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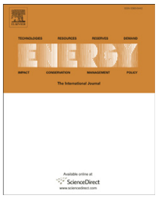

Load following with Small Modular Reactors (SMR): A real options analysis

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ABSTRACT

Load following is the potential for a power plant to adjust its power output as demand and price for electricity fluctuates throughout the day. In nuclear power plants, this is done by inserting control rods into the reactor pressure vessel. This operation is very inefficient as nuclear power generation is composed almost entirely of fixed and sunk costs; therefore, lowering the power output doesn't significantly reduce generating costs and the plant is thermo-mechanical stressed. A more efficient solution is to maintain the primary circuit at full power and to use the excess power for cogeneration. This paper assesses the technical-economic feasibility of this approach when applied to Small Modular Reactors (SMR) with two cogeneration technologies: algae-biofuel and desalinisation. Multiple SMR are of particular interest due to the fractional nature of their power output. The result shows that the power required by an algae-biofuel plant is not sufficient to justify the load following approach, whereas it is in the case of desalination. The successive economic analysis, based on the real options approach, demonstrates the economic viability of the desalination in several scenarios. In conclusion, the coupling of SMR with a desalination plant is a realistic solution to perform efficient load following.

1. Introduction

According to analysis by the US Department of Energy, the global demand of energy will increase by 50% in the next 30 years, primarily in non-OECD countries [70]. The journey towards sustainable energy therefore faces several challenges, with a number of different technologies needed to achieve this long-term goal [71]. Renewable energy sources will play a lead role and need to be developed, deployed and managed, along with existing power and non-power technologies.

From this perspective, Nuclear Power Plants (NPP) can be deployed along with renewable fuel power plants and facilities (e.g. desalination plants) to achieve the long term perspective of sustainable development without the emission of greenhouse gasses (Ambitiously, the IPCC targets “zero carbon” emissions by 2100 [72]). Given the predominance of their fixed costs, NPP are considered as a base load power technology. However, given the relevant share of nuclear power in specific countries (e.g. 75% in France) and the introduction of intermittent sources of energy (i.e. solar, wind) in to the grid [73], flexibility and adaptability will be required for the load curve [1,74], as stressed by the OECD/NEA in a recent report [2]:

> *“a unit must be capable of continuous operation between 50% and 100% of its nominal power (P_n), [...]. Load scheduled variations* (should be) *2 per day, 5 per week and 200 per year”.*

Currently, NPP production follows the electricity demand (from now on “load following”) by modifying the reactivity within the core, e.g. by inserting control rods and neutrons absorbers into the coolant [1]. By doing so, the power is reduced, with a waste of potential energy and a thermo-mechanical stress on the plant whenever the power regime is changed. Unlike gas fuelled power plants, there is not a relevant cost saving in operating an NPP at a lower power level due to the substantially fixed nature of nuclear costs. Besides investment costs, O&M (Operation & Maintenance – mainly personal and insurances) costs are fixed and independent

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from the power rate. Again, in contradiction to conventional gas-fired plants (where fuel accounts for approximately 70%–80% of the generation cost) nuclear fuel accounts for only about 10% of generation costs, making it significantly less influential [3,4]. A lower power rate does not translate into a significant fuel saving. Due to the complexity of the neutron dynamics within the core (fission, absorption by all reactor materials, reactions, leaks, poisoning etc.), the proportionality between power produced and fuel consumed is not linear [5,6]. Consequently running a power plant at 50% of its power does not save more than 4–5% of its cost, while the loss of revenue extends the recovery of the capital investment.

An alternative is to keep the NPP primary circuit always at full power and to follow the load curve by using the power (both thermal and electric) of the secondary side to cogenerate valuable by-products. The goal of this paper is to assess the technical and economic feasibility of this concept by coupling multiple Small Modular Reactors (SMR), interesting because the power is fractioned, with algae-biofuel and desalinisation.

SMR are NPP with electric power output lower that 350 MWe and therefore suitable for an intrinsically modular power station. In the last 5–10 years, SMR have received an increased attention from the scientific community and nuclear industry, with several SMR now under development [7,8]. In this paper the International Reactor Innovative and Secure (IRIS, a 335 MWe PWR) is assumed as representative of the SMR – PWR class. It is considered that its power size allows it to exploit both economies of scale (i.e. it is placed in the upper size of the SMR category), design innovation (e.g. integral primary loop) and economies of multiples (i.e. the unitary cost saving of deploying more than one unit) [9]. IRIS is a PWR integral design where every primary system component is integrated into the vessel (including fully internal primary pumps); this containment is designed to be thermodynamically coupled with the integrated primary system during accident conditions and the overall design is focused first and foremost on simplicity [10]. IRIS major design parameters and values are summarized in Ref. [11] Table 4, while the rationale for its design are recapped in Ref. [12]. Nevertheless, literature references, methodology and results for IRIS, are applicable to the whole light water SMR class.

A key advantage of adopting multiple SMR instead of a single Large Reactor (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 load following strategy is realized at site level, by diverting 100% of the electricity produced or 100% of the thermal power generated of some SMR units, to different cogeneration purposes and let the remaining units to produce electricity for the market. Either in the case of full electricity conversion or in the case of full cogeneration operation mode, the efficiency would be maximised by-design: SMR could run at full nominal power and maximum conversion efficiency and cogeneration plant size could be optimized against the thermal power rate.

Assuming 4 IRIS units, the power rates at site level would be approximately 0%, 25%, 50%, 75% and 100%; these steps are suitable for the general load following requirement by a base-load plant. Gas plants will 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 would be more gradual.

Several cogeneration plants can be coupled with a nuclear reactor using its thermal power and/or the electricity. The plants analysed in this paper are a biorefinery (algae) and a desalination plant because:

- These plants require low enthalpy thermal energy, as it is the case for the steam produced by Light Water Reactor SMR. More advanced GEN IV designs can provide fluids to higher temperature for a large range of industrial purpose (e.g. steel production [75]). However GEN IV design are not expected for commercial deployment in the near future, while Light Water (as PWR) is the technology implemented in the vast majority of NPP built in the last 10 years.
- These plants require higher input in terms of thermal energy than electric energy. This is ideal with the modular approach.
- The interest of institutions and countries for biofuels: the EU has set a goal of 10% of biofuel consumption on the total fuel for transportation by 2020 [13].
- Biofuel (including biogas) from microalgae is a promising technology still in the development phase. There are different types of technologies and biomass under consideration, some more promising that other. Tedesco et al. [76] gives an account of the biogas yields obtained from co-digestion of seaweed biomass and show that some species of microalgae are preferable to others.
- Nuclear-Desalination is a proven technology with PWR reactors [14–17].

2. Cogeneration plants: technical analysis

2.1. Biorefinery

The production of biofuels will play a key role within the economic, industrial and political strategy in the near future [13,18,19]. A biorefinery is a plant whose input is 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 literature divides them in three generations:

- first generation is composed by conventional crops (corn, soybean, rapeseed, sugarcane, etc.),
- second generation is composed by lignocellulosic biomasses (mainly forestry and agricultural waste),
- third generation is represented by innovative feedstock among which the most promising are microalgae [20].

Nowadays most of the biofuels are produced from first generation feedstock. In particular, in USA, ethanol is produced from corn or soybean, in Brazil from sugarcane, in Europe from rapeseed. In order to address the issues related to these conventional feedstocks (mainly the competition with food market), other options are considered. Lignocellulosic biomasses are regarded as a viable solution, but require a more energy intensive conversion process. Therefore, in the recent years several studies focused on the third generation biomasses, particularly microalgae, which are simple microorganisms similar to bacteria. The advantages are:

- do not compete with food market [21–23].
- have lower water and land demands in comparison to the first generation biofuel [22,24].
- no lignin content and therefore the possibility to rely on more conventional industrial processes for their transformation [25].

