shale System (NROSS) to heat the steam which is sent in the subsoil. In this case, the oil shale would be heated to between 210 and 250°C using closed steam heating lines, and then a further heating of the steam (to 370°C) would be made by electric heaters. They assert that the resource is sufficiently dense for a full-size reactor to supply steam for a 60 year lifetime within a 2 km radius. Moreover, the physical characteristics of the rock would permit to provide the energy only during low electricity demand hours, so constant heating would not be required. If the statements made by (Curtis et al. 2014) are confirmed, Oil Shale extraction could be a suitable application for the LF with Nuclear Power. Some provisions, especially regarding the 60 years of continuous energy supply from the NPP, seem optimistic. In the case of less operation time on a site, NPPs capable of moving from one site to another would be required, and this would recall into question the investment and would have serious licensing implications (Ramana et al. 2013; Sainati et al. 2015). This option is therefore extremely controversial.

## 3.4 Algae – Biofuel

Fossil fuels provide a major contributor of greenhouse gases (GHGs) to the biosphere. In this context, countries across the globe developed state policies toward the increased and economic utilization of biomass for meeting their future energy demands. The biorefinery is a plant whose input are mainly biomass, thermal and electrical energies and whose output is one or more types of biofuel. Many types of biomasses are used to produce biofuels: the first generation is composed by conventional crops; the second generation is composed by lignocellulosic biomasses; the third generation is represented by innovative feedstock among which the most promising are microalgae (Adenle et al. 2013).

(Locatelli et al. 2015) propose a bio-refinery plant for the coupling with a NPP, according to the LF strategy. They explain that the fermenter is the most viable option for the microalgae cultivation since all other technologies require vast space (thousands of hectares) for a reasonable coupling with a plant that has an installed power in the order of magnitude of GW. They conclude that a fermenter bio-refinery would have to be operated on a continuous base, because of the perishability of the biomass and because the most significant power requirements are in the first steps of the production chain that have to be considered a continuous process. Consequently, the bio-refinery is not suitable for the LF.

## 3.5 District heating

District heat involves the supply of hot water through a district heating system, which consists of thermal power plants (usually as cogeneration from electricity) and a network of distribution and return pipes. In many countries, such as central and northern European countries and former soviet countries, district heat has been widely used for decades. District heating has the following technical requirements (IAEA 2008):

- It requires a heat distribution network to transport steam or hot water in a typical temperature range of 80-150°C;
- the heat source must be relatively close to the customer, typically within 10–15 km;
- the district heat generation capacities are determined by the collective demands of the customers. In large cities a capacity of 600–1,200 MWth is usual;
- the heat is supplied only in the colder part of the year;
- a backup capacity is required to assure a reliable supply of heat.

Coal and gas currently dominate the fuels used for district heating, and several countries (Bulgaria, China, Czech Republic, Hungary, Romania, the Russian Federation, Slovakia, Sweden, Switzerland and Ukraine) already have experience in nuclear cogeneration for district heating, so the technical aspects can be considered well proven (IAEA 2008). The key issue related to the deployment of new district heating capacity is the high capital cost. As presented in the case of the UK (ETI 2015) if the price of heat is reasonably high (in the region of 80-100 £/MWh) the investment might become justified. Nevertheless, this price of heat would cover only the operation cost while the capital cost to install the infrastructure (piping, back up plants etc.) might be financed in another way. In summary this system is technically viable, and the economics would mostly depend by the electricity and market heat in the country.

## 3.6 Plastic pyrolysis

Because of their non-biodegradability, plastic materials contribute significantly to the problem of municipal waste management (Kumar et al. 2011). Thus, the collection and recycling of the plastics is a relevant environmental issue. (Kumar et al. 2011) review the four possible approaches regarding the plastics recycling:

- *Primary recycling* is realized with clean, uncontaminated, single-type waste and its products' quality is *comparable* with virgin plastics;
- *Secondary recycling* is destined to waste plastics which are converted into *lower quality products*;
- *Tertiary recycling* is *chemical* recycling. Plastics are converted into smaller molecules, which are reused in other chemical processes. They are: Chemolysis, Hydrolysis, Alcoholysis, Glycolysis, Methanolysis, Gasification, Cracking (or Pyrolysis).
- *Quaternary recycling* includes the *recovery of the energy content* of plastic wastes by incineration. This is the last in order of preference between the recycling possibilities.

