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Large and small baseload power plants: Drivers to define the optimal portfolios

Giorgio Locatelli *, Mauro Mancini [1]

Politecnico di Milano, Dept. Management, Economics and Industrial Engineering, Via Lambruschini 4/b, 20156 Milano, Italy

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ABSTRACT

Despite the growing interest in Small Medium sized Power Plants (SMPP) international literature provides only studies related to portfolios of large plants in infinite markets/grids with no particular attention given to base load SMPP. This paper aims to fill this gap, investigating the attractiveness of SMPP portfolios respect to large power plant portfolios. The analysis includes nuclear, coal and combined cycle gas turbines (CCGT) of different plant sizes. The Mean Variance Portfolio theory (MVP) is used to define the best portfolio according to Internal Rate of Return (IRR) and Levelised Unit Electricity Cost (LUEC) considering the life cycle costs of each power plant, Carbon Tax, Electricity Price and grid dimension.

The results show how large plants are the best option for large grids, while SMPP are as competitive as large plants in small grids. In fact, in order to achieve the highest profitability with the lowest risk it is necessary to build several types of different plants and, in case of small grids, this is possible only with SMPP. A further result is the application of the framework to European OECD countries and the United States assessing their portfolios.

1. Introduction

As a consequence of the electricity markets liberalization, utilities are able to determine the production strategy and to create a power plant portfolio according to their risk attitudes. This paper aims to determine optimal baseload technology portfolios. Many portfolio theories are available in literature showing how the Mean Variance Portfolio theory (MVP) is the simplest and most effective method currently available (Table 1). Many studies in literature apply MVP to power plant generation portfolios; however, they are always composed of large size plants (Table 2) and quite surprisingly do not consider IRR but only LUEC.

This work investigates if and when the SMPP competitiveness can move the investors' choice to small plant portfolios. Under this prospective the paper investigates the main drivers in a market, including the effects of CO_2 emission costs, Electricity Price (EP) and market dimensions. Many economic and financial indicators can be used for this purpose, but this paper focuses on IRR and LUEC, to comprehend the private and public investors' point of view. MVP is the main tool to perform the analysis and requires as inputs the probability distributions of IRR and LUEC; these have been elaborated updating the model and the data of (Locatelli and Mancini, 2010).

The analysis focuses on baseload plants in charge to provide the continuous and levelled electricity production (Sovacool, 2009). In the medium term, baseload demand does not change significantly over time, especially in European OECD countries and in the USA. Peak load is much less certain and it is often influenced by climatic conditions that change demand for building heating and cooling (Nicholson et al., 2010). Wise and Dooley (2006) overlook the fact that peaking (and intermediate) load electric power plants face different economic trade-offs from baseload plants. Different generators serve different loads. Baseload supply varies from country to country and networks, but can typically represent 60–80% of total energy supply (Nicholson et al., 2010). Small Medium sized Power Plants (SMPP) are becoming popular because they can offset some of the cost due to the economy of scale[2] with a higher degree of freedom in terms of Spinning Reserves Management, Technical Siting Constraints, Impact on national industrial system, etc.

In particular, as far as NPP is concerned, the small reactors have the potential to present an enhanced level of safety with respect to a large plant because of (Ingersoll, 2009):

- the reduced inventory of radionuclides produced from the fission process,
- the potential to eliminate design features that introduce accident vulnerabilities,

* Corresponding author. Tel.: +39 02 2399 4096; fax: +39 02 2399 4083.
E-mail addresses: giorgio.locatelli@polimi.it (G. Locatelli), mauro.mancini@polimi.it (M. Mancini).
[1] Tel.: +39 02 2399 4057; fax: +39 02 2399 4083.

[2] The Economies of scale link the increase of a size of a plant to the reduction in the average cost of its production. This reduction is due to e.g.: fixed or semi- fixed cost sharing, better specialization, improved technology (Hayes and Wheelwright, 1984)

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Table 1
Portfolio theory literature review.

Method	Advantages	Disadvantages	Notes	References
Mean-Variance Portfolio theory (MVP)	Easy application. Clarity of results. Improvement direction identifiable. Expandable and adaptable in order to consider additional input	Expensive from a computational point of view, especially with the increasing of the number of considered assets. Requires standard deviations, correlations and expected values of the output	It is the most widely used technique in electricity generation portfolios	Markowitz (1952) Awerbuch and Martin (2003) and Roques et al. (2008)
Maximization of the geometric mean returns	Identifies the portfolio with the higher probability to reach the maximum return	It does not consider and detect the minimum risk portfolio—identifies only one solution	The efficient portfolio belongs to the range defined by the MVP optimal solutions	Latanè (1959), Young and Trent (1969), Vander Weide et al. (1977) and Jean (1980)
Value at risk (VaR)	Very flexible, it considers variances, co-variances and interactions between factors	Diversification does not permit to reduce risks—considers only the probability of risk neglecting the size of the leak. Subjective, the investor selects the limit value, it does not identify general solutions		Jorion, (1997) and Duffle and Pan (1997)
Safety first (SF)	Very simple and easy, makes a choice based on the probability of returns below a certain threshold	It does not consider co-variances and interactions between factors, too simplistic. Subjective, the investor selects the desired return value, it does not identify a general solution	SF results are almost equivalent to MVP results	Bawa (1978) and Roy (1952)
Stochastic dominance (SD)	Ranks and compares the various alternatives by identifying the optimal point in a range of already defined solutions	It does not consider the investor and his aversion to risk—requires a large amount of data. Identifies a single solution	Can be used after the MVP theory application	Fishburn (1964), Hardy et al. (1934), Bawa (1982) and Levy (1992)

- the opportunities to passively respond to unexpected transients.

Safety is a fundamental concern after the Fukushima catastrophe and therefore the investigation of the economics of small reactor/small plant is even more urgent.

The main goals of this paper are:

- To define a framework able to evaluate the optimal portfolio composition not only considering the cost of electricity (LUEC) but also the Return on investment (IRR).
- To investigate the impact of four fundamental drivers: plant size, Electricity Price, Carbon Tax and Market Dimension. By 'market dimension' we mean, from the point of view of a utility (or the investor), the total MWe to be deployed.

As a by-product of this two main targets in chapter 5 there are some considerations not in terms of single utility but in terms of single OECD countries (since efficient "national portfolio" is fundamental to deliver affordable electricity and many insights can be replicated).

2. Literature review

Portfolios theories were developed firstly for financial uses and then some of them were adapted to the energy generation sector. Many portfolio theories have been reviewed in order to determine efficient power plant portfolios (Table 1). From this comparison MVP is the simplest and most effective available method that allows for a clear graphical representation of portfolio performances on the Mean–Standard Deviation plane and can be easily applied to the power generation sector.

MVP, created by (Markowitz, 1952) and originally applied to financial cases, identifies a range of optimal solutions characterized by the following property: "maximize the expected return for each risk level". Optimal portfolios lie on the so called "Efficient frontier"; all the portfolios that belong to this frontier are considered optimal solutions. The investors can choose their own portfolios according to the rule: "The higher the risk, the higher the expected profit, or the lower the expected cost, and vice versa".

Bar-Lev and Katz (1976) were the first to use MVP to optimize the energy generation sector. The analyses were concentrated on the procurement of fossil fuels in the electricity industry in the United States. They showed that utilities efficiently diversify their investments, but their portfolios were characterized by a relatively high rate of return and risk.

Humphreys and McClain (1998) applied the MVP theory to evaluate the energy mix generated in the United States and found that since the early 1980s utilities gradually moved toward more efficient portfolios of installations. The transition to natural gas in the 1990s could be justified by

- a greater return on investment,
- risk aversion, since it may not be possible to recover a large portion of the investment in generating plants, particularly nuclear power plants (Nunez, 2007).

Awerbuch (1995) and Awerbuch (2000a) showed that adding wind, solar and other renewable sources to a conventional portfolio in the United States could reduce overall costs and risks of the portfolio itself even, if costs of generation for each single plant were higher.

More recently, Krey and Zweifel (2006) and Krey and Zweifel (2008) applied the MVP theory to identify electricity portfolio efficiency in the United States and in Switzerland. The researchers identified a range of efficient portfolios in these two scenarios. They identified in the American case an optimal portfolio composed exclusively of nuclear power plants and in the Swiss case composed exclusively of solar power stations. However the authors recognize that there are no overnight feasible solutions, since there are already power plants and a supply chain shaped on a mix of plants. Moreover the Electricity Grid needs a mix of plants, for instance the solar plants do not produce Electricity during the night. Therefore constraints on admissible shares of technologies were imposed.