Given the intrinsic advantages of microalgae, this research paper focuses on a “microalgae biofuel plant”. Because of the novelty of this technology, commercial scale plants are still under development and few companies have already started the construction phase [26]. A complete summary of the state of the art is found in Ref. [27]. For the purpose of this study, the main production phases of the biorefinery are [28]: cultivation, harvesting and dewatering,

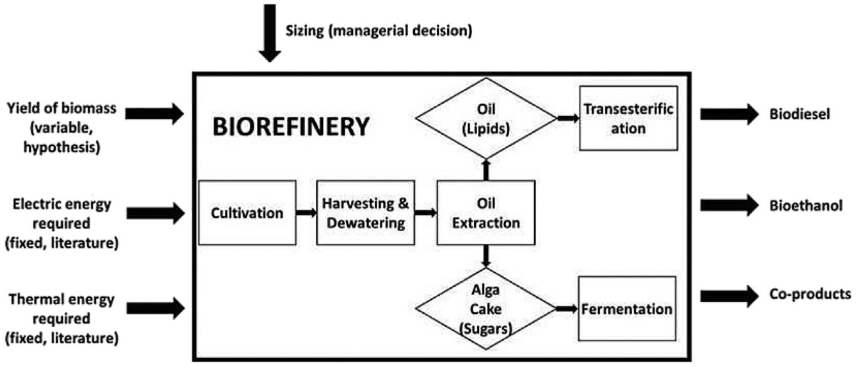

Fig. 1. The biorefinery black-box model.

oil extraction, biodiesel production (via transesterification reaction) and bioethanol production (via fermentation). Fig. 1 summarises the process inputs, outputs and the main phases. Further information and references are in Appendix A. In this paper (Table 1), 5 scenarios are assessed, with the aim to investigate how some cultivation parameters (e.g. nutrients, weather, algal strain and cultivation system) can affect the final yields of biofuels and the production economics. The most effective scenario is selected and assumed for a large-scale application, to study the coupling with the SMR.

In order to work in load following mode, about the 50% of the energy produced by the nuclear power station (composed by multiple SMR) must be directed, overnight, to the cogeneration plants. Based on this requirement, the biorefinery has been sized at approximately 270 Million of Litres Per Year (MLPY) of biodiesel and 45 MLPY of ethanol, using about 340 MWe and 180 MWt.

Table 1
Details of the 5 scenarios investigated. Power consumptions and yields listed in the second half of this table come from calculations and references detailed in Appendix A.

Item		Open pond Standard	Fermenter	Unfavourable climate	Lipid rich algal strain	Low *N*
Cultivation type		Open pond raceway	Fermenter	Open pond raceway	Open pond raceway	Open pond raceway
Algal strain		*Chlorella Vulgaris*	*Chlorella Protothecoides*	*Chlorella Vulgaris*	*Botrycoccus Braunii*	*Chlorella Vulgaris*
Dimension of a single pond (Length × Width × Depth) [m × m × m]		100 × 10 × 0.3 [29]	–	100 × 10 × 0.3 [29]	100 × 10 × 0.3 [29]	100 × 10 × 0.3 [29]
Dimension of a single fermenter (High × Diameter) [m × m]		–	10.5 × 3.5	–	–	–
High-to-diameter ratio		–	3 [24,30]	–	–	–
Single unit area [m^2]		1000	9.6	1000	1000	1000
Single unit area occupied [m^2]		1000	17.3	1000	1000	1000
Single unit volume [m^3]		300	100	300	300	300
Capacity utilized [%]		100%	80% [23]	100%	100%	100%
Number of units		4000	160	4000	4000	4000
Total land occupied [ha]		400	0.3	400	400	400
Total volume [millions of L]		1200	16	1200	1200	1200
Average yearly temperature [°C] [23,31]		13	–	7	13	13
Average yearly solar irradiance [kWh/m^2d] [23,31]		3.65	–	2.8	3.65	3.65
Optimal temperature [°C] [23]		26	28	26	22	26
Final cell concentration [g/L]		0.33	51.2 [32]	0.21	0.33	0.26
Time needed for the growth		Continuous	167 h [33]	Continuous	Continuous	Continuous
Volume harvested per day [%]		25% [34]	–	25% [34]	25% [34]	25% [34]
Volume harvested per day [m^3/d]		300,000	–	300,000	300,000	300,000
Yield [g/m^2d]		24.75 [29]	–	15.47 [23]	24.75 [29]	19.25 [29]
Composition of alga	Protein	29.00% [25,35]	10.28% [36]	29% [25,35]	22% [23]	7% [35]
	Lipid	20.00% [19,25]	55.20% [36]	20% [19,25]	60% (average of [28,37–39]	40% [35]
	Carbohydrate	50% [25,35]	15.43% [36]	50% [25,35]	14% [23]	55% [35]
	(Of which glucose) [40]	90.4%	90.4%	90.4%	90.4%	90.4%
Area [ha]		**400**	**0,3**	**400**	**400**	**400**
Volume [ML]		1200	16	1200	1200	1200
Biomass harvested [ton/d]		99	94	62	99	77
Electric power [MWe]		5.22	16.37	4.94	5.14	5.10
Thermal power [MWt]		8.76	8.58	5.48	8.22	7.18
Total power [MWt]		24	57	20	24	22
Biodiesel [MLPY]		4.54	13.11	2.84	13.63	7.07
Ethanol [MLYP]		6.52	2.19	4.08	1.83	5.58
Total biofuels [MLPY]		11.07	15.3	6.92	15.45	12.65
Specific power [MWt/LY]		2.2	3.76	2.92	1.52	1.77
Specific land requirements [ha/LY]		36.15	0.02	57.83	25.88	31.63
Productivity of biofuel per alga harvested [L/kg]		0.340	0.495	0.340	0.475	0.500

Table 1 shows that fermenter is the most viable option for the microalgae cultivation, since the others require excessively extensive areas for an industrial application. Land occupation is 3 order of magnitude smaller for fermenters than ponds. This is explained by the fact that ponds are 10–30 cm deep (30 cm are assumed here, according to the majority of existing studies – see Table 1, Appendix A and [29]), whilst fermenters are assumed to be 10.5 m high [24,30]. Along with a higher cell density within the fermenters, this contributes to a more effective use of space.

As outlined in Fig. 2 most of the energy is required by the early phases of the process (i.e. cultivation and thermal dewatering). The time needed to reach the highest cellular level is 167 h [33]. During this time, the fermenters must be constantly monitored and stirred. Once the biomass is harvested, it should immediately enter the chain of dewatering processes, to avoid perishing and to avoid additional space and machineries for transportation and storage. Energy for the cultivation, harvesting and dewatering processes must be continuously provided over the day. As shown in Fig. 2, obtained from the biorefinery model explained in the Appendix A, the plant requires 98%–99% of the overall electric energy needs and 73% of the thermal energy on a continuous base. Therefore, from the technical point of view, an algae biorefinery is not suitable for the load following.

2.2. Desalination plant

The first desalination plants were built in 1960s and since then the installed capacity has been increasing very rapidly (about 50% per year), especially in the last decade [41]. The Nuclear-Desalination is a proved technology [14–17]. There are two main types of desalination technology: membrane or thermal. The former is the most adopted and needs electricity only, while the latter needs mostly thermal energy. The thermal process avoids the intermediate conversion of thermal power to electricity. The thermal process consists of the evaporation of the feed water stream through different stages, each one with a lower pressure than the previous.

The two main thermal technologies are the Multi Stage Flash distillation (MSF) and the Multi Effect Desalination (MED). The MSF is the simplest, but with the highest energy demand and the lowest cost effectiveness; the MED is cost-competitive with the Reverse Osmosis (the most common membrane technology), and is the preferred option for the new installed capacity. A Thermo Vapour Compressor (TVC) is usually coupled with MED to reduce the specific energy demand [42]. MED-TVC is suitable for the load following because:

- The desalination plant can be switched on and off anytime during the day and fresh water is very easy to stock. For a prompt activation, the pressure of the stages should be held constant during the day by steam ejectors or by a vacuum pump, both sized to vent the air leaking from the gaskets.
- The process is relatively simple and robust.
- The modularity of the MED-TVC plants permits very flexible arrangements for the cogeneration.

Nevertheless, some limitations exist:

- Switching on/off the desalination units is inefficient: the quality of the water produced in the start-up phase is poor and the output level is just 20–30% of the nominal capacity. The minimum power lever that must be supplied to the MED-TVC, in order to guarantee the immediate availability of standard quality water production is 25% of the nominal capacity.
- In the same manner, in the nuclear secondary loop, a minimum quantity of steam must always be provided to the turbines: a minimum level of 7.8% of the nominal steam rate could avoid the overheating when the SMR plant works in a "full cogeneration" mode [43].