Even though the first two recycling approaches are preferable, not all the collected plastics can be recycled into new plastics. Plastics that have high calorific value can be converted back to useful energy, by mean of tertiary recycling processes (Kumar et al. 2011), such as the catalytic pyrolysis. This is a non-combustion heat treatment that chemically decomposes waste material by applying heat, directly or indirectly to the waste material in an oxygen free environment. These processes are endothermic, and the required energy is typically applied indirectly through the walls of the reactor into which the waste material is fed.

In 2012, out of 25 Mtonne of generated plastic waste, 6.6 Mtonne had been recycled in Europe, and approximately 8.9 Mtonne have been reused for Energy Recovery (Plastic Europe 2015). Nowadays, plastic pyrolysis is a niche technology, so almost the whole of the Energy Recovery is represented by incineration, and even if the share of pyrolysis raise, it remains a certain quote of plastic which cannot be subject to any treatment, except for incineration. There are some plastic pyrolysis pilot plants in the world, one the largest plant has a size of 20,000 tonne/year of processed feedstock: Akron, Ohio (Esposito 2013), but power consumption data is not disclosed. The “most optimistic case scenario” assumes that pyrolysis can totally replace incineration and is feasible to bring all the European plastic waste in a single plant. In such scenario, according to a research team of Tohoku University involved in this field[2]., approximately 6 MJ/kg are required to process waste plastics into diesel oil. For the whole plastic feedstock available in Europe, this means the following:

$$AnnualRequiredEnergy = 6 * 10^6 * 8.9 = \left[\frac{GJ}{Mtonne}\right][Mtonne] = 53.4 * 10^6 GJ$$
$$= 14{,}833\ GWh$$

Proportionally, a plant like Akron (Esposito 2013) approximately requires 33 GWh per year. Considering that a single SMR would generate 5,548 GWh thermal energy (calculated from (Shropshire 2011) ) during 1 year, the supply for processing the wholly suitable waste plastic in Europe, would be provided by roughly 6 SMR. Therefore is clear that there is no plastic feedstock enough in Europe for this option to be “mass deployed”. Moreover:

- Would be expensive to transport all the European plastic in a single plant. Therefore plastic waste has to be processed within a limited geographical area. Considering one of this plants each 5 or 10 millions of citizens, at least, 50-100 of this plants would be necessary for Europe ;
- Pyrolysis reactors are sophisticated and do not easily process inhomogeneous mixtures of different plastics that contain trace of specifically unsuitable polymers (e.g. that develop gases or dioxin)[3];

Thus, plastic pyrolysis is not suitable on a large scale for the coupling with a NPP.

## 3.7 Wood palletisation

Pellet fuels (or pellets) are fuels obtained from compressed organic matter, i.e. biomass. They are generally made from compacted sawdust and related industrial wastes from the milling of lumber, manufacture of wood products and furniture, and construction.

According to (Uasuf & Becker 2011) large volumes of pellets are nowadays produced for the large-scale generation of heat and power, in order to replace coal with sustainable energy

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[2] Personal communication with Dr. Guido Grause, Tohoku University, date: 02.19.15

[3] Personal communication with Prof. Tiziano Favarelli, Polytechnic of Milan, date: 03.16.15

resources. The manufacturing process of wood pellets consists of  grinding and refining (if required, depending on the feedstock), drying, size reducing, pelletizing (pressing), cooling and then screening and packaging (Mani et al. 2006). Among these processes, the most significant from the energetic point of view are drying (thermal energy) and the pressing, for which it is necessary electrical energy.

