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Using Real Options to value two key merits of Small Modular Reactors

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Abstract. Small Modular Reactors (SMRs) can be better choice respect to large reactors, according to their inherent construction flexibility and their short construction time. In the energy sector, the Discounted Cash Flow (DCF) is usually used to evaluate an investment. However, "Real Options" method is a better choice respect to DCF approach underestimates the importance of flexibility during the investment decision. In this chapter, starting from real options approach, two fundamental characteristics for the choice of the construction of SMRs are defined: the time to market and the adding of a new plant on a typical portfolio. The computational model described in this chapter assesses the superior performance of SMRs in the UK.

Keywords: Energy, Economics & Finance, Management

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1 Introduction

The International Atomic Energy Agency [1] defines Small Modular Reactors (SMRs) as *"newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises"*. Several SMRs designs, detailed in [1–3], are currently at different stages of development. [4] provides a good summary of the innovative feature of SMRs; "*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.*"

A recent review related to the economics and finance of SMR is presented in [5].

One of the key SMR characteristics is the smaller size with respect to traditional Large Reactors (LRs), determining the lack of the economy of scale [6, 7]. Several documents discuss the competitiveness of SMRs vs LRs and how SMRs might balance the "diseconomy of scale" with the "economy of multiples" [8–10]. Modularisation (factory fabrication of modules, transportation and installation on-site [11]) allows working in a better-controlled environment reducing cost and schedule [7, 12–15]. The degree of modularisation influences SMR capital costs [13, 16]. Furthermore, SMR smaller size and simpler design further reduce construction schedule [9, 17]. The SMR expected schedule is 4/5 years for the FOAK (first-of-a-kind) and 3/4 years for the NOAK (nth-of-a-kind), even if licensing can be a challenge [18]. SMR incremental capacity addition can allow overcoming one of the key barriers in building LRs: the massive and risky upfront investment [19].

Another key SMR advantage to consider is the possibility to have multiples units on the same site [8, 12, 20]. Other factors to consider in SMR economic and financial evaluation are: suitability for cogeneration [21–24], expected higher learning rate [10, 25], better adaptability to market [8], equal or higher capacity factor than current LRs [26]. Once these factors are taken into account, the capital cost is comparable between the two technologies [27].

One of the key SMRs advantages is the possibility to split a large investment into smaller ones. The construction of a single LR is a risky investment. The construction of n SMRs is an investment decision with n degrees of freedom that allows hedging investment risks. The economic merit of flexibility can be calculated using the Real Options (ROs) approach.

The construction of large projects in general, and Power Plants (PPs) in particular, is jeopardised by over budget and delay [28–30] Since ROs assess the decision maker's options (i.e. degrees of freedom) to hedge the investment risks, they increase the expected returns and, at the same time, minimise the volatility of the investment considered. "*RO theory postulates that projects under uncertainty might possess RO; the projects become flexible if the RO can be identified and timely executed; flexibility adds value to the projects"* [31]. In the energy sector the RO model evaluates opportunities such as waiting for the most advantageous moment to invest;

abandon a not profitable investment; switching from a technology to a more profitable one, produce outputs for more than one market [32] etc.

This chapter presents an appraisal based on ROs with two key peculiarities:

1. The modelling of the Time to Market (TTM) effect
2. The investment in a certain Power Plant (PP) considering the utility portfolio.

The TTM is the time from a product concept definition to its availability for sale [33]. In this chapter, the TTM is the time between the decision to build a PP and the beginning of commercial operations. In the energy sector reducing the TTM means reducing the risk (e.g. from electricity price fluctuation) and collecting early revenues increasing the Net Present Value (NPV). SMRs can be built faster than LRs, which is a relevant aspect to consider. The utility portfolio is relevant since PPs might not be considered as a "single asset" investment but must fit into a broader strategy of a utility owning a portfolio of PPs.

2 Real Options in the Energy Sector

Real options model has been applied in the energy sector by a lot of researchers since the '70s. [34] introduce for the first time the term "Real Option", and he highlighted the possibility to consider an investment as a call option on a real asset. [35] underlined the key role of RO in the evaluation of investments within an uncertain scenario. Even [36] focussed on RO advantage to support the decision making process in an uncertain surrounding business. RO method allows to establish the optimal project in terms of cash flow and to consider the better choice of investment in terms of the exercise rules of the option [37].

It is possible to highlight three important RO in previous literature [38]: invest, defer, abandon. Table 1 summarises relevant examples of papers applying the RO theory in the power and energy sector and shows the difference with the RO approach explained in this chapter.

It is also possible to join in a "compound option" two or more ROs to practically evaluate a more realistic scenario. For example, it is possible to create the "wait & build" option that is the compound option joining the option to build and the option to wait. This compound option allows introducing in the model the possibility for the investor to realize a postponed investment.