Awerbuch (2004b) used the same approach to model the potential contribution of renewable generation portfolio in the

Table 2
Literature review.

	This work	Roques et al. (2008)	Madlener et al. (2009)	Awerbuch and Martin (2003)	Awerbuch (2004a)	Bar-Lev and Katz (1976)	(Krey and Zweifel, 2006))	Kaplan (2008)	Jansen et al. (2006)
Input									
Fuel cost	Discrete distributions	Normal distributions	Historical data	Normal distributions	Unspecified	Normal distributions	Historical Data	Historical data	Normal distributions
Capital cost	Discrete/continuous distributions	Deterministic	Considered but unspecified	Normal distributions	Unspecified	Not considered	Historical data	Historical data	Normal distributions
O&M cost	Discrete distributions	Deterministic	Considered but unspecified	Normal distribution	Unspecified	Not considered	Historical data	Historical data	Normal distributions
Decommissioning cost (nuclear)	Deterministic	Deterministic	Unspecified	Not considered	Unspecified	Not considered	Historical data	Historical data	Deterministic but unspecified
Technologies	Nuke, CCGT, coal	Nuke, CCGT, coal	CCGT, coal, wind, oil, nuke, biomass	CCGT, coal, nuke, wind, oil	Gas, coal, nuke, oil, wind	Coal, oil, gas	Nuke, hydro, solar, wind, coal, oil, gas	Coal, nuke, gas, oil, wind, hydro	Gas, coal, nuke, renewable wind and biomass
Plant size	Large and Small	Large	Large	Large	Large	Large	Large	large	Large
Countries	Europe OECD/Italy	UK	UK/Sweden	USA/Europe	Mexico/ Europe/USA	USA	Switzerland/USA	Switzerland/USA	Netherlands
Emissions cost	Scenario dependent	Normal distribution	Historical data	Not considered	Unspecified	Not considered	Unspecified	Unspecified	Scenario dependent
Electricity Price	Continuous distribution/ scenario dependent	Normal distribution	Historical data	Not considered	Unspecified	Not considered	Not considered	Not considered	Not considered
Method									
Network size/market dimension	Modeled	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered
Economical model type	Cost drivers and discounted cash flow	Cost drivers and discounted cash flow	Cost drivers	Cost drivers	Cost drivers	Cost drivers	Cost drivers	Cost drivers	Cost drivers
Plant switch off	Considered	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered
Input correlation$	Not considered	Considered	Not considered	Considered	Unspecified	Not considered	Considered	Considered	Considered
# iterations	Enough to obtain robust results	100.000	Unknown	Not required	Not required	Not required	Not required	Not required	Not required
Output									
Indicators	IRR, LUEC	NPV	Return/output ($/MWh)	Return (kWh/US cent)	Return (kWh/ cent)	1/C (C=Fuel Cost)	LUEC	LUEC	LUEC
Benchmarking with already existing portfolio	Considered	Not considered	Considered	Considered	Considered	Considered	Considered	Considered	Considered

European, American and Mexican markets. He identified in each case the efficient frontier and the position of the current generation portfolio for the various countries.

Roques et al. (2008) claim that utilities should consider risk when making their decisions, and they analyze technology portfolios according to the MVP criteria. Their model, based on the Monte Carlo simulation applied to the Mean Variance Portfolio theory, identifies the portfolios which maximize returns to the stakeholders, given portfolio risk levels. In the same paper the first real application of MVP with large production units in a liberal energy market is developed: the researchers investigated the correlation between the inputs and the final composition of portfolios representing fuel cost, electricity and CO_2 as a normal distribution of random variables obtained from historical data. The paper shows how the correlation between EP and gas prices increases the percentage of gas-fired plants in the optimal portfolio.

Finally Madlener et al. (2009) applied the MVP theory to generation portfolios in the United Kingdom and Sweden, identified the efficient frontier and in both cases the inefficiency of the existing generation portfolio (in a similar manner as Bar-Lev and Katz (1976)).

All the previously quoted works are compared in Table 2 according to inputs, method and outputs respect to this work.

3. Methodology

3.1. The two models approach

The framework to perform the portfolio analysis is composed of two models as shown in Fig. 1.

Model one has to provide the inputs for MVP. Such inputs are the IRR and LUEC probability distributions and their correlations. This first model is an improved version of the economical model, INCAS, presented in Locatelli and Mancini (2010). The improvement and updated values have been synthesized in Appendix 1. This model requires two sets of inputs. The first set is specific to the power plant technology i.e. Overnight cost, Operation and Maintenance (O&M) cost, fuel cost and, for nuclear power plants (NPP) only, the Decommissioning and Decontamination (D&D) costs. The second set is related to the market including the CO_2 cost and the EP. The outputs of model one are the IRR and LUEC distributions and correlations to be used in Model two.

Model two receives as input the IRR distributions and correlations among the different power plants, the LUEC distributions and correlations among the different power plants and the market/grid size (GWe). With these inputs Model two implements the MVP approach in different scenarios.

In each scenario two kinds of portfolios are considered: ideal and real.

In ideal portfolios the market size (or the utility size) is infinitely greater than the plant size; therefore, it is possible to build each mix of plants without any constraint to the percentage of each technology. All the papers quoted in Table 2 rely on this assumption.

Real portfolios consider a finite market size. If the market size is small (e.g. 2 GWe) the mix of plants (especially large plants) can be composed of only one technology (e.g. a single monolithic nuclear reactor), therefore it is not possible to exploit the advantages deriving from investment diversification.

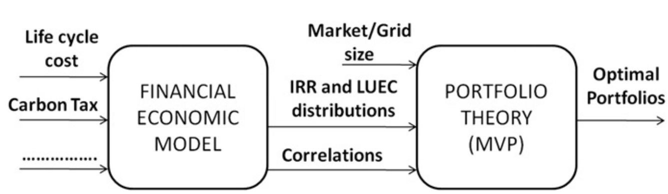

Fig. 1. Framework adopted in the research.

Given a certain market (characterized by Electricity Price, Carbon Tax) we aim to investigate the effects of shifting from ideal to real portfolio.

The market size is not a significant parameter in ideal portfolios; the installation of a plant in this case has an infinitesimal weight. In the real case, the installation of one plant does not have an infinitesimal weight and only a few real portfolios are available and selectable by the investors. In our analysis the market size is fixed and not related to the Electricity Price and costs.

3.2. Input data

3.2.1. Settings

This research considers only baseload power plants of Combined Cycle Gas Turbines (CCGT), coal and NPP (Gen III and III+). Hydroelectric plants are not included since in the OECD countries the existing hydroelectric plants cover most of the potential capacity (UNDP, 2000) and largely depend on the water cycle as seasonal rains (Sovacool, 2009). Oil power plants provide a negligible contribution to the base load (EEA, 2010).

Nuclear, coal, and CCGT power plants considered in this paper are clustered in two groups according to size (Table 3).

The data used to perform the Monte Carlo analysis comes from the most reliable institutes and are already summarized in (Locatelli and Mancini, 2010). This dataset is integrated by the most recent data in Appendix 2 of this paper. The overall distributions have been modified by a 2–3% of their mean value.

For nuclear and coal plants the full site dimension is 1340 MWe. A full site can host one nuclear or two large coal plants. For SMPP one site is again 1340 MWe and can host four SMPP of the same technology. For CCGT the maximum site dimension is 1500 MWe. In this case the site can host six SMPP or three large plants.

3.2.2. Overnight and O&M costs

Overnight costs have been updated to 2011 through the escalation factors elaborated from:

- the Power Capital Costs index (IHS, 2009),
- the Chemical. Engineering Plant Cost index (Ulrich and Vasudevan, 2010),
- the Marshall and Swift's index (Chemical Engineering, 2010a, 2010b.

In each case the overnight cost distributions were normalized to the reference sizes. As the overnight costs, operation and maintenance costs have been updated to 2011 and normalized to the reference plant size. The program "Best-Fit" has been used to determine the best statistical distribution. The distributions found have been assessed with the X2 test (for all the distribution), the Kolmogorov–Smirnov test and the Anderson–Darling test (for the appropriate distribution). If any of these tests returned a reliable distribution, a discrete distribution has been used. The results of these statistical analyses are summarized in Tables 4 and 5.