All over the world, there is a relevant wood pellets production: only in North America 13 plants, for a total capacity of 2.9 Mton per year are currently under construction (biomassmagazine.com 2015); adding this to the already operating plants, a total plant capacity of over 22 Mton/year is reached. The most part of these plants have sizes ranging between 10,000 and 400,000 ton/year, but even larger ones are present; the largest one is in Waycross, GA (owned by RWE Innogy Cogen): 825,000 ton/year. As for the power consumptions, the companies that operate large plants do not easily disclose these data. Nevertheless a company[4] operating in this sector with a medium size plant (120,000 ton/year) shared its technical data, shown in Table 2. Starting from these values, the total power inputs (thermal and electric) are presented in Table 3.

| Production (Output) | 120,000 | tons / year |
|---|---|---|
| Grinding | 0.25 | MWe |
| Refining, (mills) | 0.7 | MWe |
| Drying | 13.7 | MWth |
| Sieving | 0.53 | MWe |
| Pelletizing | 1.05 | MWe |
| Packing | 0.03 | MWe |

**Table 2 Power input for each pelletisation process step (medium size plant)**

| | | |
|---|---|---|
| Thermal Power | 13.7 | MWth |
| Electric Power | 2.56 | MWe |
| Annual Th Energy required | 120 | GWh_th |
| Annual El Energy required | 22.4 | GWh_e |

**Table 3 Thermal and Electric Power Input and annual Energy consumed (medium size plant)**

The energy requirement shown in Table 4 is obtained by scaling up to 1 Mton/year output size; it has been considered that the plant would operate during 8 hours per day (overnight, LF mode):

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[4] Personal communication. The name of this company and the following companies providing the data is kept confidential for commercial reasons

| | | |
|---|---|---|
| Annual Th Energy required | 1,000 | GWh_th |
| Annual El Energy required | 187 | GWh_e |
| Thermal Power | 343 | MWth |
| Electric Power | 64 | MWe |

**Table 4 Thermal and Electric Power Input and annual Energy consumed (Large size plant)**

The total annual thermal energy required is then:

$$AnnualRequiredEnergy = ThermalEnergy + \frac{ElectricEnergy}{PWR\ thermal\ efficiency} =$$
$$= 1{,}000 + \frac{187}{33.5\%} = 1{,}558\ GWh_{thermalequivalent}$$

This value is still less than the excess energy from a single SMR. Moreover, even though there is no evident technical limit preventing the possibility to build palletisation, for plants larger than 1 Mton/year, the upper bound on the output size is set by logistic issues, which is related to the waste wood procurement. Indeed wood is a valuable material and is primarily used for the manufacture of furniture and other objects, rather than for producing wood pellets. The raw material used in these plants is the waste wood. Given that the value added by the process in terms of energy is relatively low, the key factor for the economic profitability of the pellet is represented by the logistics and procurement of the lumber: collect and make the wood travel through long distances (about 30—40 km at most) before processing it, means that transport costs outweigh possible revenues. For this reason, these plants are placed at the center of very large districts of woodworking, and their size is limited by the amount of waste material locally available.

For the aforementioned reasons, despite pellets plants have significant power needs and good characteristics of flexibility, they are not suitable for the LF with NPPs.

## 3.8 Hydrogen

In industrialized and developing countries, motor vehicle emissions are major contributors to low urban air quality. Hydrogen is one of the clean fuel options for reducing motor vehicle emissions in the future (Balat 2008). Nowadays there is already a large hydrogen production worldwide: 50 million tonnes per year (IAEA 2008), which roughly corresponds to 560 billion of $Nm^3$. $H_2$ has many applications as a chemical product (IAEA 2008): mainly ammonia ($NH_3$) synthesis and petroleum industry. Although current use of hydrogen in energy systems is limited, its future use could increase exponentially, should fuel-cell vehicles be deployed on a large commercial scale (Felgenhauer & Hamacher 2015).

If the whole hydrogen was produced by water electrolysis, assuming an energy consumption of 48 MWh/tonne_$H_2$ (approximate value from (Felgenhauer & Hamacher 2015)); it would mean that $2.4*10^6$ GWh of electricity would be necessary for the annual worldwide production of H2. If only the 1% of total hydrogen production was made by NPPs in LF mode (e.g. dedicating 50% of their thermal power), then some 17 NPPs of 1GW size would be required. This proves that the hydrogen production in the world is already enough to justify a cogeneration by a NPPs of any size. NPP are potentially suitable for those processes based on water splitting. However, the electrolysis is not cost competitive with the production of hydrogen from natural gas. This is true as long as the electricity price in the night become so low that even electrolysis might become cost competitive.