As representative case, the paper focuses the analysis on a nuclear power station composed by 4 IRIS, i.e. 4000 MWt, consequently:

- Two IRIS are always set to produce electricity. They are always connected only to the grid, working at full power capacity.
- Two IRIS are connected to both the grid and the MED-TVC, in a way to switch their operation mode from "full electric power" (100% thermal power converted into electricity to the grid) to "full cogeneration" (100% thermal power diverted to desalination).

Therefore, the two IRIS connected to the MED-TVC would provide a maximum 1844 MWt to MED-TVC, net of the minimum amount of steam flowing into the turbines:

$$2{*}1000\ \mathrm{MWt} - (2{*}1000\ \mathrm{MWt}{*}7.8\%) = 2000\ \mathrm{MWt} - 156\ \mathrm{MWt} = 1844\ \mathrm{MWt}$$

A reasonable assumption for the thermal energy consumption of MED-TVC is 50 kWh/m^3 [42]; therefore, the output size of the cogeneration plant is 885,120 m^3/day:

$$\frac{1844\ \mathrm{MWt}{*}1000{*}24\mathrm{h/d}}{50\ \mathrm{kWh/m^3}} = 885,120\ \mathrm{m^3}\big/\mathrm{day}$$

This size is comparable to the biggest worldwide desalination plants: Jubail (Saudi Arabia) has 27 MED-TVC sub – units for a total capacity of 800,000 m^3/day.

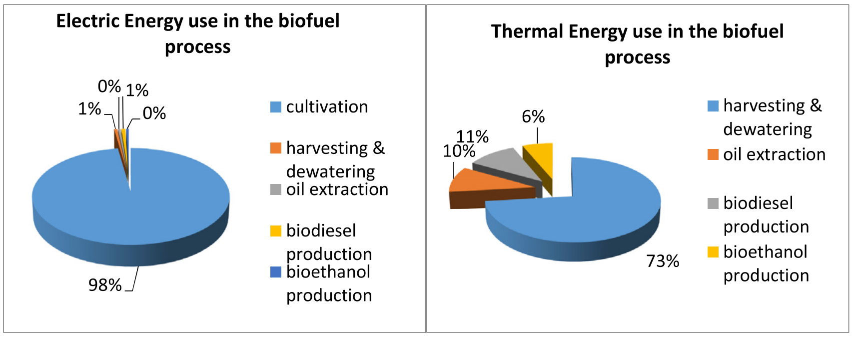

Fig. 2. Electric and thermal energy use in the biofuel process.

3. Economics

3.1. Methodology

Traditional methods for project economic appraisal are based on the Discounted Cash Flow (DCF) analysis that is based on the estimation of costs and revenues over the project life. Because of the time value of money, each cash flow is discounted back to current value, using the formula:

$$\mathrm{PV}_t = \frac{\mathrm{FV}_t}{(1+\mathrm{WACC})^t} \tag{1}$$

where FV = future value of the cash flow; PV = present value; WACC (Weighted average cost of capital) = discount rate per time period, i.e. weighted average remuneration rate expected for the financing sources mix invested in the project; t = number of the time periods.

The project NPV is the sum of the PVs of all the cash inflows and cash outflows:

$$\mathrm{NPV} = \sum_{t=0}^{T} \mathrm{PV}_t = \sum_{t=0}^{T} \frac{\mathrm{FV}_t}{(1+\mathrm{WACC})^t} \tag{2}$$

The rule is to invest in the project (i.e. build the cogeneration plant) if NPV is positive. The DCF methodology, although simple and easy to implement, presents three substantial criticalities:

1. The results are very sensitive to the choice of the discount rate.
2. The stochastic nature of the cash flows is not considered: DCF cannot capture market uncertainties, like electricity and fuel prices, or technical uncertainties, like construction costs that vary considerably along construction time [44], because cash flows are deterministic.
3. The implicit inadaptability of the management, unable to assume new decisions and improve the results after the resolution of some uncertainties [45].

These issues fostered to develop a new framework for the project appraisal called "*Real Options Analysis*." (ROA) The most common options available in the investment analysis are [46]:

- Option to defer and build: the possibility to postpone the decision to build, waiting for more favourable conditions and/or information, and eventually abort the project (not to build).
- Option to switch: the possibility to change the types of outputs produced or inputs used.
- Option to abandon: the possibility to abandon current operations permanently if market conditions became extremely unfavourable.
- Option to expand, contract, or extend the life of facility: possibility to increase capacity if it is profitable.
- Option to temporarily shut down the production process: possibility to stop and then start again the operations if they have become profitable.

The key advantage of the Real Options (e.g. building, delaying, switching etc.) is that, if properly managed, options can create an extra value and reduce risk for the investors that can exercise them [47]. ROA is most valuable when uncertainty is high; management has significant flexibility to change the course of the project in a favourable direction and is willing to exercise the options. Kodukula and Papudescu [48] summarises the main differences between DCF and ROA.

There are several methods to evaluate Real Options [52,53]. The choice of the evaluation method depends on the complexity of the problem and can be divided in three classes: Partial Differential Equations (PDE), lattice and simulations. PDE can be solved with Closed-Form models, using for example Black–Scholes or other similar formulas, analytical approximations or numerical methods like finite difference method. Lattice involve the creation of matrix that can be binomial, trinomial, quadrinomial or, in general, multinomial. Finally, simulations are based on Monte Carlo (MC) techniques. The methods adopted to valuate Real Options are summarized in Table 2.

The MC simulation is based on the idea that, by simulating thousands state variables' trajectories it is possible to approximate the probability distribution of terminal asset values. For every simulation, a defined number of paths is generated, sampling the values out of their stochastic processes. Since MC is computationally heavy, it is indicated for complex cases with many sources of uncertainty. In recent years the availability of powerful business computers and dedicated software are fostering more and more the adoption of MC simulation. MC methods allows to simulate several scenarios and provides useful information to the investors (e.g. forecasted NPVs) for their decision to invest in a plant able to switch the operation mode.

Because of the complexity surrounding decision about the investment the cogeneration plants, the MC simulations is adopted here and used to simulate the following uncertainties:

- Price of electricity;
- Price of water;
- Capital Cost of desalination plant;
- O&M for every plant just listed.

Table 2

Advantages and limits of the main models used in real options approach.

Solving technique	Partial differential equation		Lattice	Simulation
Method	Closed-form models (Black–Scholes equation)	Finite Difference Method	Binomial	Monte Carlo
Advantages	• Widely used in financial options • Very low computational effort	Accurate and Effective	• Volatility and strike price are easy to change over the option life • Flexible • Transparency in its underlying framework	• Very accurate method: it is possible to introduce realistic scenarios for the power industry • Conceptually easy to understand
Main disadvantages	• Difficult to apply for practitioners because of its mathematical complexity • Being developed for the financial market most of the hypotheses are not met in power plant investment evaluation	• Very complicated • Requires undefined time to resolve the equations	• More approximations involved (less accurate) • Requires higher time increments to reach a good approximation	• High computational power required

3.2. Option to defer and build the MED-TVC plant

For the purpose of this work, SMR are assumed as already built, and the option to build is applicable only to the desalinisation plant. In other words, the investment in the nuclear reactors is out of the decision scope: consequently, construction, operation and maintenance costs (O&M) of the SMR are not considered as relevant and differential in the decision about building the desalination plant. The decisions maker is assessing the interest in building an MED-TVC plant close to its existing fleet of SMR.

In the option to build conceptual framework, it is possible to proceed with the investment only when the uncertainties are solved in a positive way. The investor can wait for a period to see how some uncertainties (i.e. market prices) are evolving and to accumulate enough information to perform a reliable forecast. In this way, the risk associated with the project decreases and the probability of success increases. The investor has the possibility to choose whether to build straight away, or to wait to build the plant, or eventually abort the plan. Then, the option to build gives an extra worth to the investment, considering that for the investor it is not mandatory to invest under unfavourable conditions.