There are some examples of compound option in literature, also in other sectors rather than energy and power. [39] applies RO method to evaluate the risky coupon bond problem considering how to price an option on another one that is a type of compound options approach. [40] apply the RO method to renewable energy power plants life-cycle. [41] introduce an evaluation of compound options using a binomial lattice model to create a versatile management framework. [42] use compound option to evaluate different possibilities for energy storage. In this chapter, the compound options method is used to simulate the typical "Stage-gate process" of the energy sector.

Table 1. Recent applications of real options in the energy field. NPV = Net Present Value; E= Expected; σ = standard deviation. [43]

	This Work	[44]	[45]	[46]	[47]	[48]
Scope of Work	Building a realistic investment model in the energy sector by considering the TTM Effect and the Actual Portfolio of a utility.	Evaluate how all risks and uncertainties impact on the development of new Nuclear PP in China	Help a utility determine the value of sequential SMR	Analyse different RO model type to assess the best for making an investment in the energy sector.	Examine energy switching from non – renewable to renewable technologies in Mongolia	Apply a RO to a mini-hydro PP case comparing its results with the results obtainable through the classical DCF approach
Real Option Evaluation Method	Simulation with Optimized Exercise Thresholds (see [43])	Partial Differential Equation	Dynamic Programming Method	Binomial Tree	Simulation Method	Binomial Tree
Options Considered	Compound Option; Option to invest/abandon/ defer/ choose	Compound Option; Option to Invest/ Abandon	Option to Invest; Option to Abandon	Option to defer; Option to invest	Option to Switch	Option to invest
Outputs	E(NPV); σ(NPV); Exercise Thresholds; Efficient Frontier 2D for each technology; Efficient Frontier 3D for each Portfolio	Value of the Option	E(NPV); Classical NPV	Value of the Options	Decision to switch; Option Value	E(NPV); Classical NPV; Option Value

3 Portfolio Analysis

The boundary conditions of the electricity markets encourage utilities to diversify their portfolio. [49] highlights that a new investment has always to consider the company portfolio: "*The risk position of the company is determined by the entire portfolio and the interaction of various positions. Therefore, the decision to enter into new contracts cannot be taken independently from the current portfolio"*. Portfolio management was initially stated for the financial sector and then converted for the energetic company uses. The model proposed in this chapter is a development of the Mean-Variance Portfolio theory (MVP) because:

- It is a well-known method, used a lot in literature and suitable for decision-makers;
- It is versatile and it can be used with different objectives (e.g. maximisation of the NPV Mean; minimisation of risk);
- It can be used to evaluate a portfolio of investment or a single investment joining also RO method.
- Every single portfolio can be directly compared to the others in terms of Expected NPV (E(NPV)) and risk (σ(NPV)).

[50] substantially starts research about MVP. According to the MVP theory presented in [51], each portfolio has two attributes: its mean value (μ) and its standard deviation (σ). The mean value is the mean value of the controlled variables (e.g. the NPV), while the σ represents the risk on the investment. In the energy sector, it is possible to obtain a lot of different portfolios, combining different type and numbers of power plants. Each portfolio is characterised by its μ and σ. However, only few of them represent a rational choice because, given a certain μ, it is reasonable to choose only the portfolio with the lowest σ, i.e., the lowest risk. Alternatively, from the opposite point of view, given a certain σ, a reasonable investor implements only the portfolio with the highest μ; therefore, there is a one-to-one link among μ and σ. Given a certain level of μ, the more beneficial σ is automatically linked (and vice versa). Considering Fig. 1, it is possible to highlight the so-called "efficient frontier", the continuous line from "A" to "B", where all the best portfolios are. . "A" is the portfolio with the lowest return and risk, while "B" has the highest return and risk. "C" is another optimal portfolio because, given a certain level of risk, it maximises the return or, given a certain level of return, it minimises the risk. "D" is not a rationale portfolio since, for the same risk, the "C" portfolio provides a higher return. "E" is not a rationale portfolio since, for the same expected return, the C portfolio has the lowest risk.

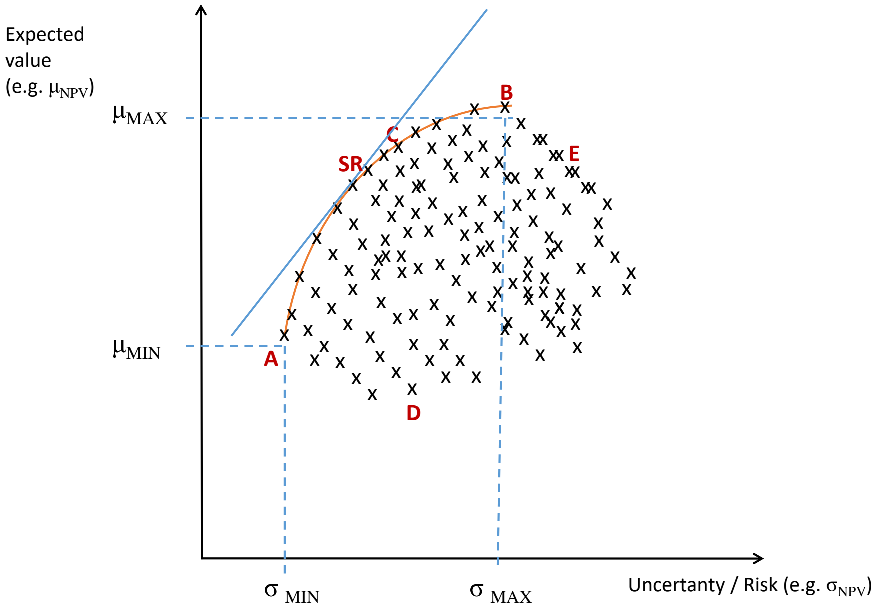

Fig. 1. Efficient Frontier: the classical MVP Theory [43]