Table 3
Power plant sizes adopted in the analysis.

Size	CCGT (Mwe)	Coal (Mwe)	Nuclear (Mwe)
Small	250	250	335
Large	500	670	1340

Table 4
SMPP summary.

SMPP	Nuclear	Coal	CCGT
Size (MWe)	335	335	250
Overnight cost ($/kWe)	Distribution: gamma α=7.0295, B=468.15, shift=819.03, mean=4109.9, dev st=1241.2, min=819.03 max=+∞	Distribution: discrete Max=3408, min=1684, mean=2349, dev st=458	Distribution: discrete Max=1462.6, min=470.7, mean=942.9, dev st=239.4
O&M cost ($/kWe-Year)	Distribution: discrete Max=159.9, min=68.9, mean=98, dev st=20.12	Distribution: discrete Max=140.4, min=36.4, mean=86, dev st=29	Distribution: discrete Max=80.4, min=20.4, mean=41.3, dev st=14.2

Table 5
Large plants summary.

Large plants	Nuclear	Coal	CCGT
Size (MWe)	1340	670	500
Overnight cost ($/kWe)	Distribution: LogLogistic γ=−3859.5 β=7228.4 α=16,315 T inf=1760 Mean=3446 Dev st=779.5 Min=1760 Max=+∞	Distribution: discrete Max=2913.5 Min=1503 Mean=1982.2 Dev st=385.9	Distribution: discrete Max=1335.6 Min=399 Mean=828.2 Dev st=219.5
O&M cost ($/kWe-Year)	Distribution: discrete Max=98 Min=48.7 Mean=64.3 Dev st=12.7	Distribution: discrete Max=114 Min=29.7 Mean=69.6 Dev st=23.6	Distribution: discrete Max=62.6 Min=16.12 Mean=32.5 Dev st=11

The values reported in the previous tables refer just to stand alone power plants. Since the paper deals with portfolios, it is necessary to include the cost savings due to replications and co-siting economies. The ideal scenario (infinite market and grid capacity) considers infinite sites and all the sites include the maximum number of power plants. The real scenario considers finite number of power plants grouped in the maximum possible number of full sites and one last incomplete site built with the remaining plants.

Therefore, depending on the number of plants in the site, the overnight cost is corrected using the INCAS model mainly based on Delene and Hudson (1993), Hayns and Sheperd (1991) and Kadak, (2002).

3.2.3. Fuel costs

3.2.3.1. Coal. As the starting value for the fuel is assumed 5.29 $/MWh (reference year 2008 EIA (2010)), this value has been updated to 2011 and into the future through an annual escalation index extracted from the discrete distribution in Table 6.

3.2.3.2. Gas. 15 $/MWh (Huppmann et al., 2009) is assumed as starting value; this has been updated to 2011 and into the future through an annual escalation index extracted from the discrete distribution in Table 7.

3.2.3.3. Nuclear fuel. Front-end and back-end costs have been extracted from the discrete distributions in Tables 8 and 9. The annual uranium inflation is equal to +0.50% every year.

Table 6
Coal annual inflation distribution.

Reference	Scenario	Annual inflation (%)
Annual Energy Outlook 2010 (EIA, 2010)	Base 2008–2020	−0.22
	Base 2020–2035	−0.32
	Low 2008–2035	−0.6
	High 2008–2035	3.3

Table 7
Gas annual inflation distribution (Huppmann et al., 2009).

Scenario	Mean price 2030 ($/MWh)	Annual inflation (%)	Class
Base Case	31.54	3	Base
Barnett Shale	29.8	2.8	
In the Ground	39.17	3.9	High
Post Bali Planet	28.25	2.5	Low
Eastern Promises	36.18	3.6	
Shutting off the Middle East	34.14	3.3	
Tiger and Dragon	33.27	3.2	
Pretty Coast California	31.53	3	

3.2.3.4. Carbon Tax. The Carbon Tax (CT) has been assumed in the sensitivity analysis from 0 $/t to 100 $/t.

3.2.3.5. Electricity Price (EP). Three values for EP are considered:

- 90 $/MWh—simulating Italian scenario (GME, 2010),
- 70 $/MWh—simulating UK scenario (APX, 2010),

– 50 \$/MWh—simulating USA scenario(e.g. in Luisiana) (DOE, 2010).

The Electricity Price has been modeled as a Beta distribution and approximated as a Pert (Kirytopoulos et al., 2008) to avoid the existence of infinite tails of the distribution.

3.2.3.6. *Defining*.

$$\frac{\mu_{EP}}{\sigma_{EP}} = X$$

It is possible to compute the minimum (m) and maximum (M) value as

$$m = \mu_{EP} - \frac{3\mu_{EP}}{X}$$

$$M = \mu_{EP} + \frac{3\mu_{EP}}{X}$$

where, respect to the Pert distribution: μ_{EP} is the mean value of EP, σ_{EP} is the Standard Deviation of EP, m is the minimum value and M is the maximum value.

Table 8
Uranium front-end cost distribution.

Reference	Year	Front end cost (\$/MWh)
MIT (2003)	2003	4.3
Ayres et al. (2004)	2004	3
		4
Tolley and Jones (2004)	2004	4.35
IEA (2007)	2007	4
WEC (2007)	2007	3.5
		4.5
INL (Taylor et al., 2008)	2008	3.91
		2.45
		3.85
		3.86
		4.35
		3.73
		3.83
		3.83

Table 9
Uranium back-end cost distribution.

Reference	Year	Back end cost \$/MWh
Gallanti and Parozzi (2006)	2006	1
INL (Taylor et al., 2008)	2008	2.73
		2.64
		2.74
		2.75
		2.76
		2.72
		2.73
		2.73

In this model the EP distributions depend on μ_{EP} (the mean level) and X (the ratio between the mean and the standard deviation σ_{EP}). Therefore X represents the dispersion of the Electricity Price in relationship to the mean value.

Mean quarterly values were computed starting from on-line available daily values. Table 10 summarizes these values respect to the USA baseload Electricity Price (DOE, 2010). $X=3$ can be considered an intermediate value for this historical value as well as for the other recent studies reported in the literature (Table 11).

3.3. *Preliminary settings*

As presented in Table 2 this paper deals with two indicators as output: LUEC and IRR.

IRR: is the annualized effective compounded return rate or discount rate that makes the net present value (NPV) of all cash flows (both positive and negative) from a particular investment equal to zero. In general, the higher the risk of the investment, the higher the IRR required by the investors.

LUEC: represents the present value of the total cost of building and operating a generating plant over an assumed financial life and duty cycle, converted to equal annual payments and expressed in terms of real dollars to remove the impact of inflation. Levelized cost reflects overnight capital cost, fuel cost, fixed and variable O&M cost, financing costs and an assumed utilization rate for each plant type (DOE, 2011).

LUEC allows for the invested capital remuneration on the basis of the cost of equity (Ke) and cost of debt (Kd): no extra-profit is left to shareholders on top of the cost of equity. Hence the cost of equity exactly equalizes the IRR of the free cash flows and represents the shareholders' capital remuneration.

Since we aim to provide a model and analyze the impact of the input presented, Ke is the output of the model when considering IRR (being the IRR itself), is an input for the LUEC analysis.

According to Locatelli and Mancini (2010) Ke used in this analysis are common for USA and comparable markets.

In the first part of the proposed model (Financial Economic Model—Fig. 1) each scenario has been modeled as a combination of CT cost and EP. If the CT cost is high and the EP is low the IRR for coal and CCGT does not exist (or it is negative), therefore it is necessary to screen the scenario to assess in which of them the investors could be interested. Consequently, a preliminary test (5000 runs) was run to find out which power plants are not economically convenient in the scenarios. When IRR is negative for more than 50% of the runs, the power plant is considered unprofitable (usually an investor is looking for an IRR in the order of magnitude of at least 10–15%). All the factors considered in the analysis have been summarized in Table 12.

Table 11
X values in the literature.

