



Application of Portfolio Analysis to the Irish Electricity Generating Mix in 2020

Eoin McLoughlin, Morgan Bazilian

Working Paper

June 2006

Comments which can help to improve the analysis are welcome

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Acknowledgements

The authors would like to acknowledge the support of: John Fitzgerald, Niamh McCarthy and Laura Malaguzzi Valeri of the ESRI, Brian O’Gallachoir of UCC, and Ronan Doherty of Airtricity.

Special mention goes to Shimon Awerbuch of SPRU, and the ECN team, in particular to Luuk Beurskens for his guidance and direction throughout the process.

Disclaimer

This study utilises the online portfolio analysis tool developed by ECN. The current report is to be used as a case study in a REEEP/UNEP funded project on the application of the ECN model. Thus, part of the process was to help inform the development of the online tool for a wider audience. As far as the authors are aware, this study is the first to make use of the REEEP portfolio analysis online tool.

Although the results of the portfolio analysis cannot be directly translated into policy, it is clear that policy formation can be better informed by evaluating various portfolios of plant from both a cost and risk perspective.

Contact: eoin.mcloughlin@sei.ie

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Executive Summary

This study presents findings from applying the concept of mean-variance portfolio analysis to the future Irish electricity generating mix. The year 2020 was selected as the target year for the analysis and two likely growth scenarios presented. These growth scenarios are aligned with a High Energy Forecast (HEF) and Low Energy Forecast (LEF) for Ireland.

Energy forecasts to 2020 show a considerable aggregation in the fuel sources in the power sector. The principal areas of growth are in natural gas and renewables, both associated with significant increases in installed capacity. The forecasts predict that gas powered plants will gradually increase in importance and by 2020 will be responsible for 71% of the generation fuel mix¹. This provides an impetus for considering the portfolio of electricity plant in Ireland from the perspective of security of supply.

The mean-variance portfolio analysis (MVP) methodology allows for a broad view of the plant portfolio in terms of risks and costs. There are considerable uncertainties in quantifying costs to 2020, and even more uncertainty in completely understanding the risks. However, it is useful for investigating the overall impacts of larger shares of renewable energy electricity. Policy formation can be better informed by evaluating various portfolios of plant and their impacts on costs and risks. Various least-cost plant portfolios have already been investigated by Doherty (2006) in the context of the All-Island Working Group on Renewables Integration.

In considering policy and regulatory responses it is critical to acknowledge the role of the competitive market in electricity. While “optimal” portfolios can be considered, the key is to establish ways to incentivise behaviour by market actors. The strong EU movement towards a liberalised electricity market and away from a central planning paradigm has had its successes and failures. However, even in a security conscious world, the role of a central integrated resource plan for electricity generating plant is unlikely to re-emerge (at least in the short to medium term).

Hobbs (2000) notes, “people, firms, and government agencies have many objectives, goals, criteria, attributes, or performance indices that they use to judge possible courses of action. The problem is that it is rare that all these *desiderata* can be met or maximised by one alternative.” Hobbs put forward a thesis that by systematically examining tradeoffs and value judgements, consensus can be built. This consensus is critical in designing robust energy policy. Hobbs utilises a tool called multiple criteria decision making (MCDM). The portfolio exercises performed here and in Doherty (2005) and Fitzgerald (2005) can help inform such a process.

Results of the MVP analysis suggest that in both scenarios portfolio cost and risk can be reduced considerably. This is through the deployment of those technologies that offer both risk mitigation properties as well as cost effectiveness. Renewable technologies such as wind and biomass are ideally situated to offer such a solution. In some cases portfolio cost of electricity can be reduced by up to 43% and risk reduced by a factor of 12% when compared to the business as usual portfolio mix.

A sensitivity analysis is also performed which shows the effects of a change in some key input cost parameters. For example, an increase in the price of gas and carbon shifts portfolio cost level upwards and simultaneously creates a more attractive investment climate for renewable technologies. In cases where gas prices increase but carbon price levels remain static, only those portfolios containing gas plant technologies show a corresponding increase in cost. This demonstrates how coal, as well as renewable technologies, can help protect the Irish economy from gas price hikes.