The efficient frontier collects all the optimal portfolios [52] introduces a parameter, the *Sharpe Ratio* (SR), that compares the optimal portfolios considering their return over risk. According to [53] the SR is a measure for calculating the risk-adjusted return, and this ratio has become the industry standard for such calculations. The SR is the average return earned in excess of the risk-free rate per unit of volatility or total risk. Subtracting the risk-free rate from the mean return (the expected value of all the likely returns of investments comprising a portfolio), the performance associated with risk-taking activities can be isolated. One intuition of this calculation is that a portfolio engaging in “zero risk” investment, such as the purchase of U.S. Treasury bills (for which the expected return is the risk-free rate), has a SR equal to zero. Generally, the greater the value of the SR, the more attractive the risk-adjusted return. The investor is likely to prefer the portfolio on the efficient frontier with the highest expected return for the unit of risk (i.e. the highest SR). Geometrically the point of the efficient frontier that corresponds to the solution of this problem is tangent to the efficient frontier: the optimal portfolio received is called “Tangent Portfolio”.

This work overcomes one of the principal drawbacks in the literature about the MVP that limits its use: “MVP is a static methodology, heavily relying on past data. As a result, a portfolio that is thought of as optimal today might already be way off the efficient frontier tomorrow, depending on how the environment has changed. It is therefore a method that should only be considered within a very limited time frame” [54]. The application of RO to the portfolio analysis tackles this limitation.

3.1 Application of Real Options to perform Portfolio Analysis

In the literature, there are only a few examples of the application of RO to perform a portfolio analysis. Table 2 benchmark this work with respect to the literature.

Table 2. Examples of Real Options application to perform Portfolio Analysis [43]

	This Work	[45]	[55]	[56]
RO Evaluation Method	Simulation with Optimized Exercise Thresholds	Stochastic Grid Bundling Method	Partial Differential Equations	Dynamic programming method
Options considered	Compound Options; Option to invest; Option to choose; Option to abandon	Option to invest; option to abandon	Respectively option to invest and to abandon	Option to invest
TTM Effect	Modelled	Not considered	Not considered	Not considered
Pre – Operating Phases	Modelled as the succession of three compound options	Only the construction phase is considered	Only the construction phase is considered	Only the construction phase is considered
Actual Portfolio	Influence results	Results not influenced	Influence results	Results not influenced
Method used to perform the portfolio analysis	MVP Theory	MVP Theory	Stochastic Dominance	CVaR Method
OUTPUT Indicators	E(NPV); σ(NPV); Exercise Thresholds; Efficient Frontier 2D for each technology; Efficient Frontier 3D for Portfolio	Efficient Frontier 2D for portfolio in which every technology is a single static point on it; Value of the option	Value of the option. The efficient frontier is not built: the PDE do not find out the level of risk of the investment	Expected Cost; Level of risk; a single technology is a single static point on the plane E(cost) – Level of risk

According to Table 2, the steps followed by classical approaches to perform a portfolio analysis are:

1. Consider the historical data to identify the best strategy of investment for a certain plant type.
2. Calculate the E(NPV) and σ(NPV) of the overall portfolio.
3. Compare all the possible portfolios through the efficient frontier method to identify the one maximising the profit for a specific level of risk.

The computational model presented on the following is based on a set of different exercise thresholds (see [43] for a discussion on exercise thresholds) and it calculates the different effects on the output distribution of the overall portfolio, starting from these exercise thresholds. Therefore, each portfolio in the Cartesian graph E(NPV) – σ(NPV) is a function of the values of the exercise thresholds that, triggering the options in different conditions, modify the NPV distribution of the overall portfolio. Unfortunately, RO analysis of a real portfolio of power plants is very complex, and its application in a real situation is often impossible. However, the method described in the next sections overcomes this problem because it guarantees to the model users to analyse cases of investment in real portfolios with roughly the same effort of investments in simple portfolios.