Study	Country	Mean	St dev	U. of M.	X
Roques et al. (2008)	UK	40	10	£/MWh	4
Madlener et al. (2009)	UK	44.39	23.20	Euro/MWh	≅ 2
	SWE	36.73	14.55	Euro/MWh	≅ 2.5

Table 10
Electricity Price historical quarterly statistics in USA (DOE, 2010).

	California	Louisiana	New England	Ohio		Pennsylvania	Texas	
Mean	64.90	48.66	64.44	47.99	56.38	58.03	51.31	60.23
Dev st	39.87	16.42	19.59	15.85	13.84	17.69	17.30	30.25
X	1.6	3.0	3.3	3.0	4.1	3.3	3.0	2.0

Table 12
Scenario setting.

CT	From 0 to 100 $/t (5 steps (25 $/t))
Plant size	Small
	Large
Output	LUEC
	IRR
Market size	30 GWe
	10 GWe
	2 GWe
Electricity Price	50 $/MWh
	70 $/MWh
	90 $/MWh

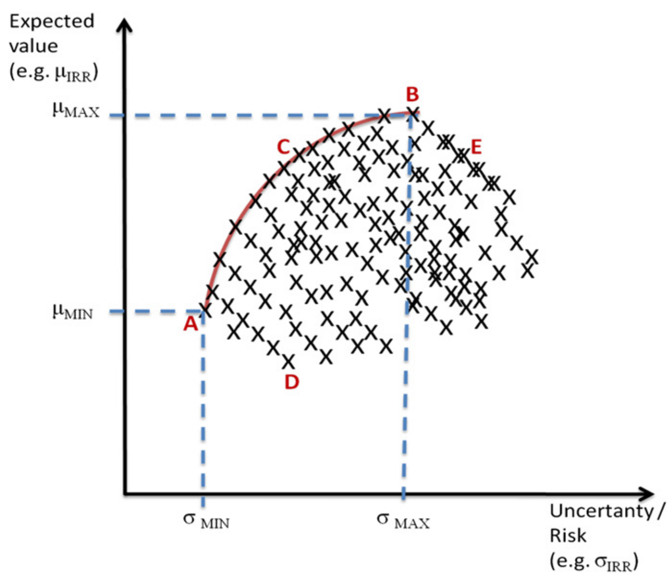

Fig. 2. Portfolio representation with the MVP theory.

4. Results

Results can be clustered in two different parts. The first deals with the analysis of optimal portfolio compositions, and the second is the sensitivity analysis on optimal portfolios managing the effects of individual factors.

4.1. Part one—optimal portfolio compositions

Fig. 2 presents the standard representation of portfolio mixes with the MVP theory.

According to the MVP theory each portfolio (the *x* in Fig. 2) has two attributes: its mean value (μ) and its standard deviation (σ). The mean value is the mean value of the controlled variables (in this case IRR or LUEC), while the Standard Deviation represents the risk on the investment, since the standard deviation is a measure of how far from the expected value the outcomes might be. Combining the different percentages of nuclear, coal and CCGT power plants it is possible to obtain thousands of portfolios, each of them characterized by its own μ and σ. However, only few of them represent a rational choice because, given a certain μ, it is reasonable to chose only the portfolio with the lowest σ i.e., the lowest risk and uncertainty. Or, from the opposite point of view, given a certain σ a reasonable investor will implement only the portfolio with the highest μ (in case of IRR) or lowest μ (in case of LUEC); therefore there is a one-to-one link among μ and σ. Given a certain level of μ the only rationale σ is automatically linked and vice versa. The optimum portfolios are on the so called "efficient frontier" i.e., the continuous line from "A" to "B". "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 maximizes the return or, given a certain level of return, it minimizes the risk. "D" is not a rationale portfolio since, for the same risk, the "C" portfolio provides a higher return. Neither "E" is a rationale portfolio since, for the same expected return, the C portfolio has the lowest risk. Since only the portfolios on the efficient frontier are a rationale choice, the diagrams summarizing their compositions have an interval from μ_{MIN}/σ_{MIN} to μ_{MAX}/σ_{MAX} (Merton, 1972). Analytically demonstrates that the efficient frontier is a curve if there are no risk-free assets, and a straight line if there are risk-free assets (but it is not the case here). These results are based on the assumptions of normal distributions, but since we deal with several types of distributions (Tables 4 and 5) it is not possible to analytically derive the equation of the curve, however, it is mandatory to use a Monte Carlo simulation.

Figs. 3–7 show how the portfolio changes according to the different levels of μ and σ. Given different levels of Carbon Tax, the following figures show how the portfolios change according to the different levels of EP: low (50 $/MWh), medium (70 $/MWh) and high (100 $/MWh). The size influence on the portfolio mix is really weak, i.e. SMPP and large plant portfolios have really similar behavior with respect to CT and EP. The paper focuses first on IRR and then on LUEC.

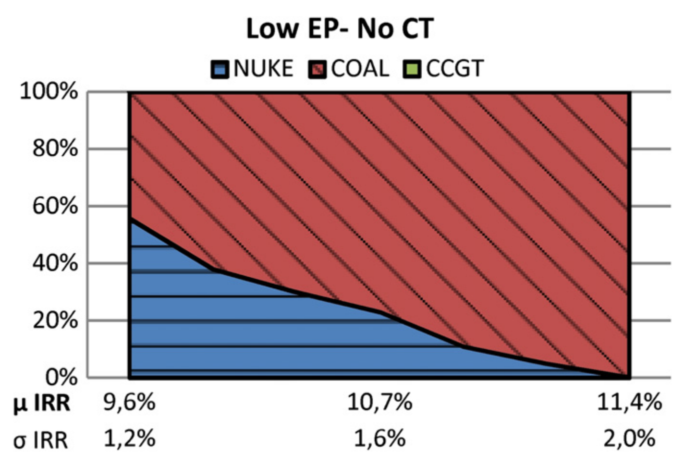

Fig. 3. Portfolios with low EP (50 $/MWh) and without CT.

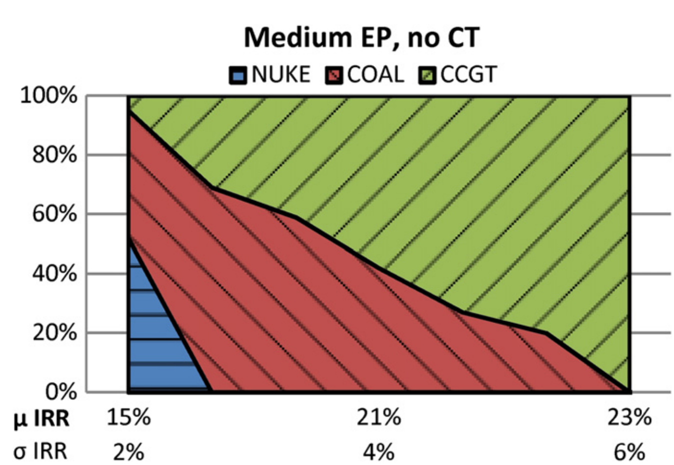

Fig. 4. Portfolios with medium EP (70 $/MWh) and without CT.

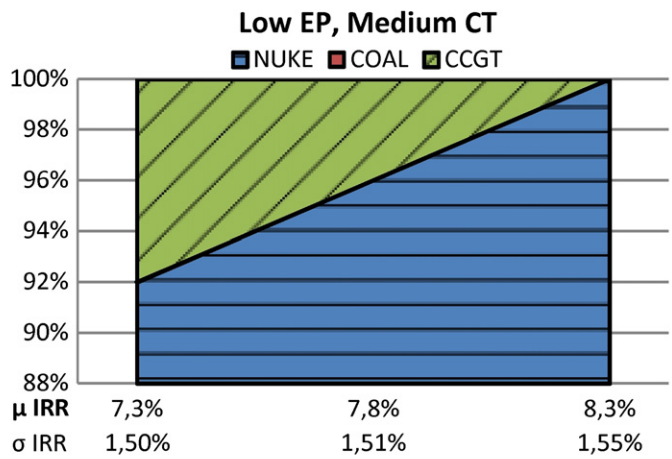

Fig. 5. Portfolios with low EP (50 \$/MWh) and medium CT (50 \$/t).