The analysis starts with the development of the classic DCF, and then the uncertainties are introduced and simulated with the MC method. By gathering more information with the time passing by (i.e. years), the algorithm, simulating the investors behaviour, can take a better decision regarding the build/wait/abort strategy. If an investment scenario has an expected negative NPV the decision is "not to build" and the opposite if the NPV of a given scenario is positive. By performing an NPV ex-ante calculation, the investment plan aborted when negative NPV are forecasted. "Negative NPV" are recorded as "NPV = 0", because the investment is aborted. Finally mean value of non-negative NPV are calculated and recorded. Further details for this calculation methodology are given in Appendix B.

3.3. Option to switch

The SMR coupled with the desalination plant has two production modes: one suits to the day-time hours, and consists of producing electricity; the other one is run at night-time, to provide desalinated water. The "option to switch" is given to the manager of the plant: depending on the current prices of water and electricity, the plant can switch from electricity to water production (and vice-versa) upon economic convenience, increasing the revenues. In real NPP this is done with the data of the "day ahead market", in a way that the plant owner already knows 24 h before IF and WHEN to switch the current production mode. With this option, the advantages of a flexible production mode have been studied (with the chance to switch the production of 2 IRIS out of 4, from electricity to water production, at any 1 h time-interval), in comparison with a "Static" load following regime, where an "automatic" production switch applies at fixed times (e.g. 10 p.m. and 6 a.m.), regardless the relative prices of electricity and water.

To simulate the daily price of electricity, time is divided in 48 equal intervals. For every time interval a random component and a drift are extracted from their distributions, to simulate the daily prices, trends are calculated from the electricity prices in UK, according to [49].

Table 3 summaries the most relevant technical parameters for the nuclear plants in the two different production regimes. When 2 out of 4 IRIS are dedicated to the desalination (off-design), they provide most of their steam to the MED-TVC plant, with the exception of the minimum stream flow to avoid the turbine overheating (7.8%); the 2 reactors producing electric energy, have to supply electricity for the desalination process.

Table 3
Electricity and water produced per hour by 4 IRIS reactors operating by-design and off-design mode.

Nuclear site. Production by-design		
	Full electricity IRIS (values per unit)	IRIS connected to MED-TVC (values per unit)
Power per unit (electric, nominal)	335 MWe	335 MWe
Power per unit (thermal)	1000 MWt	1000 MWt
Number of units	2	2
Minimum thermal power to MED-TVC	0	231 MWt
Thermal power to turbine	1000 MWt	770 MWe
Electric power	335 MWe	258 MWe
Minimum electric power MED-TVC	0	10 MWe
Electric power to the grid	335 MWe	248 MWe
Electricity for sale, per hour	335 MWh	248 MWh
Water for sale, per hour	0 m^3	4610 m^3
Nuclear site. Production off-design		
	Full electricity IRIS (values per unit)	IRIS connected to MED-TVC (values per unit)
Power per unit (electric, nominal)	335 MWe	335 MWe
Power per unit (thermal)	1000 MWt	1000 MWt
Number of units working in this production mode	2	2
Thermal power MED-TVC	0	922 MWt
Thermal power to turbine	1000 MWt	78 MWt
Electric power	335 MWe	0
Constant electric power MED-TVC	41 MWe	N/A
Electric power to the grid	294 MWe	0 MWe
Electricity for sale, per hour	294 MWh	0 MWh
Water for sale, per hour	0 m^3	18,440 m^3

When all of the 4 IRIS units are in by-design mode (full electricity production), the reactors have to provide the MED-TVC with a minimum electric and thermal power to grant the prompt plant re-start.

According to the market prices, revenues are calculated each 30 min for both by-design and off-design arrangements and then compared. If the revenues from the production of electricity are higher than the revenues from production of water, the plant switches to the full electricity production regime, and the opposite. In the calculation, only the revenues are considered, since all the costs (personnel, fuel etc.) are fixed. Consequently, a decision based on the revenues corresponds to a decision based on profit maximisation. The revenues stream on the entire lifetime of the plant are calculated in different scenarios. Annual revenues are calculated as the product of the weekly revenues, multiplied for the number of weeks in a year (52.14) and for the availability of the system (90%). Different operation modes are considered:

Table 4
Static and flexible load following output per hour, for a single nuclear reactor.

	Load following Static		Flexible load following			
			By-design IRIS stand alone		Off-design IRIS + MED-TVC	
	Electricity	Water	Electricity	Water	Electricity	Water
IRIS 1	294 MWh	0	41 MWh	0	0	0
IRIS 2	0	4610 m^3	248 MWh	0	0	13,830 m^3
IRIS 3	294 MWh	0	41 MWh	0	0	0
IRIS 4	0	4610 m^3	248 MWh	0	0	13,830 m^3
TOTAL	588 MWh	9220 m^3	577 MWh	0	0	27,660 m^3

- Load following *static*: 2 a.m.–6 a.m. off-design operation mode (2 SMR dedicated to electricity generation and 2 SMR to cogeneration), 6 a.m.–2 a.m. by design operation mode (all the SMR fleet dedicated to electricity generation)
- Load following *flexible*: variable according to economic profitability (i.e. higher revenues)
- By-design: the plant (4 SMR) always run by-design (electricity production)
- Off-design: 2 SMR always run off-design (cogeneration), while the two left are constantly operated for electricity generation.

Further details are given in Appendix B.

3.4. Scenarios definition

3.4.1. Option to defer and build

The economic effectiveness of the investment is tested under different hypothesis and, without losing of generality, the paper presents the following scenario analysis (Table 5).

Scenario 1 is defined by standard prices of the different output: water price is 1.6 $/m^3 and electricity price is 0.04 $/kWh (wholesale electricity price during the night for the specific power plant). For the assessment of the option to defer and build (from now on, “option to build”), the market price of electricity represents an opportunity cost, as far as thermal power is used to produce water instead of electricity, electricity sales are missed.

Scenarios 2 and 3 test the sensitivity of results on different prices of water. Scenarios 4, 5 and 6 perform a sensitivity analysis against different prices of electricity. In particular, in scenario 4 no economic value is assigned to the sale of the excess electricity on the market demand, during night-hours (electricity price = 0). This happens for some NPP e.g. in France during night-time and for this reason scenario 4 is also referred to as “France (pure load following)”. Scenario 5 considers a very cheap sale of electricity. Finally, in scenario 6 the market demand fixes the electricity price at 0.06 $/kWh. Scenario 7 assumes a price of water and electricity close to the breakeven point calculated for the power plant (Fig. 9). Table 5 recaps all the scenarios considered for the assessment of the option to build the MED-TVC plant.

3.4.2. Option to switch

In order to assess the “option to switch” between alternative generation modes, different prices of output products are considered. Indeed, only specific combinations of prices make the switch profitable: if water is significantly more expensive than electricity, the nuclear plant station would always work in off-design mode, maximising the exploitation of the desalination plant, and the opposite when water price is too cheap. Table 6 summarises the of electricity prices during night time (2–6 a.m.).

Table 5
List of scenarios to evaluate the option to build the desalination plant. (i) The Beta PERT distribution, a default choice in cost estimation, requires 3 values namely minimum (a), mode (b) and maximum (c).

Scenario name	Water [$/m^3]. (i) Values for the PERT distribution^{a,b,c}	Electricity. Night window [$/kWh], (i) Value for the PERT distribution^{a,b,c}
1 – standard case	1.52; 1.6; 1.68	0.038; 0.040; 0.042
2 – expensive water	2.38; 2.5; 2.63	0.038; 0.040; 0.042
3 – cheap water	1.14; 1.2; 1.26	0.038; 0.040; 0.042
4 – France (pure load following)	1.52; 1.6; 1.68	0
5 – cheap electricity	1.52; 1.6; 1.68	0.019; 0.02; 0.021
6 – night price	1.52; 1.6; 1.68	0.057; 0.06; 0.063
7 – breakeven case	1.43; 1.5; 1.58	0.029; 0.030; 0.032

Table 6
Electricity prices for 5 scenarios studied for the option to switch.