4 Application of RO to a hypothetical portfolio

The main results are summarised in Table 3. The starting point for the computational simulation is the necessity for the utility to satisfy an increased demand for electricity, equal to 1.5 GW, within 20 years. Therefore, the RO method is used to evaluate the efficient frontier for the utility portfolio as a function of the exercise thresholds. A synthesis of the main results is supplied by Fig. 2 and Table 4; however, it is possible to highlight:

- The standard DCF method supplies a useless static evaluation of the efficient frontier respect to the RO method that creates a lot of possible dynamic scenarios identifying the best options with an optimised efficient frontier.
- The points on the efficient frontier have these properties:
  - The option has to be exercised when $P_{threshold} > P_0$ (i.e. it is worth waiting)
  - After a specific value P_{lim} the points do not belong on the efficient frontier anymore (i.e. the decision has to be taken in a finite time)
- All the points on the efficient frontier have these characteristics:
  - The condition to find them is to exercise the option only when $P_0 < P_{threshold} \leq P_{lim}$
  - The portfolio on the efficient frontier can be compared in terms of SR. This is a value of the exercise threshold P_{SR} that corresponds to the tangent portfolio of the efficient frontier.

The RO method allows a more complete evaluation of the investment's strategy than the static DCF method; RO model introduces the optimised efficient frontier, as it is shown by Fig. 2. The optimised efficient frontier is composed of the best investment strategy as a function of the exercise thresholds and the desired level of risk. Table 5 shows how the decision to invest varies according to the specific objective function. The decision-maker can choose the most suitable PP depending on his/her risk appetite.

Table 3. Composition of the hypothetical existing portfolio. CCGT = Combined Cycle Gas Turbine [43]

Technology	Capacity Installed [MW]	% in the Overall Actual Portfolio
Nuclear	1500	46.15%
Coal	750	23.08%
CCGT	1000	30.77%

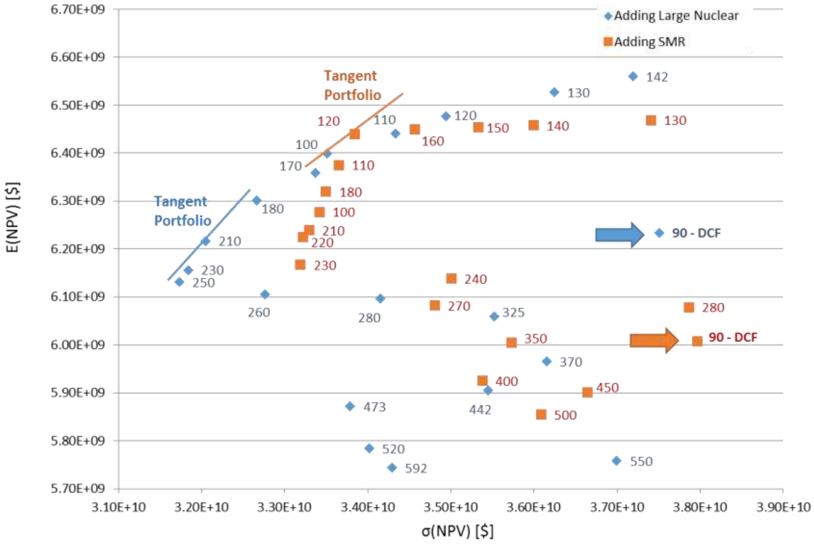

Fig. 2. Efficient Frontier of the portfolio with an additional LR or equivalent SMR power [43]

Table 4. Results obtained with the hypothetical portfolio [43]

Additional PP	Lower Bound Efficient Frontier	Upper Bound Efficient Frontier	Tangent Portfolio Condition
Large Nuclear	$P^*_{LB} = 100\$/MWh$	$P^*_{UB} = 250\$/MWh$	$P^*_{SR} = 210\$/MWh$
SMR	$P^*_{LB} = 100\$/MWh$	$P^*_{UB} = 230\$/MWh$	$P^*_{SR} = 120\$/MWh$

Table 5. Improvement of results guaranteed by this method [43]

Objective Function	Large Reactor's Results	SMR's Results	PP Chosen	Condition of investment
Maximization of NPV Mean	E(NPV) = 6560 Mln$	E(NPV) = 37193 Mln$	Large Reactor	$P^* = 142\$/MWh$
Minimization of σ NPV	E(NPV) =6131 Mln$	σ(NPV) = 31786 Mln$	Large Reactor	$P^* = 250\$/MWh$
Maximization of the SR Value	SR = 0.191	SR = 0.197	SMR	$P^* = 120\$/MWh$

4.1 Application to a UK utility portfolio

In this section the application of RO model to a UK utility portfolio is described, the model is built using both deterministic and stochastic input data, as it is shown by Table 6. The stochastic variables have been modelled as Geometric Brownian Motion (GBM). Consistently with [57] the initial values of the variables modelled with the GBM model are: gas cost 47.39$/MWh; coal cost 22.27 $/MWh and for the electricity price a value of 90 $/MWh.

The GBM functional form applied in this work on the electricity price is:

$$dp = \alpha p dt + \sigma p dz \tag{1}$$

Where α is the drift, σ is the volatility of the process in a time period, t is the time, and z is a Wiener process, where Wiener process is a continuous-time Gaussian process with independent increments used for modelling the Brownian motion. This model does not consider the Mean Reversion, Spike Jumps and Price Proportional Volatility.