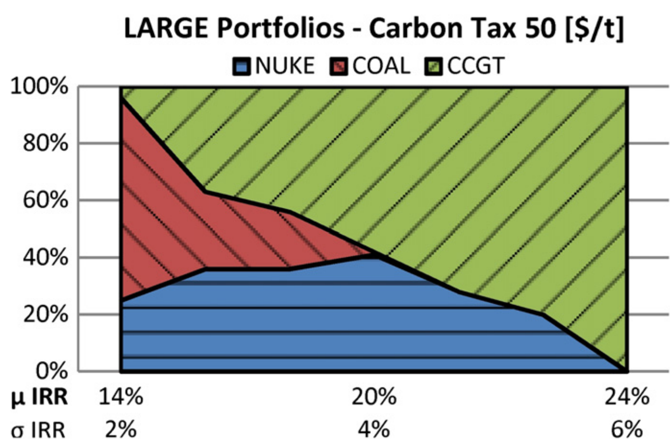

Fig. 6. Portfolios with high EP (90 \$/MWh) and medium CT (50 \$/t).

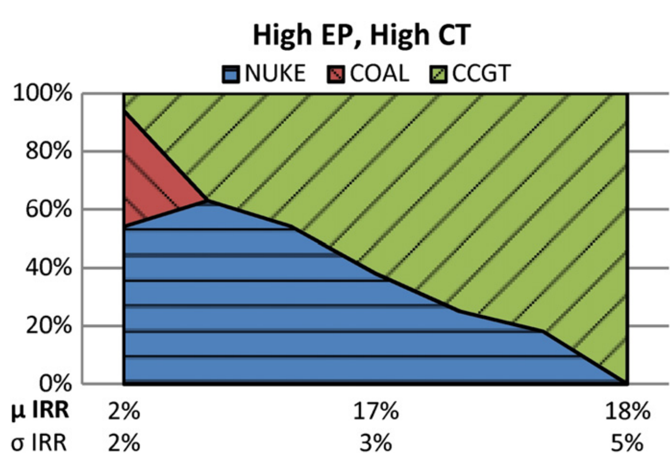

Fig. 7. Portfolios with high EP (90 \$/MWh) price and high CT (100 \$/t).

4.1.1. *IRR*

This section investigates the portfolio compositions respect to IRR according to the different levels of CT and EP. Without CT, optimal portfolios largely consist of coal plants. Depending on the EP, the remaining part of the portfolio is made up of nuclear or CCGT plants. With a low EP (50 \$/MWh), nuclear power completes the portfolio (Fig. 3). With higher Electricity Prices (70 \$/MWh or more), CCGT plants have a prominent role. The higher the CCGT percentage, the higher the return and the risk (Fig. 4).

When an EP is close to 50–60 \$/MWh (low range) the number of possible optimal portfolios is dramatically reduced, since only nuclear and coal (without CT) have a LUEC able to compete within this price range (see next section). In this situation the CT becomes the main driver:

- If the CT is close to zero the "efficient frontier" collapses on a mix of coal (with few percentages of nuclear) with a very low variability.
- If it is very high (above 80 \$/t) the only "optimal technology" is nuclear. To add a CCGT or a coal plant is not reasonable since this decreases the IRR and increases the risk, therefore the "efficient frontier" collapses in one single point: 100% nuclear.

When an EP is close to 80–90 \$/MWh (high range) more options become available for the investors since all the technologies can become a reasonable choice. The effect of a higher EP and more available technologies is to increase the gap among the portfolios with the lowest and the highest returns.

With a higher CT value (about 50 \$/t), the supposed percentage of nuclear power within optimal portfolios increases. For low Electricity Prices (50 \$/MWh), nuclear power has almost the totality of the portfolio, the maximum return/risk portfolio is composed of 100% nuclear power. Increasing the EP reduces the percentage of nuclear power within a portfolio, as well as the growing percentage of the CCGT plant, that in these conditions has the most important role (Fig. 4). The maximum return/risk portfolio is 100% CCGT while the minimum return/risk portfolio is made up of a combination of all three technologies.

With very high CT values (100 \$/t), high return portfolios are composed only of nuclear plants when the Electricity Price is 50 or 70 \$/MWh.

When the Electricity Price is 90 \$/MWh, a lower risk solution is made up of a three technology combination, the highest risk/return solution is again 100% CCGT (Fig. 7).

In order to provide a general picture, all the results have been summarized in Tables 13 and 14. To obtain a low risk (and therefore a low return) it is always necessary to diversify the investment (unless the CT is so high that only NPP are profitable). When the CT increases the portfolios exclude the coal power plant (with a low efficiency and heavy production of CO_2) and include NPPs that do not produce CO_2. The increasing of EP increases the attractiveness of CCGT power plants that suffer the risk associated to the high volatility of natural gas prices.

Table 13
IRR portfolio composition low risk/low return.

CT	Low risk/low return		
High (100 \$/t)	Nuke	Nuke–CCGT	Nuke–coal–CCGT
Medium (50 \$/t)	Nuke–CCGT (large)/nuke (small)	Nuke–coal–CCGT	Nuke–coal–CCGT
Low (0 \$/t)	Nuke–coal (large)/nuke–coal–CCGT (small)	Nuke–coal–CCGT	Nuke–coal–CCGT
	Low (50 \$/MWh)	Medium (70 \$/MWh)	High (90 \$/MWh)
		Electricity Price	

Table 14
IRR portfolio composition high risk/high return.

CT	High risk/high return		
High (100 $/t)	Nuke	Nuke	CCGT
Medium (50 $/t)	Nuke	CCGT (large)/nuke (small)	CCGT
LOW (0 $/t)	Coal	CCGT	CCGT
	Low (50 $/MWh)	Medium (70 $/MWh)	High (90 $/MWh)
		Electricity Price	

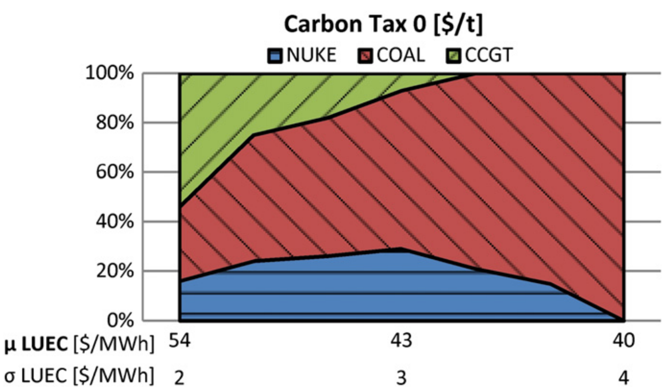

Fig. 8. Portfolios without CT.

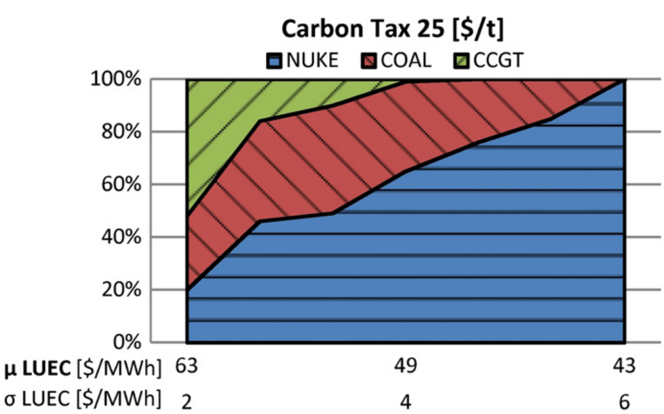

Fig. 9. Portfolio with CT equal to 25 ($/t).

Table 15
LUEC portfolio composition.

High risk/low LUEC	Coal	Nuke	Nuke
Low risk/high LUEC	Nuke–coal–CCGT	Nuke–coal–CCGT	Nuke–coal–CCGT
	Low (0 $/t)	Medium (50 $/t)	High (100 $/t)
		CT	

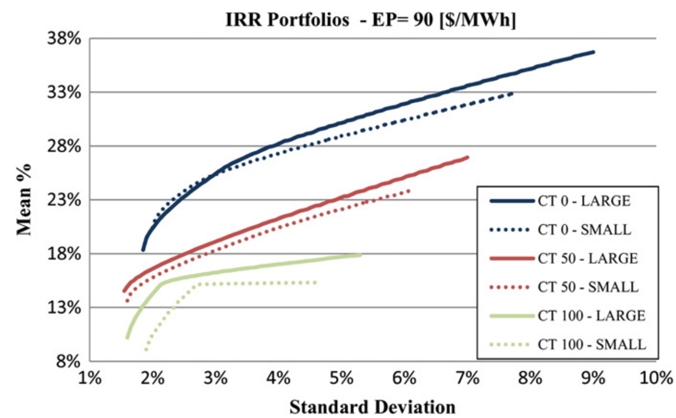

Fig. 10. Size and CT effect on IRR.