In case of coupling with high temperature reactor the Sulphur-Iodine Thermochemical cycle is one of the most attractive options. The sulfuric acid is heated until approximately 900 °C and, following a series of reactions fully described in (Yan & Hino 2011) the Hydrogen is produced. This process is still under R&D, and different options are considered (Gupta 2008; Agency 2006). With this process, the hydrogen can be produced with an overall efficiency of about 45% using almost only hear (Richards 2006). Because sulfuric acid and halogen are very corrosive, the selection of the structural materials is an important and still open issue. Screening tests have been carried out commercially available materials at GA (Trester 1981) and JAEA (Onuki 1994). In United States, France, Korea, as well as Japan, R&D on the SI cycle, is ongoing (Shiozawa 2006; Pickard 2006). The JAEA successfully demonstrated a stable and continuous hydrogen evolution carried out at the rate of 1-liter hydrogen (Kunitomi et al. 2007). The technical aspects of coupling an SI plant with a high-temperature fission reactor (GTHTR300C) are presented in (JAEA 2011). The GTHTR300C generates up to 300 MWe EE at 45-50% thermal efficiency by a direct cycle gas turbine power conversion system and up to 1.4 million $Nm^3$ hydrogen / day at about 45% efficiency by the SI process. The reactor has 600 MWt thermal power and 850~950 °C reactor outlet temperatures. By an intermediate heat transport loop, a share of the high-temperature reactor heat is delivered in piping as high-temperature process heat to the adjacent hydrogen plant. The hydrogen plant should be sited close to the reactor building to reduce thermal loss and piping cost (JAEA 2011).

# 4 Discussion

Table 5 provides an overview of the different temperature for the systems considered for cogeneration with nuclear power. This is a crucial parameter since it shows which systems are available now and enabled once that the VHTGR would be available. Indeed even PWR have already a number of options, such as seawater desalination and district heating, while VHTGR might access to further interesting options. Among these, the production of Hydrogen without using electricity in the process is surely the most interesting. However, as explained in section 2.2 the temperature is only one of the key criteria to establish the feasibility of a certain solution. The overall evaluation, considering all the criteria is presented in Table 6. Indeed Table 6 summarizes the main findings review regarding the LF with nuclear power by means of different cogeneration systems, in terms of technical and economic feasibility.

| Systems | T process [°C] | Reference | Comments for PWR | Comments for VHTGR |
|---|---|---|---|---|
| Seawater desalination | Up to 100°C | (Locatelli et al. 2015) | Proved technology | Feasible, in theory (waste of high temperature/quality heat) |
| Gasoline production | 300- 400°C | (Alonso et al. 2014) | Technically feasible with steam super-heating | Feasible, with a proper Heat Exchanger |
| Oil Sand extraction | 250-350°C | (D T Ingersoll et al. 2014) | Feasible | Feasible, with a proper Heat Exchanger |
| Algae – Biofuel production | 20-30°C | (Locatelli et al. 2015) | NOT Feasible | Feasible, in theory (waste of high temperature/quality heat) |
| District heating | 80-150 °C | (ETI 2015) | Proved technology | Feasible, in theory (waste of high temperature/quality heat) |
| Diesel-like fuel production from plastic waste pyrolysis | 500 °C | (López et al. 2011) | Technically feasible with steam super-heating | Feasible |
| Waste wood palletisation | 200-220 °C | (Lam et al. 2011) | Feasible | Feasible, with a proper Heat Exchanger |
| Hydrogen production - Electrolysis | Irrelevant (20 °C is ok) | (Yan & Hino 2011) | Not relevant - Electrical application | Not relevant - Electrical application |
| Hydrogen production - thermochemical cycle | 900°C | (Yan & Hino 2011) | Very hardly Feasible, since the temperature are very differents. | Feasible |