Scenario	Electricity night price [$/kWh]
1 – France (pure load following)	0.00
2 – cheap electricity	0.02
3 – standard electricity	0.04
4 – night price	0.06
5 – market price	Variable

3.4.3. Common parameters

Expected construction costs for MED-TVC are assumed in the range of 1300 [$/(m^3/d)] [50], and following a PERT probability distribution with the extreme values at 70% and 130% of the mean value. The expected cost escalation (drift) is also extracted from a Pert distribution. Finally, a random component is added to the drift to confer a Brownian path to the price trend. Table 7 shows other financial input to the economic analysis. The depreciation index and the plant operating lifetimes are assumed according to [42,51]. The parameters involved in the calculation of WACC include the relatively high financial risk on a large capital-intensive desalination plant.

4. Results

4.1. Investment appraisal – option to defer and build

The value of the investment and the option to build strongly depends on the scenario considered (Table 8). If it is very profitable to produce fresh water, then there is no interest to delay the investment. In other word, when the price of water to the cost of electricity ratio is above a given value, the construction of the MED-TVC becomes profitable. This applies to the scenarios 2, 4 and 5 (denominated “expensive water”, “pure load following”, “cheap electricity”). In these cases the low price of the electricity and/or the high price of the water strongly supports the construction of the MED-TVC plant. This is a remarkable result since it demonstrates that the SMR fleet operation in a load following mode can be profitable, in some countries/scenarios, by means of the coupling of an MED-TVC with the nuclear plant station.

On the contrary, if the night price of the electricity is relatively high compared to the price of water, then the investment in the desalination plant must be postponed and eventually aborted. The “option to build” does not hold any value since the negative NPV already prevents from undertaking the investment: the coupling of SMR and MED-TVC plant has no economic benefit (i.e. does not grant the required profitability). If the investment NPV calculated from the DCF analysis is either definitely profitable or negative, there is no interest in holding a build option since the investment

Table 7
Financial inputs for the economic analysis.

Depreciation index	8%
% of debt	60%
% of equity	$1 - W_d = 40\%$
Cost of debt	8%
Tax rate	40%
Cost of equity	12%
WACC	8%
Average drift price (D)	2% per year
Average plant escalation cost (E)	3% per year
O&M escalation cost (M)	2% per year
Economic lifetime for the desalination plant	25 years

Table 8
Option to build (results).

	DCF	Real option					
	Expected value [M$]	Expected value [M$]	% NPV < 0	% of NPV > 0	No Inv	Year	Option value [M$]
Standard case	−123	31	9.60%	23.10%	67.30%	10	154
Expensive water	674	674	1%	99%	0%	0	0
Cheap water	−590	0	0%	0%	100%	Not applicable	0
Pure load following	572	572	0%	100%	0%	0	0
Cheap electricity	229	229	1%	99%	0%	0	0
Night price	−583	0	0%	0%	100%	Not applicable	0
Breakeven case	−31	42	10.60%	27%	62.40%	7	73

decision and strategy is relatively clear: in these cases, the option value is very low or possibly zero. The DCF is an adequate decision tool and there is no reason for a "wait and see" strategy (Table 8).

If the price of water and electricity is relatively balanced and there is a relevant uncertainty about the investment strategy, then the "option to build" is very valuable. This very common situation has been simulated by scenarios 1 and 7 ("standard case" and "breakeven case"). In these cases, the scenario's uncertainty is reduced by waiting and acquiring more information on the market conditions, allowing the investors to prevent unfavourable histories and abort the investment plan; conversely, in favourable scenarios, investors may gain confidence about the possibility to make a profit (have a positive NPV).

In particular, scenario 7 ("breakeven case") highlights the real options approach advantages as a decision tool (see Fig. 3). With the classic DCF methods the NPV calculation is negative and the decision would be to "avoid the investment" in the desalination plant. Under the option to build approach, the investor postpones the decision and reduces the risk, avoiding most of the negative scenarios and taking advantage of the positive ones. In fact, at the beginning of the period (year 0), information is not enough to make accurate forecasts and, with the available information, the NPV calculation is negative (See Appendix B). After 5 years the asymptotic value of the option is reached, meaning that the information collected has improved at its best the NPV estimation and has offset several unfavourable scenario (the green line in Fig. 4 remains constant at about 27%).

4.2. *Option to switch*

For every scenario, the following values are investigated:

- option value: calculated as the difference between "static load following" and "flexible load following" (as defined in par. 3.3)
- option value: calculated as the difference between NO load following and "flexible load following" (as defined in par. 3.3)
- actual NPP used capacity
- actual MED-TVC used capacity

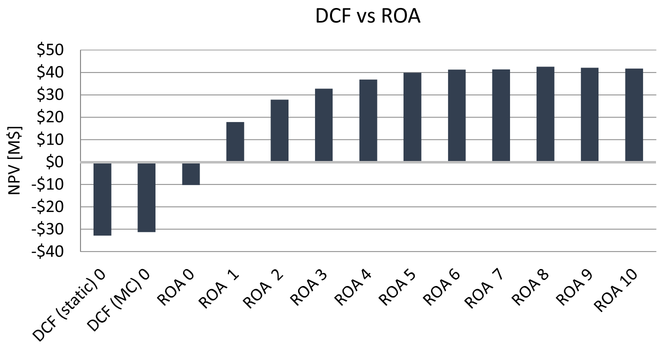

Fig. 3. NPVs calculated with DCF methods and real options approach at different years. Results for scenario 7 of desalination case.

As shown in Fig. 5, the option to switch has a positive value only when revenues from water and electricity sales are comparable. If the price of water is very high or very low the option to switch has no value, since the plant owner will always produce electricity (very low price of water, high price of electricity) or water only (high price of water, low price of electricity). Switching is profitable when the prices variability is such that, during the day, revenues from the electricity sale overcome the ones from the sale of water or vice versa.

Fig. 6 compares the revenues from the "flexible load following" (i.e. production switch according to a constantly updated calculation of the economic benefit) and the "static load following" (operation switch performed in pre-defined time windows), considering different water prices. The higher is the water price, the higher is the profit from the "flexible load following" because the operating switch flexibility allows to reap the water sale revenues. Fig. 7 compares the "flexible load following" and the no-load following (i.e. full electricity or full water production) regimes. In Fig. 6 the option value seems to reach maximum at a water price of 2.8 $/m^3$ and, based on its trend, it seems that its value could rise further; instead, whenever the price of water is very low or very high, there is no value in switching the production mode: the preferred output will always be either electricity (with low water's price) or water (with high water's price). With "static load following mode", off-design operations are activated between 2 a.m. and 6 a.m., if during this period of time, revenues from water sale are lower than electricity (e.g. due to low price of water) higher profit opportunity is missed. On the contrary, flexible load following would allow to keep the operations on the full electricity generation, without switching to a less profitable output (i.e. water). Fig. 7 shows the influence of water price on the difference

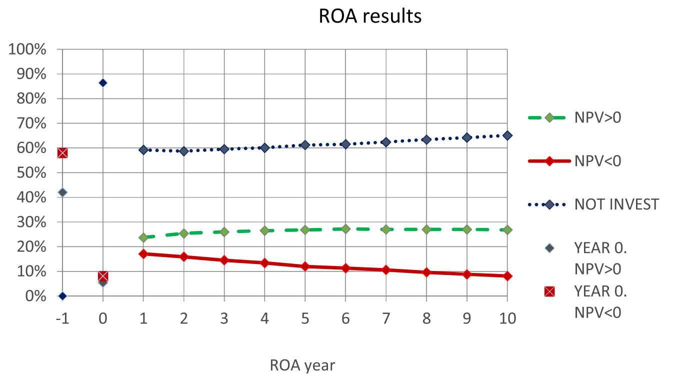

Fig. 4. Probability of not investing because of the likelihood of having negative NPV (blue dotted line); probability of final positive NPV (green dashed line) and final negative NPV (red continuous line). Results obtained for scenario 7 of desalination case. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