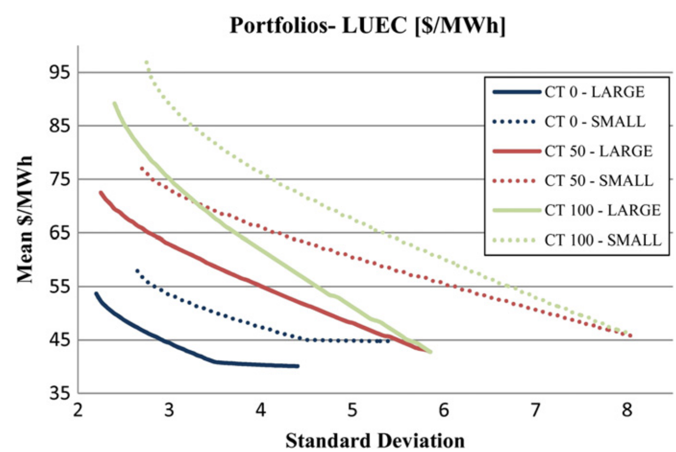

Fig. 11. Size and CT effect on LUEC.

4.1.2. LUEC

LUEC is the EP [$/MWh] able to pay back all the costs incurred in the life cycle and to provide the expected remuneration of the debt and equity. The lower the LUEC, the higher the attractiveness of the technology. Since EP is the output, the only variable in the analysis is the CT price.

Without CT, optimal portfolios are largely composed of coal plants. The minimum LUEC portfolio (but with the highest risk) is totally composed of coal plants. The risk reduction is obtained by adding nuclear and CCGT plants to the mix (Figs. 8 and 9).

The increment of CT leads to a radical change in the optimal portfolio composition. With a CT of 25 $/t, the efficient frontier (i.e. the only reasonable combination of μ and σ) largely consists of NPP. The percentage of nuclear in portfolios continues to increase along with the escalation of the CT value. In each case the minimum risk portfolio is composed of a mix of all three technologies with different scenario dependent percentages. The minimum LUEC portfolio, with the exception of the absence of CT, is always composed only of NPPs.

The results are summarized in Table 15.

4.2. Sensitivity analysis

The best way to perform the sensitivity analysis is to show how the efficiency frontier is modified by changing one parameter. Fig. 10–14 show the efficiency frontier according to different scenarios. Each line (continuous in case of large plants, dotted in case of SMPP) represents the possible combinations of portfolios that, given a certain level of risk (i.e. the Standard Deviation σ), maximize IRR or minimize LUEC. While the previous sections investigated the impact of EP and CT on the portfolio mix, this section investigates how the overall portfolio is affected by the EP, CT, market/grid dimension and size of the plants.

4.2.1. Plant size

Considering IRR, SMPP are competitive vs. large plants: large plants gain only a few extra IRR points, especially in case of low risk/low return portfolios. In case of higher returns the best solution is represented by large power plant portfolios that allow higher expected returns for each risk level. CT is, with EP, the

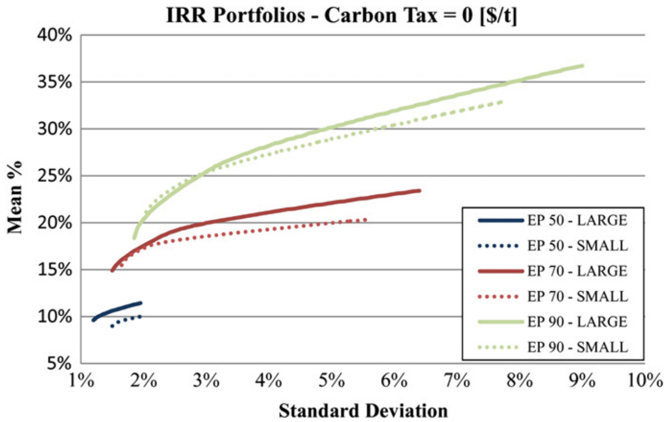

Fig. 12. Size and Electricity Price effect on IRR.

main driver and dramatically reduces the profitability of the investment (Fig. 10).

In case of LUEC indicator, large plant portfolios are always the best possible choice: SMPP's efficient frontiers are always far from the large plant for both low and high risk portfolios (Fig. 11).

The effect of the plant size on portfolio performances are shown in Table 16. If there are no constraints imposed by the grid

Table 16
Plant size effect summary.

	Min risk/min return	Max risk/max return (min LUEC)
IRR	Small/large	Large
LUEC	Large	Large

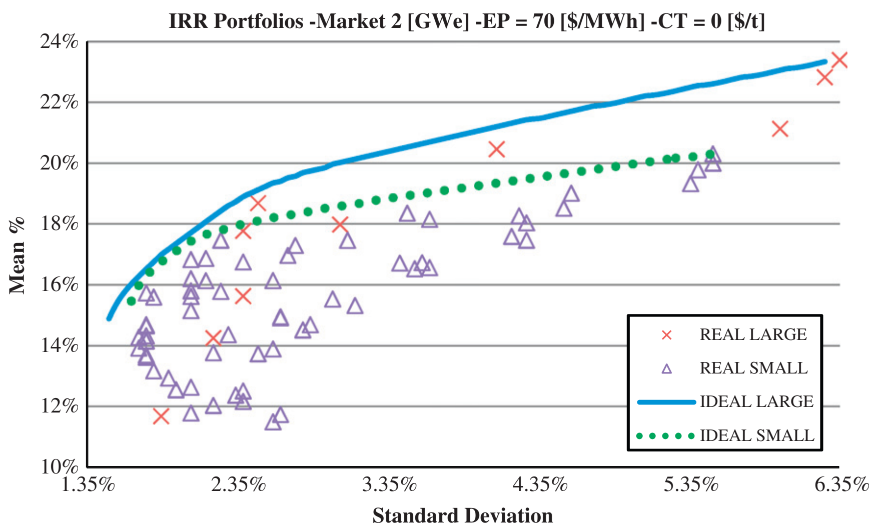

Fig. 13. Market dimension effect on IRR.

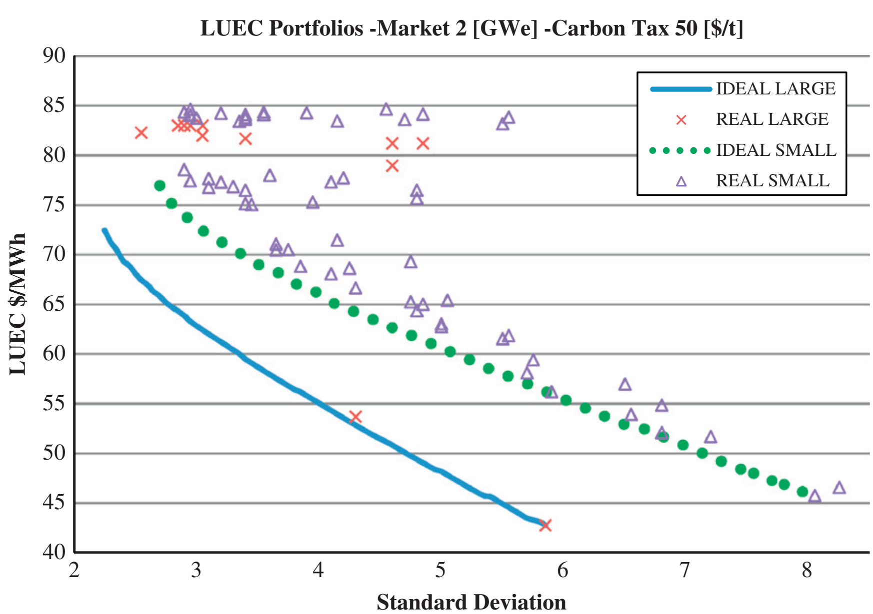

Fig. 14. Market dimension effect on LUEC. This figure shows how the ideal curve of large plants (continuous line) is not representative of the real portfolios of large plants (X points). On the contrary, the ideal portfolios of small plants (the dotted line) fits the real distribution of the plants.