**Table 5 Process temperature for the different cogenerative systems. The reference temperature for SMR (IRIS) is 330 °C (Karol et al. 2015) and for the VHTGR (GTHTR300C) is 950°C (JAEA 2011)**

| | Technical Feasibility | Economic Feasibility | Key References |
|---|---|---|---|
| Seawater desalination | Yes | Depends on water price | (Gowin & Konishi 1999; Hidayatullah et al. 2015; Nisan & Dardour 2007),(IAEA 2007a; IAEA 2008) |
| Gasoline (petroleum refining) | Yes | Most likely not | (Alonso et al. 2014) |
| Oil shale extraction | Yes, but there are challenges related to licensing | Under investigation | (Paterson et al. 2007; Wang & Chuang 2009; Curtis & Forsberg 2013) |
| Algae-Biofuel | Perhaps for cogeneration, not for LF | No | (Locatelli et al. 2015) |
| District heating | Yes | Depends on the heat cost | (Safa 2012; ETI 2015) |
| Plastic pyrolysis | No | / | (Kumar et al. 2011) |
| Wood palletisation | No | / | (Uasuf & Becker 2011) |
| Hydrogen production - electrolysis | Yes | Under investigation | (Felgenhauer & Hamacher 2015) |
| Hydrogen production - thermochemical cycle | No for PWR<br>Yes for VHTGR | Under investigation for VHTGR | (JAEA 2011) |

**Table 6 Summary of LF and Cogeneration technologies with Nuclear Power**

The thermal applications are preferable since they use steam before conversion into electricity, avoiding a loss of efficiency, but need to satisfy the specific requirements presented in section 2. In this paper, a preliminary analysis has been conducted on different possible systems, in order to verify the feasibility of coupling them with a NPP operating in the LF mode. Some processes seem suitable for a coupling with a NPP operated in LF mode. Seawater desalination process is flexible enough to be coupled with a nuclear power source, and the largest existing desalination plants have a size compatible with cogeneration purpose by NPP. This is extremely relevant since many countries in the Middle East have plans for the construction of NPPs and they need fresh water. The gasoline production can use nuclear energy, but this would be not economically competitive given the current gas price and $CO_2$ emissions fee. It is possible to provide nuclear energy to the oil shale extraction process, even in the LF mode, but uncertainties remain on the quantity of energy required on daily bases and over the life cycle of a single site, which could be not compatible with the typical NPP lifetime. At the state of the art, algae-biofuel cultivation techniques are not suitable for cogeneration purpose since they require a continuous source of energy. Therefore, it might be suitable just for “stable cogeneration”, but not for LF. Preliminary calculation shows that for the plastic pyrolysis and wood pelletisation the feedstock procurement is limited. Therefore, the maximum size of the cogeneration plant theoretically achievable is still too small to absorb all the ‘excess energy’ coming from the NPP.  Hydrogen has a theoretically infinite feedstock availability, and the current production is one thousand of times the output obtainable with the energy supply of a single NPP. Thus, the hydrogen is a by-product that deserves a deeper feasibility analysis.

# 5 Conclusions

This paper is targeted mainly for scholars, policy and decision makers aiming to understand the challenges and opportunities of using cogeneration for the LF of NPP. It provides an overall rationale and investigation results on some key candidate technologies. Although NPP have been mainly seen as a base-load source, the evolution of power generation portfolios and the requirements recently set by relevant institutions ask the NPP to work in LF mode as well, accommodating variations in electricity demand in a time frame in the order of hours. NPP are capital intensive, and almost all of their related costs are fixed or sunk, so to be economically affordable, NPP need to maintain a high capacity factor. Reducing the power production would increase the incidence of fixed costs on the unit output cost. Therefore, this work stems from the idea to use the excess power produced during off-peak hours coupling the NPP with an auxiliary system in a co-generative layout.

The real challenge for this research field is to find a suitable industrial process to be coupled with the NPP. Different cogeneration technologies have been reviewed on the basis of some key, preliminary requirements:

- cogeneration technology that can be scaled up;
- feedstock should be available in a sufficient amount;
- market demand for cogenerated products should be consolidated and wide enough;
- heat quality, power rate and operation flexibility of the cogeneration process should be compatible with the LF operation of the NPP.

In conclusion, the most relevant technologies that might be relevant for the LF, especially with SMR are:

- District Heating, particularly in countries where there are several months with low temperature
- Desalination, particularly for countries where the electricity price between day and night are different (at least by 100%) and the water has a high price
- Hydrogen, in particular if the electricity price during the night decreases getting close to zero or new high temperatures reactors might be able to improve the efficiency of the process. Further researches are needed, particularly considering the possibility to use high efficient method of production with VHTGR.

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