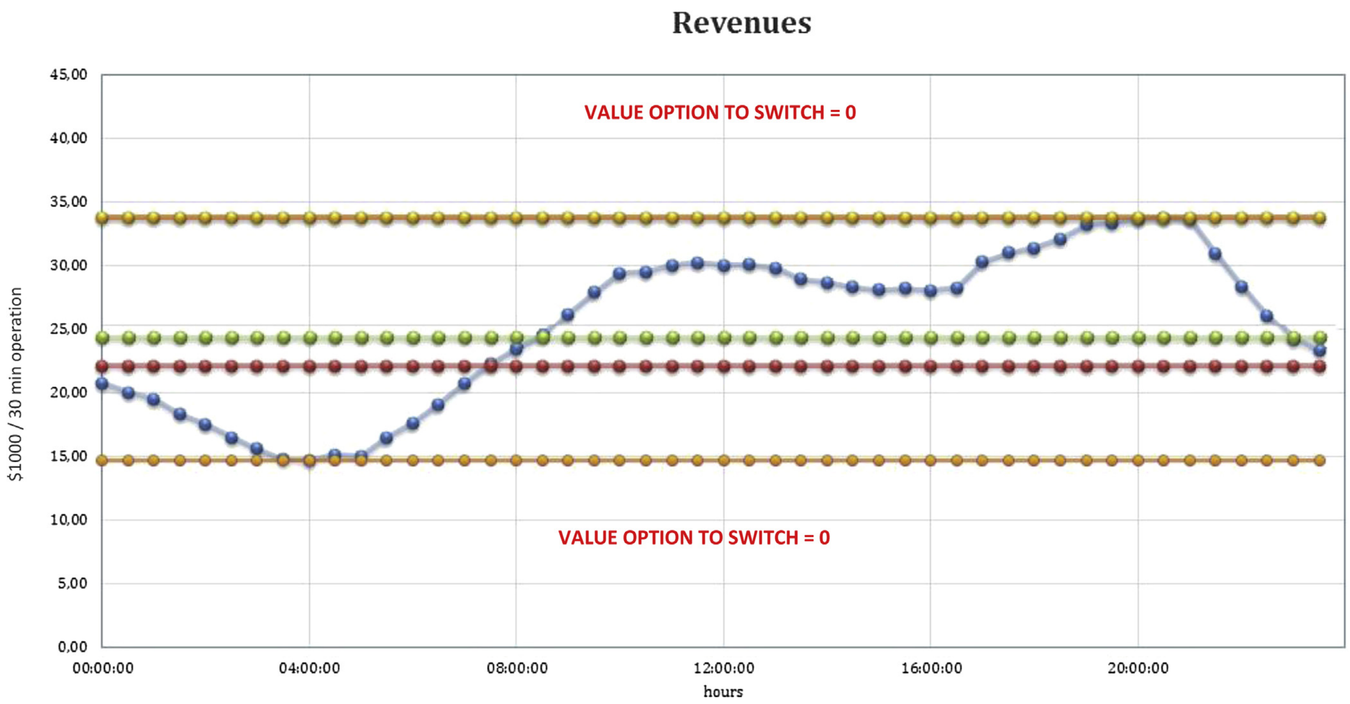

Fig. 5. The option to switch is valuable only between specific thresholds for the price of water and electricity. blue = revenues from the sale of electricity, red = revenues from the sale of water, green = average revenues from the sale of electricity, yellow = MAX and min revenue from the sale of electricity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between flexible load following and no load following. Values are obtained by recursively applying the option to switch algorithm, as described in Appendix B, over a range of water prices. The figure shows that, as said, whenever the price of water is very high (i.e. above from 2.8 $/m^3) or very low compared to the electricity price, the option to switch has no value because it is convenient to set the operation on the water cogeneration or the opposite, respectively. When revenues from the water sale are in the range of the electricity sale, then the option to switch gets a positive value.

With low water price the desalination process is activated only few hours per day and only if the price of water is higher than 0.8 $/m^3. Otherwise, the capacity of the MED-TVC plant is fixed to 25%, which represents the minimum working level. In the range of 0.5–1 $/m^3 the advantage of the flexible load following is minimum in comparison with the static load following, because the production mix and the plant operation mode resulting from an economic trade-off calculation in the flexible mode, is very similar to the static load following. The benefit of operating flexibility is even more evident when the electricity price is cheap (Fig. 7).

When the water price is in the range 1.5–2 $/m^3, the value of the switch option is significant both in comparison with the static load following and with the no-load following (always off-design production). Within this range, there is also a good trade-off in the plants exploitation: the used capacity is approximately 60–70% (see Fig. 7). When the price of water rises over 2–2.5 $/m^3, the switch option loses its value because it becomes preferable to produce as much water as possible: indeed, in Fig. 8 the used capacity of the desalination plant overcomes 80%.

4.3. Discussion

The liberalization of electricity markets and the increasing deployment of non-dispatchable renewable energy sources, such as solar and wind, poses a challenge for traditional plants (fossil and

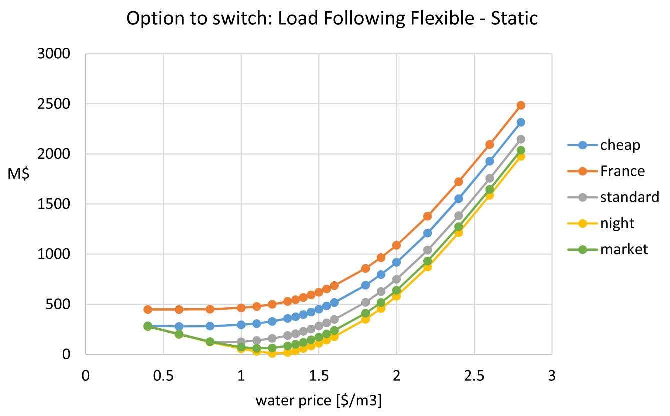

Fig. 6. Value of the option to switch based on water price. Comparison between a flexible and a static load following.

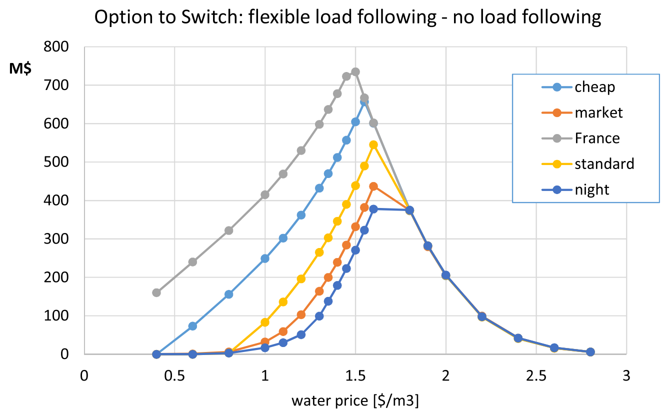

Fig. 7. Value of the option to switch based on water price. Comparison with no load following mode.

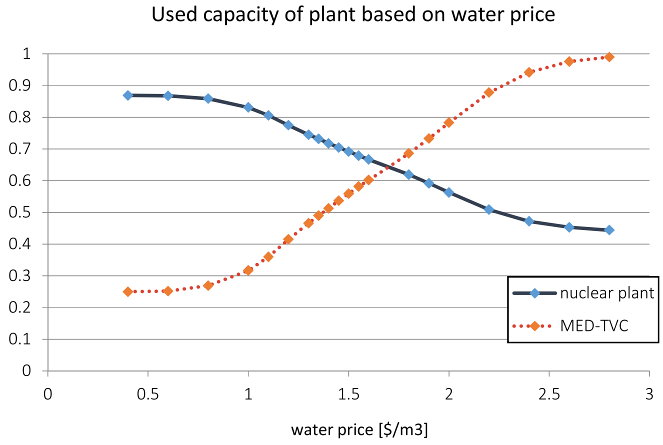

Fig. 8. Percentage of used capacity of the power and desalination plants, at different water prices. Results displayed for scenario 5 (market price).

nuclear) in terms of generation flexibility. For base-load power plants, (usually coal and nuclear) this is a new scenario requiring the development of new technical/economic models to assess the possibility of operating in a load following mode. The investment in a nuclear power plant is a multi-billions cost for the utility and the electricity production has to be maximized in order to recover the investment as soon as possible. The results in section 4.1 and 4.2 reveal that the production of fresh water by desalination is a reasonable way to maintain profit when the demand and price for electricity is particular low. In fact there is a break-even price for desalination, above which it becomes more profitable than electricity (as shown in Fig. 9 — water price vs. night-time price of electricity). On the one hand, if residual electricity demand is left unsatisfied by the supply in the night hours (and consequently electricity is sold at a price of about 0.05–0.06 \$/kWh) the break-even price of water is as high as about 2–2.2 $\$/m^3$. But, if there is an excess of electricity supply, it is reasonable to assume that it could be sold at very low prices and the power generation is reduced in the primary side of the nuclear plants (as in France). In these conditions, the breakeven price of water is lower: about 1–1.8 $\$/m^3$. These break-even price ranges of water match with those that maximise the option value and makes desalination a convenient process.