The main advantages of the proposed model are:

1. The computational simplicity. The model is based on a time-independent Monte Carlo simulation and it considers only the price and the volatility of the electricity price at time zero. However, to consider also the long-term uncertainty the electricity price is evaluated through a GBM process:

$$E(P_{t+n}) = P_t \tag{2}$$

$$Var(P_{t+n}) = P_t{}^2(e^{\sigma^2}n - 1) \tag{3}$$

2. It can be implemented in a simple Excel spreadsheet.

3. The model is coherent even with the removal of the mean reversion and jumps because it considers a baseload scenario and so the importance of these two parameters is very low.

The following equation models the electricity price:

$$P_{t+1} = P_t + \sigma P_t W_t \tag{4}$$

Where P_t is the electricity price at time t, W_t is a standard normal variable, σ is the volatility of the process in a time period and $\sigma = 0{,}3$ as in [51]

The same description can be considered for the gas cost and for the coal cost too.

The Total Capital Investment Cost (TCIC) follows the method developed by [35] and [58] as:

$$dK = -\,Idt\ + \sigma(IK)^{1/2}\,dz \tag{5}$$

As in [58] the mean and the variance of the TCIC are described by these relationships:

$$E(TCIC)\ =\ K \tag{6}$$
$$Var(TCIC) = \frac{\sigma^2 K^2}{2-\sigma} \tag{7}$$

Since the evaluation model is discrete time based this stochastic process is modelled with:

$$K_{t+1} = K_t -\ I\ + \sigma(IK)^{1/2} W_t \tag{8}$$

Where W_t is a standard normal variable that gives the variability to this data.

The computational model considers a speculated portfolio of a typical UK energy utility and it is composed by the following contributions in terms of electric power output: 116 MWe from renewable power plants, 8741 MWe from nuclear power plants, 3987 MWe from coal power plants and 1306 MWe from gas power plants.

Table 6. The deterministic inputs used in this work [43]

	Nuclear	**Coal**	**CCGT**	**SMR**
Capacity [MW]	1500	750	500	335
Capacity factor (%)	85%	85%	85%	95%
Overnights Cost [$/KW]	5335	3220	1003	6362
O&M Cost [$/MWh]	13.96	13.4	15.03	21.28
Fuel Cost [$/MWh]	8.26	22.27	47.4	8.26
Carbon Cost [$/MWh]	0	23.96	10.54	0
Construction Time [years]	6	4	3	5
Study Time [years]	1	/	/	1
Design Time [years]	2	/	/	2
Life [years]	60	40	30	60

Fig. 3 summaries the results of the model described in [43]:

1. Without considering the compound options in the pre-operational phase, every PP portfolio solution belongs to the efficient frontier. In this case, an investment in SMR or LR supplies a profit greater than the profit provided by a gas PP or a coal PP but it has a higher level of risk.

2. Considering a flexible approach in the pre-operational phase with the compound option method, the simulation output changes a lot. The risk related to SMR and LR is reduced by the possibility to abandon the investment if it is not profitable anymore.

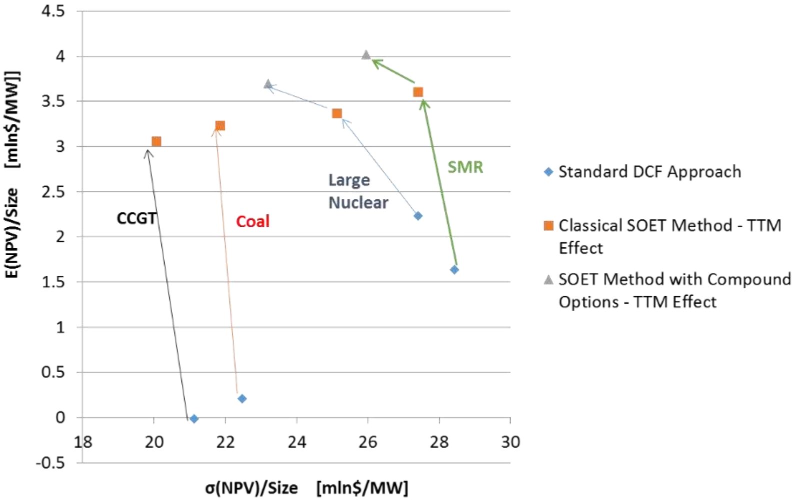

Fig. 3. Comparison between the results considering the TTM Effect [43]

In **Fig. 4**, a comparison between three of the possible output of the computational model is shown the classical DCF approach with the MVP Theory for each of the four possible additional PP

1. The classical DCF approach with the MVP Theory for each of the possible additional PP;
2. The value of the compound options with the option to defer for each of the possible additional PP;
3. The value of the pre-operational phase of the additional PPs as the succession of three sequential compound options with the option to defer.

Fig. 4 shows how compound options increase more the value of the investment in SMR or LR than investment in CCGT or Coal PPs.