¹ Note that these results indicating which plants generate electricity in each period are the output of an economic dispatch model. Policy considerations may impose constraints on this dispatch (or through longer term signals) in order to change the mix for security of supply reasons.

1. Introduction

Energy plays a vital role in Irish society, underpinning all areas of economic activity. The economic impact of supply disruptions or price fluctuations can therefore be significant and wide-ranging. This creates an incentive for governments to ensure that secure, reliable, and competitively priced energy sources are readily available. There is surprisingly little in the way of specific indicators developed for security of energy supply on a national basis. This is in part due to the complexity and diversity of the subject. This report attempts to consider one aspect of the Irish energy sector (namely electricity generation), using one analysis methodology (portfolio theory).

The Department of Communications, Marine & Natural Resources (DCMNR) has announced plans to publish an Energy Policy Green Paper later this year setting forth its future energy policy agenda. This study utilises financial portfolio analysis, based on Markowitz Mean Variance Portfolio Theory (MVP), to assess the portfolio of electricity generating plant in Ireland in 2020. This type of analysis highlights the interplay between the cost and risk aspects of the Irish power system. Consideration of the plant portfolio explicitly allows for insights into the security of supply and competitiveness dimension of energy policy. The environmental aspects are considered implicitly through modelling the impacts of increased deployment of Renewable Energy (RE) on the portfolio's performance. The modelling simulations may be useful in informing future energy policy and associated regulation.

MVP is built on the foundation that a portfolio of well-chosen assets has reduced risk properties when no perfect mutual correlation between the return on each pair of assets exist. Conversely, portfolio (cost) risk may be minimised in a portfolio of well-chosen generating technology options as a result of less than perfect correlations between their cost characteristics (Jansen, 2006).

This study utilises the approach taken by the Energy Research Centre of the Netherlands (ECN) which proposes some adjustments to the theoretical framework developed by Awerbuch and Berger (2003). The model has been formulated as an on-line tool. Part of this project has been to beta test that online tool. The ECN report (Jansen, 2006) has been used as a template for this Irish report. The current report will be used as a case study in a REEEP/UNEP funded project on the application of the ECN model.

In this study, the MVP approach is applied to future Irish generating mixes for the year 2020, evaluating risk against two energy forecast scenarios developed by the Economic and Social Research Institute (ESRI) and Sustainable Energy Ireland (SEI) i.e. High Energy Forecast (HEF) and Low Energy Forecast (LEF). Furthermore, a sensitivity analysis is undertaken, focusing on changes in the price of natural gas and carbon as well as the cost of capital (WACC).

This report is structured as follows. Section 2 provides an introduction to the concept of portfolio analysis as applied to the electricity production sector. Section 3 applies portfolio analysis to the Irish 2020 generating mix. Section 4 describes and analyses the sensitivity of the outcomes to variations in CO₂ prices, gas prices and the cost of capital. Finally, section 5 presents the main conclusions of the study.

2. Application of Portfolio Analysis to Energy Planning

2.1 Introduction

This study employs the MVP approach, the portfolio analysis framework for asset investments introduced by Harry Markowitz in the early 1950s (Markowitz, 1952). Its original and still most widely used application is to determine optimal portfolios of financial assets (Fabozzi et al., 2002). In its initial application, MVP relates expected portfolio return to the total portfolio risk, measured as the standard deviation of past (periodic) returns.

The MVP approach can be considered one way to examine costs and risks from an investment perspective. It proposes how rational investors will use diversification to optimise their portfolios. An investor can reduce portfolio risk simply by holding assets, the returns of which show diverging patterns of co-variation. In other words, investors can reduce their exposure to individual asset risk by holding a diversified portfolio of assets. If the returns on any two assets in the portfolio have a correlation of less than one, the portfolio volatility will be less than the weighted average of the volatilities of the portfolio's individual assets (Jansen, 2006).

MVP has been introduced as an approach to make allowance for mitigation of non-systematic risk by diversifying portfolios of financial assets. The same principle can be applied to portfolios of electricity generating technologies.

It has been shown that by including portfolio (cost of electricity) risk, the MVP approach set out in this study enables policy makers to integrate the three core energy policy goals (competitive energy prices, energy supply security, mitigation of adverse environmental impacts) into one quantitative framework. The proposed approach enables policy makers to monitor electricity cost risk developments using an energy supply security metric as a benchmark.