5. Conclusions

NPP are base-load plants but present and future scenarios with significant share of renewable power in the generation portfolios require them to operate in a load following mode. NPP are capital-intensive plants with an operation cost almost independent from the amount of electricity generated. To maximise profitability and safety NPP need to maximize their load factor. Performing the load following by reducing the power rate in the primary side has two drawbacks: it introduces thermo-mechanical stresses and postpones the investment pay-back time. Therefore, the goal of this work is to assess the option of using the excess thermal power for cogeneration purposes, thus improving the investment economics and the capability to adapt the electricity production to the market demand. In particular the research focuses on multiple SMR because they offer the possibility to split the total power of the power station: some units may be fully dedicated to the electricity production (during off-peak hours) and some others to the cogeneration of alternative products (i.e. desalinated water). This enables the electricity load following at site level, while keeping all the plants at maximum efficiency. The load following with large units is less attractive since off-design operation at reduced power rates decrease the overall conversion efficiency.

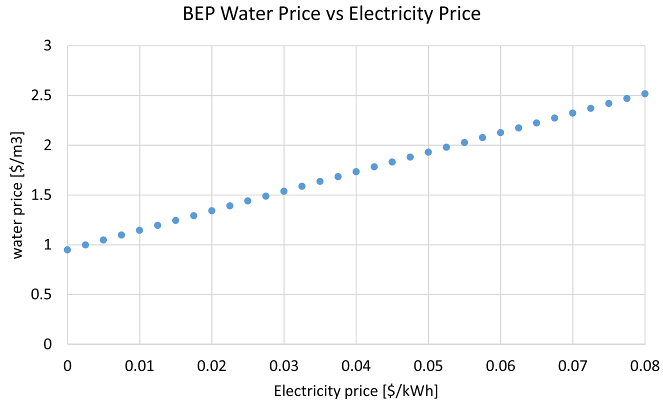

Fig. 9. Comparison between the price of water and the price of electricity to reach the Break-Even Point.

In particular this research tested two possible by-products for cogeneration purposes: biofuel from algae processing and water desalination with an MED-TVC plant. The main technical results are:

- among all the possible technologies to cultivate the biomass for a biorefinery, fermenters are the most viable option from an economic point of view, due to their reduced land occupation.
- the fermenter biorefinery must 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 biorefinery is not suitable as a thermal power “buffer” for the excess nuclear power.
- on the contrary, a desalination plant gives a nuclear site a flexible buffer for its excess power generation, according to the load following strategy.
- the size required for an MED-TVC plant in this simulation is similar to the largest plants existing worldwide and therefore feasible.

With a cogeneration plant, the load following operation of an NPP site would be driven by economic considerations and the above-mentioned technical issues would be solved by running the primary side at full capacity. Economics results show that the desalination plant can be a viable investment in several scenarios. Moreover, the model empirically validates the ROA theory: if there is uncertainty about the outcome of an investment, the ROA can evaluate more positively the profitability of this project in comparison to what it is obtained with a classic DCF method. In addition, the Option to Switch is able to add an extra worth to the investment project given by the operation flexibility. The advantage given by the possibility to switch between two alternative output products strongly depends on the combination of relative prices of water and electricity. Nevertheless, the break-even prices of electricity and water fall reasonably close to current market values. This suggests that performing the load following with a combination of multiple SMR and MED-TVC is technical and economically feasible.

Appendix A. Biorefinery Model

The aim of this appendix is to clarify how the biorefinery has been modelled and how the authors obtained the results used in this paper. The Biorefinery process includes the following phases (see Fig. A1): Cultivation, Harvesting & Dewatering, Oil Extraction, Transesterification and Fermentation.

Cultivation – the following technologies have been analysed [23]: open ponds, photobioreactors and fermenters. Since photobioreactors have demonstrated poor energy efficiency, commercial reliability and cost-effectiveness [52,53], they have not been further considered. Ponds and fermenters are very different from both a biological and a technical point of view. Within ponds, the microalgae grow autotrophically and need much more water than in fermenters. Fermenters have a more compact layout, in which algae grow heterotrophically in a stirred fluid (medium) with a very high density. The input of cultivation phase is electric energy: in the case of open ponds, it is required to mix and pump the water and to supply CO_2 to the algae [19,25,54]; in the case of fermenters, energy is used to continuously stir the fluid [55–57].

Harvesting and Dewatering – The oil extraction from algae will require a water content reduction of the medium, to reach a dry content of 90% [29,58]. The most reliable dewatering technology is thermal drying, which is a very energy intensive process. Various mechanical drying methods are introduced upstream [59]: many electro-mechanical dewatering techniques are currently employed, even simultaneously: sedimentation, flocculation, floatation, centrifugation and filtration [23,60]. In this study dewatering is carried out in four steps: flocculation, centrifugation (disk stack centrifuge), filtration (chamber filter press) and thermal drying, consistently with [25,53]. The input data for dewatering are: cultivation yield, process efficiency (e.g. the percentage of microalgae lost), water content achieved in the process and energy needs for each step.

Oil Extraction – This third phase separates the "main bricks" of the biomass. It isolates the lipids and the carbohydrates to drive them to the different chemical processes for the production of biodiesel and bioethanol respectively. There are few well-documented procedures for extracting oil from microalgae, i.e.: mechanical pressing, homogenization, milling, solvent extraction, subcritical or supercritical fluid extraction, enzymatic extractions, ultrasonic-assisted extraction and osmotic shock [61]. In this study the solvent extraction method has been selected, due to its reliability, popularity in relevant studies and consequently greater availability of data. The solvent (hexane) extraction is further divided in sub-steps as well: grinding, oil extraction, meal processing, solvent recovery, oil recovery, oil degumming and waste treatment [62]. The input data for oil extraction are: dried biomass quantity from the thermal drying, overall efficiency (percentage of lipid extracted) and the power needs.

Transesterification – It is currently the most common chemical reaction used to produce biodiesel. It includes the following sub-steps: oil refining, two-step transesterification, biodiesel purification, glycerin purification (glycerin is a saleable co-product of this chemical reaction), methanol recovery and waste water treatment [62,63]. The input data of this phase are: the crude oil yield from the oil extraction, process efficiency and power consumption.

Fermentation – This phase convert the "waste" coming from the oil extraction into ethanol. The waste of the extraction process is typically called "algae cake" and has a very high content of carbohydrates (glucose of starch) and cellulose that are hydrolysed via an enzymatic process [40,64]. Fermentation includes: pretreatment, fermentation, distillation, dehydration, purification and drying. The input data of this phase are: the mass of the "algae cake", the efficiency (percentage of glucose hydrolysable by the enzymes) and the power consumption.