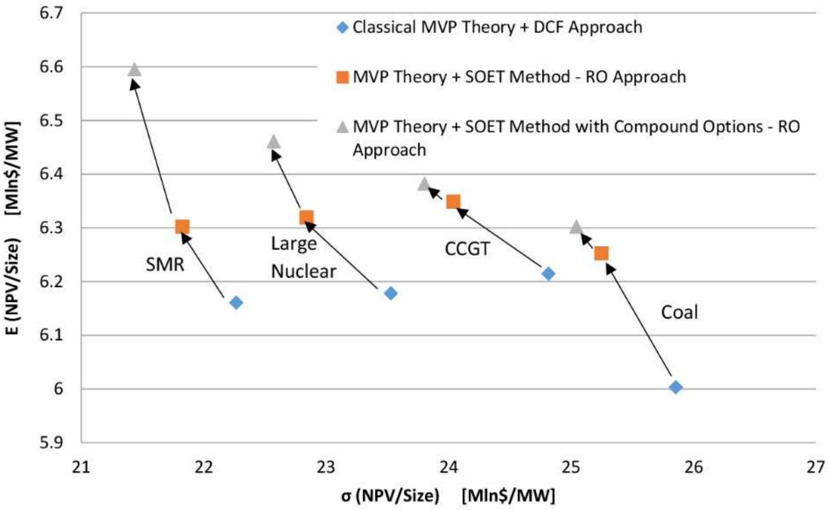

Fig. 4. Results obtained considering the utility portfolio in the UK [43]

5 Conclusions

The main conclusion of the proposed model is a confirmation of the economic profitability of an investment in SMR, that is independent from an important factor such as the diseconomy of scale. Some of the main advantages of SMRs are the shorter construction times respect to LRs and the possibility to obtain a greater variation of the portfolio according to the smaller size of the investment rather than considering LRs. The advantages of SMRs respect to LRs are mainly related to an intuitive idea of reduction of the risk of the investment, but a key point is to quantitative evaluate these advantages. In this chapter, the issue is tackled through the development of a computational model based on the RO approach to evaluate the investment appraisal in the energy sector. Some of the most important aspects of the proposed model are the inclusion of the Time to Market (TTM) evaluation and the assessment of the overall "portfolio effect".

TTM evaluation is very useful because it allows to consider the economic value of longer construction time, such as for a nuclear power plant respect to a conventional plant, and, at the same time, to assess the possibility to abandon the project if the market conditions change. Even if the MVP is a traditional static method (very dependent from past data), in this model the portfolio analysis is dynamic, thanks to RO approach that allows the assessment of an optimised efficient frontier with an added degree of freedom respect to traditional models. The RO method allows to consider also the more relevant options in the future, so the resulting model has a dynamic component. The complete evaluation of the result obtained by the model considering a speculated utility portfolio in the UK, suggests the SMRs as ideal option to maximise the NPV mean and the SR minimising the risk respect to the profit.

6 References

1. IAEA: Advances in Small Modular Reactor Technology Developments. (2016)
2. Hidayatullah, H., Susyadi, S., Subki, M.H.: Design and technology development for small modular reactors – Safety expectations, prospects and impediments of their deployment. Prog. Nucl. Energy. 79, 127–135 (2015). https://doi.org/10.1016/j.pnucene.2014.11.010
3. Karol, M., John, T., Zhao, J.: Small and Medium sized Reactors (SMR): A review of technology. Renew. Sustain. Energy Rev. 44, 643–656 (2015). https://doi.org/10.1016/j.rser.2015.01.006
4. Ingersoll, D.T.: Deliberately small reactors and the second nuclear era. Prog. Nucl. Energy. 51, 589–603 (2009)
5. Mignacca, B., Locatelli, G.: Economics and finance of Small Modular Reactors: A systematic review and research agenda. Renew. Sustain. Energy Rev. 118, (2020). https://doi.org/10.1016/j.rser.2019.109519
6. Lokhov, A., Cameron, R., Sozoniuk, V.: OECD/NEA study on the economics and market of small reactors. Nucl. Eng. Technol. 45, 701–706 (2013). https://doi.org/10.5516/NET.02.2013.517
7. Carelli, M.D., Ingersoll, D.T.: Handbook of Small Modular Nuclear Reactors. (2014)
8. Barenghi, S., Boarin, S., Ricotti, M.E.: Investment in different sized SMRs : economic evaluation of stochastic scenarios by INCAS code. In: International Congress on Advances in Nuclear Power Plants 2012, ICAPP 2012. pp. 2783–2792. , Chicago, USA (2012)
9. Vegel, B., Quinn, J.C.: Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures. Energy Policy. 104, 395–403 (2017)
10. EY: Small modular reactors - Can building nuclear power become more cost-effective? (2016)
11. Mignacca, B., Alawneh, A.H., Locatelli, G.: Transportation of small modular reactor modules: What do the experts say? In: 27th International Conference on Nuclear Engineering (ICONE27). Japan Society of Mechanical Engineers, 19-24 May 2019, Tsukuba, Japan (2019)
12. Boldon, L., Sabharwall, P., Painter, C., Liu, L.: An overview of small modular reactors: Status of global development, potential design advantages, and methods for economic assessment. Int. J. Energy, Environ. Econ. 22, 437–459 (2014)
13. Maronati, G., Petrovic, B., Van Wyk, J.J., Kelley, M.H., White, C.C.: EVAL: A methodological approach to identify NPP total capital investment cost drivers and sensitivities, (2017)
14. Mignacca, B., Locatelli, G., Alaassar, M., Invernizzi, D.: We never built small modular reactors (SMRs), but what do we know about modularization in construction? In: 26th International Conference on Nuclear Engineering (ICONE 26). ASME (2018)
15. Lloyd, C.A., Roulstone, A.: A Methodology To Determine SMR Build