(i.e. infinite market and grid) large plants are always the most reasonable choice.

4.2.2. Carbon Tax

As already pointed out, an increase in the value of CT largely impacts the economy of a coal-fired plant. Coal-fired plants have the highest CO_2 emissions. As a consequence, coal plants are disadvantaged by any emission cost.

In case of an IRR indicator, an increment in CT pulls down the efficient frontiers (Fig. 10).

Higher CT values have also a risk reducing effect. Efficient frontiers with higher values of emission costs are in the left part of the mean-variance plane. This is because higher emission costs do not permit power plants to reach high returns. As a consequence, power plant probability distributions are less wide (Lower limit is fixed by plant switch off).

Respect to the LUEC indicator, an increase in CT pulls up the efficient frontiers (Fig. 11). In fact better performances are obtained without CT. Higher CT efficient frontiers are situated on the right respect to frontiers without CT. Higher CT values lead to a risk increment (the opposite behavior of IRR). This is due to the fact that higher emission costs oblige the plants to reach higher LUEC. As a consequence, power plant probability distributions are wider.

Among the CT side effects, low CT reduce the gap between large and SMPP efficient frontiers. This reduction is mainly in the low risk area (which is usually composed of a mix of all three technologies). This is due to the fact that a reduction of CT reduces the weight of the cost of emissions within the economy of plants. That reduces the impact of fixed costs, mainly the Capital cost where the economy of scale is strong.

4.2.3. Electricity Price

High EP moves up the efficient frontiers (Fig. 12) since power plants can achieve high returns. The second most remarkable effect is that: the higher the EP is, the closer the SMPP and large IRR efficient frontiers are; a higher EP reduces the importance of fixed or semi-fixed costs and, therefore, of the economy of scale. Generally the economy of scale increases the costs while the revenues (depending on the total size) are fixed. Therefore, as much as the EP increases the relative importance of the fix cost decreases, and so does the economy of scale. Moreover, it is possible to see in Fig. 12 – for EP equal to 90 [$/KWh] in the low risk/low revenue area – the dotted line of SMPP crosses the continuous line of large plant. The Nuclear Power Plants are in this area. Since SMPP have a higher load factor, if the Electricity Price is high, it can collect enough extra-revenues to cover the part of the economies of scale unrecovered by the economies of multiples.[3]

Fig. 10 for CT0 and Fig. 12 for EP90 show as the SMPP can become, in some particular circumstance slightly more profitable than large plant. The high revenues achieved by a high Electricity Price and a low Carbon Tax allow to reap huge profits, since economy of scale deals with costs its effect drops. Moreover the correlation coefficients change improving the advantage of SMPP. However, the advantage for SMPP is in the order of magnitude of 1%, given the uncertainties in the investment evaluation is more reasonable to assume that SMPP are attractive as large plant rather than to point out a strong advantage.

[3] Economies of multiples refer to the economic advantages in deploying many identical units. If 100$ is the cost of a single unit the deployment for n identical units is less than $100\$ \times n$ because of the cost savings from: industrial learning, standardization and mass production, cost sharing of non-recursive costs (e.g. in the Engineering, in the design), sharing of site fixed, semi-fixed costs, etc. (Boarin and Ricotti, 2011; IAEA, 2005; Ingersoll, 2009).

4.2.4. Grid/market dimension

One of the most interesting results of this portfolio analysis is related to the effect of the size of the grid/market. In an ideal scenario (as in the other studies of Table 2) the grid is assumed so wide that the installation of a power plant has an infinitesimal weight. As a consequence without constraints on plant size the portfolio composition is independent from the "market size". With a constraint on plant size it is no longer true. In small grids and small markets, where the plant size is near to the network dimension, the simplification of infinitesimal weight is unrealistic. In these scenarios the installation of a plant has a great impact that depends on both the plant and market dimensions. In fact, in these scenarios, there is not enough market to install more than one/two large power plants. Therefore, only few portfolios (defined by the market and the plant size dimensions) are really available to the investor. Figs. 13 and 14 show the difference between the ideal portfolios (continuous and dotted lines) respect to the real portfolios (crosses and triangles) that it is possible to build. As much as the crosses and triangles are closer to the lines as much as it is possible to build portfolios able to optimize the trade-off between risk and profitability (Fig. 13) or risk and affordable electricity (Fig. 14).

In case of an IRR indicator, the efficient frontiers are very close to each other in particular in the low risk/low revenue area for high Electricity Price levels and low CT values. The advantages given by a reduction in size are fundamental in a real case, for a market size of about 2 GWe. In these small markets, small plant portfolios allow the investor to obtain the minimum risk on the investment.

Fig. 13 clearly points out this aspect: the triangles, representing SMPP portfolio are the only plants in the low risk area. Furthermore, this figure clearly shows how the “real portfolios” (i.e. triangles and x) are really badly described by the ideal portfolios (the continuous lines). Large portfolios remains the best solution to the maximization of return (i.e. the area top right of Fig. 13), but a mix of SMPP is an excellent solution for minimizing risks. Moreover, frontiers of "ideal small" and "real small" are close, but the efficiency frontiers of "real large" and "ideal large" are very different. Whereas small plants are not valuable in the ideal scenario they could be highly valuable in the real scenario. In fact these portfolios are the most diversified, and thus the size constraint is more likely to be binding for large plants.

Regarding the LUEC indicator, the situation is slightly different. Even decreasing the size of the network, large portfolios maintain better performances than SMPP portfolios. The choice is large technologies both for minimum LUEC and minimum risk. However, increasing the value of CT, SMPP portfolios become more competitive with regard to risk reduction. Although the minimum standard deviation portfolio is based on large plants, if the investor is willing to accept a slight increase of risk, by selecting SMPP it is possible to reach a significant LUEC reduction. Fig. 14 clearly shows how in the area with a standard deviation of about 3 the “real small portfolios” have a lower LUEC than “real large portfolio”, even if the ideal large portfolios (continuous line) have a lower LUEC. At higher emissions costs and lower market dimension, there is a substantial competition between small and large portfolios in case of risk reduction. In conclusion, Figs. 13 and 14 show how size reduction is an important advantage in small markets. Given a certain amount of power, size reduction allows for the creation of portfolios with a mix of technologies able to better optimize the trade-off among risk and profitability (or LUEC). Large plants saturate the market demand with a single technology from a couple of technologies; therefore, they cannot achieve the advantages from portfolio diversification. This demonstrates also why, considering a 2 GWe market, the approximation of ideal market with real market is no longer valid.

5. Application to OECD countries

5.1. Introduction

Considering the renewed interest toward NPP and CT it is worth applying the model to real markets: European OECD countries and the United States. Using the LUEC indicator it is possible to eliminate the result dependence from the Electricity Price (different in each country).

Two different types of portfolio were calculated: the first called "Construction" and the second "Actual". "Construction" portfolio considers uncertain the overnight costs. "Actual" portfolio considers the sunk overnight cost by placing a deterministic value (equal to the expected value of the distribution). "Construction" portfolio allows a comparison if the investor builds a portfolio from scratch. "Actual" portfolio considers overnight costs already incurred with variability only on fuel and O&M cost. "Actual" portfolios are meaningful if the investor buys an already built plant.

While "construction" portfolio performances are hypothetical or future projections, "actual" portfolio is representative of the actual situation in each country.

The analysis is based on the latest data by the European Environment Agency (EEA, 2010).

5.2. Results

Without CT (Fig. 15), the "actual" portfolio curve is always on the left side of the "construction" curve. This is because the calculation of "Actual" power plants does not consider the overnight cost variability. A deterministic overnight cost leads to a reduction in standard deviation of LUEC for the three technologies.