Fig. A1 shows the model of the biorefinery with inputs and outputs for each phase. The data used for the calculation are summarized in Table A1. The calculation of the ethanol yield is done according to the equation (A1). Data from this Appendix has been used to calculate the power consumptions for different scenarios, as detailed in Table 1 and Fig. 2.

$$\text{Ethanol yield} = \frac{\%\text{carbohydrates} \times \%\text{glucose hydrolizable} \times \%\text{ethanol yield}}{(1 - \%\text{lipid} \times \%\text{oil extracted})} \tag{A1}$$

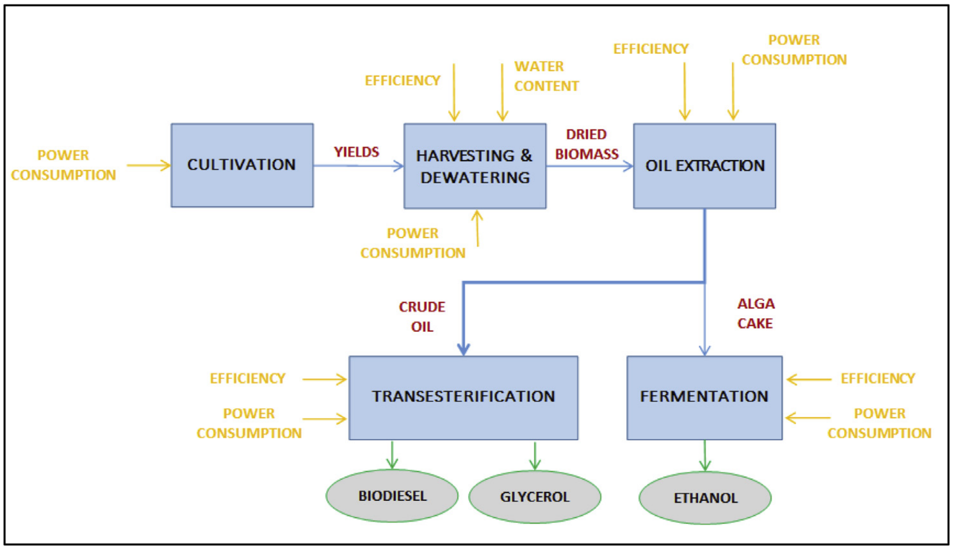

Fig. A1. Biorefinery inputs/outputs scheme.

Table A1
Key values for the biorefinery.

Phase	Sub-step	Efficiency	Power consumption
Cultivation	Mixing & pumping water (open pond only)	–	71.2 kWh/m^3 [25] (electric energy)
	CO_2 circulation (open pond only)	–	3.72 W/m^3 [65]. (electric energy)
	Stirring medium (fermentation only)	–	1 kW/m^3 [57] (electric energy)
Harvesting & dewatering	Flocculation (0.033%–2%) [23,25,29,60]	91% (average of [29,66])	0 (Flocculation requires only pumping water, which is already counted in the cultivation phase)
	Centrifugation (2%–12%) [53,60]	90% [23]	1 kW/m^3 [60] (electric energy)
	Filtration – press (12%–27%) [53,60]	90% [67]	0.88 kWh/m^3; [53] (electric energy)
	Thermal drying (27%–90%) [25,29,53,67]	95% (conservative assumption)	2.26 MJ/kg [latent heat of evaporation (at $p = 1$ bar)] (thermal energy)
Oil extraction (via solvent extraction with hexane)	Whole process, from the grinding to washing, oil recovery and oil degumming (see text)	92.5% [62]	25.46 kWh/ton [62] (electric) 284.22 kWh/ton (thermal)
Biodiesel production (via transesterification)	Oil refining	96% [62]	100 MJ/ton (electric) 600 MJ/ton (thermal) [63]
	Transesterification and downstream process	Biodiesel 99.4% Glycerol 0.093% [62]	200 MJ/ton (electric) 1600 MJ/ton (thermal) [63]
Ethanol production (via fermentation)	Pre-treatment	–	0.775 MJ/L [42]
	Fermentation and downstream process	27.7% (see previous equation)	6.27 MJ/L [42]

Appendix B. Algorithms

Consistently with the textbooks [68,69] the algorithm is based on a series of Monte Carlo simulations. As discussed in Section 3.1, Monte Carlo simulations allow for more realistic modelling of the key uncertainties affecting the project when compared to closed form models, such as the Black and Scholes equation.

Option to build

The algorithm to evaluate the option to build follows these steps:

STEP 1 – Inputs definition. Values and distributions of capital cost, operation cost, revenue and WACC, for each scenario (see section 3.4.3).

STEP 2 – Calculation of the NPV as described in section 3.1. The NPV is calculated with a Monte Carlo evaluation – called "DCF (MC)" – and using the mean value of the different distributions, called "DCF (static)". The latter is the typical result of a deterministic business plan. In a Monte Carlo evaluation with N iterations, the NPV is calculated N times. The result is the probabilistic distribution of the expected NPV.

STEP 3 – This is the kernel of the real option evaluation. A set of values is extracted (from data at Step 1) for the first time period ($t = 0$). The investor must wait and decide if investing or not at the end of the period $t = 0$, on the basis of the information available at this time. If this information (which is assumed to be constant on the whole lifecycle) leads to the forecast of a positive NPV, then the investor will decide to invest. Therefore the decision-maker invests "I" times and abort the project "N–I" times. For "I" times the algorithm runs the complete Monte Carlo evaluation (with the random components) and records both positive and negative NPV. The NPV of the N–I stories where the investment is aborted is set to zero. The average of all the NPV is called "ROA 0".

STEP 4 – The investor must wait and decide if investing or not at end of year 1, knowing the values (input and output) of year 0 and 1. The algorithm assumes that the trend from year 0 to 1 will last for the whole plant lifecycle. If this information translates into a positive NPV forecast, the investor decides to invest. Therefore the decision-maker invests "L" times and the abort the project in the residual "N-L" cases. For "L" times the algorithm runs the complete Monte Carlo evaluation (with the random components) and records both positive and negative NPV. The N-L cases where the investment is not performed, correspond to NPV = zero. The average of all the NPV is called "ROA 1".

STEP 5 – The investor must wait and decide if investing or not at end of year 2, knowing the values of year 0, 1 and 2. The algorithm assumes that the trend highlighted in years 0, 1 and 2 will last for the whole project lifecycle. If this information leads to the calculation of a positive NPV, the investment is approved. Here again the decision-maker invests "M" times and the project is aborted "N-M" times. For "M" times the algorithm runs the complete Monte Carlo evaluation (with the random components) and records positive and negative NPV. When the investment is not pursued, NPV is set to zero. The average of all the NPV is called "ROA 2".

In the same way, this approach ("wait, evaluate and decide if building or not") is replicated for the following years and, consistently with the Real Options theory, waiting for new information decreases the chance to have a negative investment NPV. On the other hand, due to the time-value of money, if the investor "waits too long" the present value of future cash flows becomes very small. After a certain number of years (about 7, see results in section 4.1), the benefit from new information gained balances the effect of discounting; waiting further will decrease the value of future cash flow. For this reason, the algorithm is stopped after 11 years (i.e. 10 years of information gathering).

STEP 6 – All the value recorded, "DCF (MC)", ROA 0, ROA 1, ROA 2, etc. are plotted in a graph. Consistently with the real options theory, the difference between the maximum ROA result (usually ROA 6 or 7) and "DCF (MC)" is positive and represents the value of the option.

Option to switch

As said in paragraph 3.4.2, there are two operating modes for the NPP and desalination combined plant: one is electricity production mainly during the day-time; the other is the cogeneration of desalinated water by two out of the four SMR, mainly during night-time. There may be a "static mode" to perform the load following that does not imply any production switch option: e.g. every night, form 2 a.m. to 6 a.m. it is decided that two SMR are dedicated to water desalination. In this "static mode", the plant does not have any degrees of freedom, therefore there is no option to exercise. A real option exists if the plant manager can decide if and when to switch between different operating modes, based on the available information on the output product prices. The steps to calculate the value of the switch option are:

STEP 1 – Inputs. Values and distributions for capital cost, operation cost, revenue and WACC are introduced for each scenario (see sections 3.4.2 and 3.4.3).

STEP 2 – Simulation of the trend of wholesale electricity's price, using UK data from Ref. [49]. The day-time is divided in 48 intervals of 30 min. For every time interval a drift and a random component are extracted by their respective distributions (see sections 3.4.2 and 3.4.3). The price of water is assumed to be constant over the week, only an annual trend is introduced.

STEP 3 – The plant manager knows the wholesale electricity price in advance thanks to the "day ahead market"; he can calculate costs and revenues of producing electricity or water and select the most profitable option. Revenues are therefore calculated for each 30 min for both the operation modes: "static switch" and "flexible switch" with a real option to exercise for the investment profit optimisation.

STEP 4 – The revenues and cost for the entire time life of the plant are calculated and discounted back to the present, by means of an appropriate WACC.

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