Schedule And The Impact Of Modularisation. In: 26th International Conference on Nuclear Engineering, ICONE26. pp. 1–8. , Lundon, United Kingdom (2018)

16. Maronati, G., Petrovic, B., Banner, J.W., White, C.C., Kelley, M.H., Van Wyk, J.: Total capital investment cost evaluation of smr modular construction designs. In: International Congress on Advances in Nuclear Power Plants, ICAPP 2016. pp. 943–948 (2016)
17. Playbell, I.: Economy, safety and applicability of small modular reactors. In: Proceedings of the Institution of Civil Engineers (2016)
18. Sainati, T., Locatelli, G., Brookes, N.: Small Modular Reactors: Licensing constraints and the way forward. Energy. 82, 1092–1095 (2015). https://doi.org/10.1016/j.energy.2014.12.079
19. Sainati, T., Locatelli, G., Smith, N.: Project financing in nuclear new build, why not? The legal and regulatory barriers. Energy Policy. 129, 111–119 (2019)
20. Boarin, S., Ricotti, M.E.: An evaluation of SMR economic attractiveness. Sci. Technol. Nucl. Install. 2014, 1–8 (2014). https://doi.org/10.1155/2014/803698
21. Locatelli, G., Boarin, S., Fiordaliso, A., Ricotti, M.: Load following by cogeneration: Options for small modular reactors, gen IV reactor and traditional large plants. In: 25th International Conference on Nuclear Engineering, ICONE 2017; Shanghai; China. American Society of Mechanical Engineers (ASME) (2017)
22. Locatelli, G., Fiordaliso, A., Boarin, S., Ricotti, M.E.: Cogeneration: An option to facilitate load following in Small Modular Reactors, (2017)
23. Ingersoll, D.T., Houghton, Z.J., Bromm, R., Desportes, C.: NuScale small modular reactor for Co-generation of electricity and water. Desalination. 340, 84–93 (2014). https://doi.org/10.1016/j.desal.2014.02.023
24. Ingersoll, Houghton, Z.J., Bromm, R., Desportes, C.: Integration of NuScale SMR With Desalination Technologies. In: ASME 2014 Small Modular Reactors Symposium, SMR 2014. , Washington, DC, USA (2014)
25. NNL: Small Modular Reactors (SMRs) Feasibility Study. (2014)
26. Shropshire, D.: Economic viability of small to medium-sized reactors deployed in future European energy markets. Prog. Nucl. Energy. 53, 299–307 (2011). https://doi.org/10.1016/j.pnucene.2010.12.004
27. Carelli, M.D., Mycoff, C.W., Garrone, P., Locatelli, G., Mancini, M., Ricotti, M.E., Trianni, A., Trucco, P.: Competitiveness of small-medium, new generation reactors: A comparative study on capital and o&m costs. In: International Conference on Nuclear Engineering, Proceedings, ICONE (2008)
28. Flyvbjerg, B.: From Nobel Prize to project management: Getting risks right. Proj. Manag. J. 37, 5–15 (2006)
29. Invernizzi, D.C., Locatelli, G., Brookes, N.J.: Cost overruns - Helping to define what they really mean. Proc. Inst. Civ. Eng. Civ. Eng. 171, 85–90 (2018). https://doi.org/10.1680/jcien.17.00001
30. Locatelli, G.: Why are Megaprojects, Including Nuclear Power Plants, Delivered Overbudget and Late? Reasons and Remedies - Report MIT-ANP-