In the absence of CT and considering an "actual" portfolio type, "nuclear countries" such as France, Sweden and Switzerland are very close to the efficient frontier while in the case of "construction" portfolios they are at high risk. This is quite realistic: regarding Light Water Reactors the risks come from the cost escalation in the

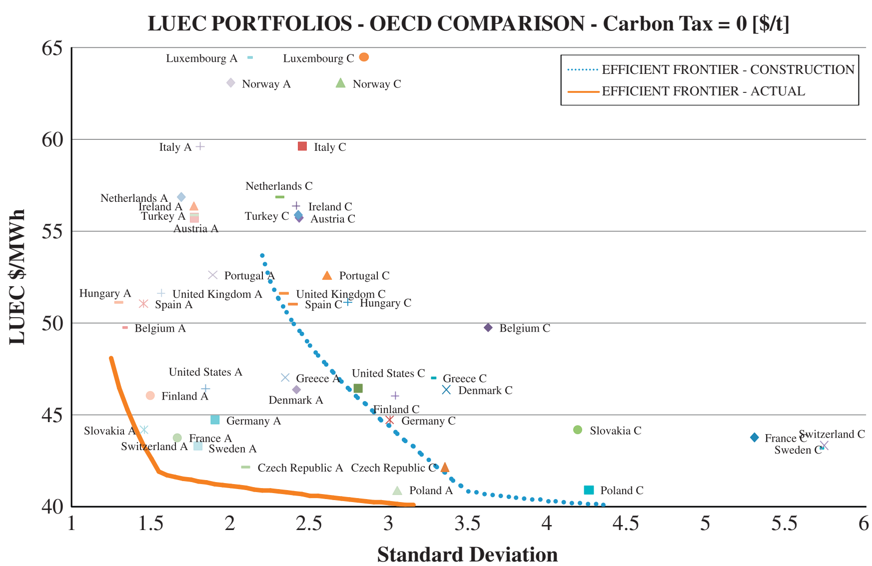

Fig. 15. OECD European portfolios comparison, CT=0 $/t.

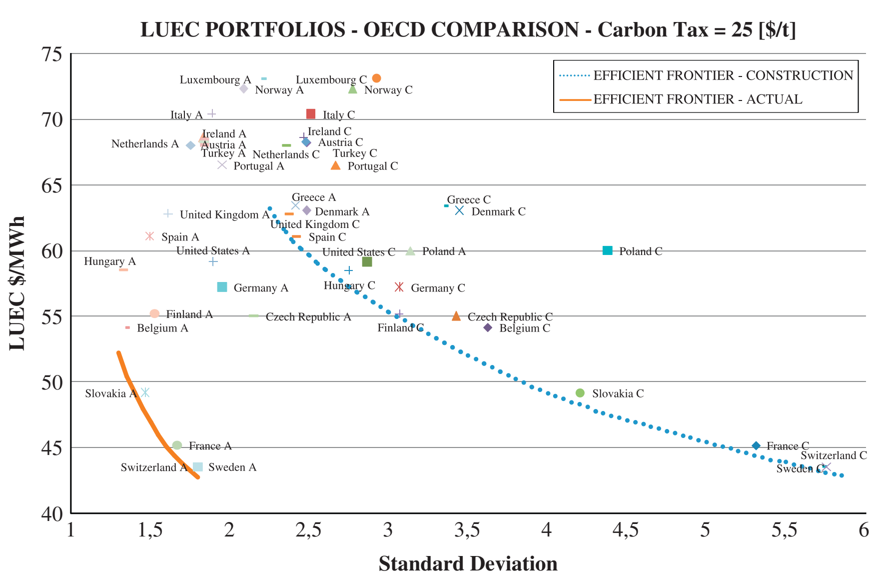

Fig. 16. European OECD portfolios comparison, CT=25 $/t.

construction phase while the O&M and fuel costs are quite stable and account for less than 50% of the life cycle cost.

Regarding the construction portfolio, coal based portfolios are the most efficient without CT. Without CT, countries such as Poland producing electricity using primarily coal technology are close to efficiency. Poland having in its portfolio 97% of coal plants is the closest to the minimum LUEC in both “actual” and “construction” cases. The CT (Fig. 16) allows portfolios with a higher weight of nuclear power to be closer to the efficient frontier than others countries for both “construction” and “actual” portfolio. Slovakia, France, Sweden and Switzerland are the countries that are the closest to frontier. Countries without nuclear energy, such as Italy, are in a very inefficient part of the mean-variance plane. Poland, that in the absence of a CT presents a high efficiency, is now in the top right corner of the plane in the area at highest risk and cost. Despite the increase in CT, many countries such as Germany, Finland and Spain are still close to the efficient frontier for construction portfolios. Looking to “actual” portfolios, however, these countries with their existing portfolios cannot get the same ideal efficiency they could have in a “construction” case. In fact their portfolios are at a considerable distance from the efficient frontier.

The European situation is very wide: without CT a large number of countries have an efficient (or very close to efficiency) generating portfolio. By increasing the cost of emissions, only the most-nuclear countries maintain a position of efficiency in the mean-variance plane, all other countries are in the top right corner of the plane in the area at great risk and high LUEC.

6. Conclusions

The optimal technology mix is usually determined by the load curve and the ratio between fixed costs and variable costs of the various technologies. In fact, a reasonable technology mix is composed of:

- base load plant usually with high fixed costs and low variable costs, e.g. coal and nuclear,
- peak load plant usually with low fixed costs and high variable costs, e.g. heavy duty gas turbines.

In our analysis we investigate the economics of base load portfolios.

In the international literature several studies deal with the applications of portfolio theory in the power generation sector, but none of these focuses on SMPP or small grid dimension and IRR. The goal of this work is to fill the gap by analyzing the effects of Electricity Price, CT, plant size and network/market dimension on the identification of optimal portfolios.

The results of the analysis show how the ideal large plant portfolios have better performances for the LUEC indicator than SMPP portfolios, and comparable performances to the IRR. In case of a large market (> 10 GWe), the real situation is not significantly different from the ideal, large plants portfolios being the best alternative in most cases. However, in case of small size market (2 GWe), portfolios of SMPP are able to provide a lower investment risk than large portfolios for both IRR and LUEC indicators because of a diversification that is not possible for large plants.

In the absence of CT, the best performances are provided by portfolio based on coal-fired plants. An increment in Electricity Price or a reduction of CT decreases the gap between the SMPP and the large plants efficient frontiers. The optimal mix is largely composed of nuclear plants if there is a medium/high cost of emissions or in case of low Electricity Price.

Appendix 1. Models comparison

See Table A1.

Appendix 2

See Table A2.

Table A1
Models comparison.

	Locatelli and Mancini (2010) Model	Updated model
Thermal efficiency CCGT	50%	57% (Bhattacharya and Cropper, 2010; Claeson Colpier and Cornland, 2002; NASA, 2009; Persson et al., 2007)
Overnight cost	Updated to 2009	Updated to 2011
O&M cost	Updated to 2009	Updated to 2011
Coal and CCGT fuel costs	Fixed once an iteration from a discrete distribution	Trimestral estrapolation from a discrete distribution for each iteration
Nuclear fuel cost	Fixed once an iteration from a discrete distribution	Trimestral estrapolation from a discrete distribution for each iteration—updated to 2011
Coal and CCGT plants switch off	Not required	Implemented. If the EP drops below the marginal production cost the power plant is considered “closed” and there are not revenue and variable cost. Because of the volatility of natural gas this option is valuable in particular for CCGT power plants
Electricity price	Deterministic—scenario dependent	Probabilistic distribution—trimestral estrapolation—scenario dependent
CT	Scenario dependent—0$/t to 40$/t	Scenario dependent—0 $/t to 100 $/t

Table A2
Updated Nuclear power plants overnight cost.

Study	Country	Design	Size (MWe)	Reference YEAR	Specific cost ($/kW)	Status	Value
NEA (2010)	France	EPR	1643	2010	3860	Under construction	Updated
	USA	APWR	1700	2010	2970	EPRI forecast	New
	USA	ABWR	1356	2010	2970	EPRI forecast	New
WNA (2010/07))	Carolina USA	AP1000	1117	2008	4924	Under construction	New

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Glossary

CCGT: Coal and Combined Cycle Gas Turbines;
CT: Carbon Tax;
D&D: Decommissioning and Decontamination;
EP: Electricity Price;
IRR: Internal Rate of Return;
Kd: Cost of Debt;
Ke: Cost of Equity;
LUEC: Levelised Unit Electricity Cost;
MVP: Mean Variance Portfolio theory;
NPP: Nuclear Power Plants;
NPV: Net Present Value;
O&M: Operation and Maintenance;
OECD: Organisation for Economic Co-operation and Development;
SD: Stochastic Dominance;
SMPP: Small Medium sized Power Plants.