TR-172, Center for Advanced Nuclear Energy Systems (CANES), Massachusetts Institute of Technology. (2018)
31. Martínez Ceseña, E.A., Mutale, J., Rivas-Dávalos, F.: Real options theory applied to electricity generation projects: A review. Renew. Sustain. Energy Rev. 19, 573–581 (2013). https://doi.org/10.1016/j.rser.2012.11.059
32. Locatelli, G., Boarin, S., Pellegrino, F., Ricotti, M.E.: Load following with Small Modular Reactors (SMR): A real options analysis. Energy. 80, 41–54 (2015)
33. Cohen, M.A., Eliashberg, J., Ho, T.H.: New product development: The performance and time-to-market tradeoff. Manage. Sci. 42, 173–186 (1996)
34. Myers, S.C.: Determinants of corporate borrowing. J. financ. econ. 5, 147–175 (1977). https://doi.org/10.1016/0304-405X(77)90015-0
35. Pindyck, R.S.: Investments of uncertain cost, (1992)
36. Driouchi, T., Bennett, D.J.: Real Options in Management and Organizational Strategy: A Review of Decision-making and Performance Implications. Int. J. Manag. Rev. 14, 39–62 (2012). https://doi.org/10.1111/j.1468-2370.2011.00304.x
37. He, Y.: Real options in the energy markets, (2007)
38. Kodukula, D.P., Papudesu, C.: Project Valuation Using Real Options - A practiotioner's Guide. (2007)
39. Geske, R.: The Valuation of Corporate Liabilities as Compound Options. J. Financ. Quant. Anal. 12, 541–552 (1977). https://doi.org/10.2307/2330330
40. Siddiqui, A.S., Marnay, C., Wiser, R.H.: Real options valuation of US federal renewable energy research, development, demonstration, and deployment. Energy Policy. 35, 265–279 (2006). https://doi.org/10.1016/j.enpol.2005.11.019
41. Cheng, C.-T., Lo, S.-L., Lin, T.T.: Applying real options analysis to assess cleaner energy development strategies. Energy Policy. 39, 5929–5938 (2011). https://doi.org/10.1016/j.enpol.2011.06.048
42. Locatelli, G., Invernizzi, D.C., Mancini, M.: Investment and risk appraisal in energy storage systems: A real options approach. Energy. 104, 114–131 (2016). https://doi.org/10.1016/j.energy.2016.03.098
43. Locatelli, G., Pecoraro, M., Meroni, G., Mancini, M.: Appraisal of small modular nuclear reactors with 'real options' valuation. Proc. Inst. Civ. Eng. - Energy. 170, 51–66 (2017)
44. Shi, H., Song, H.: Applying the Real Option Approach on Nuclear Power Project Decision Making. Energy Procedia. 39, 193–198 (2013). https://doi.org/10.1016/j.egypro.2013.07.206
45. Jain, S., Roelofs, F., Oosterlee, C.W.: Construction strategies and lifetime uncertainties for nuclear projects: A real option analysis. Nucl. Eng. Des. 265, 319–329 (2013). https://doi.org/10.1016/j.nucengdes.2013.08.060
46. Zambujal-Oliveira, J.: Investments in combined cycle natural gas-fired systems: A real options analysis. Int. J. Electr. Power Energy Syst. 49, 1–7 (2013). https://doi.org/10.1016/j.ijepes.2012.11.015
47. Detert, N., Kotani, K.: Real options approach to renewable energy investments

in Mongolia. Energy Policy. 56, 136–150 (2013). https://doi.org/10.1016/j.enpol.2012.12.003

48. Santos, L., Soares, I., Mendes, C., Ferreira, P.: Real Options versus Traditional Methods to assess Renewable Energy Projects. Renew. Energy. 68, 588–594 (2014). https://doi.org/10.1016/j.renene.2014.01.038
49. Hlouskova, J., Kossmeier, S., Obersteiner, M., Schnabl, A.: Real options and the value of generation capacity in the German electricity market. Rev. Financ. Econ. 14, 297–310 (2005). https://doi.org/10.1016/j.rfe.2004.12.001
50. Markowitz, H.: Portfolio Selection. J. Finance. 7, 77–91 (1952). https://doi.org/10.2307/2329297
51. Locatelli, G., Mancini, M.: Large and small baseload power plants: Drivers to define the optimal portfolios. Energy Policy. 39, 7762–7775 (2011). https://doi.org/10.1016/j.enpol.2011.09.022
52. Sharpe, W.F.: The Sharpe Ratio. J. Portf. Manag. 21, 49–58 (1994). https://doi.org/10.3905/jpm.1994.409501
53. Investopedia: Sharpe Ratio, http://www.investopedia.com/terms/s/sharperatio.asp, (2016)
54. Madlener, R., Wenk, C.: Efficient Investment Portfolios for the Swiss Electricity Supply Sector. SSRN Electron. J. (2008). https://doi.org/10.2139/ssrn.1620417
55. Liu, Z.: Energy Portfolio Management with Entry Decisions over an Infinite Horizon. Appl. Math. 03, 760–764 (2012). https://doi.org/10.4236/am.2012.37113
56. Fuss, S., Szolgayová, J., Khabarov, N., Obersteiner, M.: Renewables and climate change mitigation: Irreversible energy investment under uncertainty and portfolio effects. Energy Policy. 40, 59–68 (2012). https://doi.org/10.1016/j.enpol.2010.06.061
57. EIA-DOE, EIA: Assumptions to the Annual Energy Outlook 2012. (2012)
58. Schwartz, E.S.: Patents and R&D as Real Options. Econ. Notes. 33, 23–54 (2004). https://doi.org/10.1111/j.0391-5026.2004.00124.x