It is recognised that there are a number of ways to consider power system generating portfolios. The MVP approach has a number of weaknesses that will be further expounded in the following section. However, this study, and the ECN modelling tool utilised, use this approach as one way to consider a medium to long-term societal perspective of various technology deployment portfolios (Jansen, 2006). In certain cases it may also be desirable to consider the portfolio mix from a utilities perspective (Roques, 2006). It is also important to note that like all models, it is an abstraction from reality. It can thus serve to inform decisions, but not predict outcomes with any certainty. This is especially true in the liberalised electricity market, where the notions of integrated resource planning are no longer entirely applicable. Therefore, models that consider the entire portfolio of plant do not take into consideration the varied and unpredictable actions of market actors.

2.2 Theoretical Approaches to Measuring Diversity

Most risk analysis in power systems and elsewhere is based on either probabilistic or unknown-but-bounded models. The application of MVP or Markowitz Portfolio Theory (MPT) is an example of the former technique. As discussed, this approach maximizes portfolio return at any given level of portfolio risk as measured by the standard deviation (SD) of past portfolio returns. A number of other methods for considering portfolios are outlined in this section. These serve to illustrate the varied approaches that can be useful in approaching this area.

For instance, some criticism has been levelled at the MVP approach on the presumption that the past is not always a reliable guide to the future (Stirling, 1995, 1996). Stirling's criticism of MVP is twofold. Firstly, he argues that approaches based on the financial theory concept are constrained by their rather narrow rate-of-return performance notions and additionally, that they are limited to a small, circumscribed region of the full uncertainty-space. The complete range of relevant technology performance attributes, according to this reasoning, extends well beyond those addressed by ordinary financial rate-of-return models. In addition, the future potential for 'surprise' goes well beyond the more limited range of possible outcomes implicitly addressed by historic variance and covariance data (Awerbuch et. al, 2004).

Stirling instead proposes a multicriteria diversity analytic (MDA) approach that seeks to cover the full spectrum of risk, reaching into areas of uncertainty where there is little confidence in the basis for assigning probabilities. Like MVP, MDA rests on optimization concepts, although it adopts a broader decision analytical framework. It minimizes portfolio uncertainty by maximizing diversity at any given level of portfolio performance (Awerbuch et. al, 2004).

And yet, a potential criticism of MDA is that, unlike MVP, it does not exploit additional information in the risk-region of the uncertainty spectrum where such information is sufficiently robust to have decision-making value. The diversity approach neglects the historic variances and co-variances of outcomes, even where these may provide some reliable guide to future performance (Awerbuch *et al.*, 2004).

One way of overcoming the limitations of the two models is to combine them into a single optimisation known as *full-spectrum risk analysis*. This allows users to define a set of user-weighted efficient frontiers that reflect their degree of confidence in history versus their concern about intractable future uncertainty. Such a fully articulated model enriches both MVP as well as MDA techniques. A full explanation of the model can be found in Awerbuch (2004).

Stirling (2004) in his work has also adapted the *Shannon-Wiener Diversity Index (SWD)* in examining diversity in the energy field. This is a useful metric for considering a country's electricity fuel mix from the perspective of security of supply. This index has the merit of incorporating both the concepts of variety and balance, recognising that a system which relies on a given number of fuel types may be more or less diverse, depending on the proportion of generation accounted for by each of these fuel sources (Grubb, 2005). The SWD index is calculated according to:

$$\sum_{i=1}^I -p_i \ln(p_i)$$

where p_i is the proportion of generation represented by the i th type of generation.

With just one generation type the index has the value of zero (Fig. 2.1). A system with two equal components has a value of 0.69, with three equal components this rises to 1.1, and with ten equal components to 2.3. The diversity index rises above 2 for a system with more than 7 equal components.

From Figure 2.1 it is apparent that a value below one indicates a system that is highly concentrated and dependent upon one or at most two sources, to a degree that would clearly threaten security of supply in the event of any sustained interruption. A value above two indicates a system with a measure of diversity; such a system is considered to be reasonably secure in the face of an interruption to any of the individual supply components (Grubb, 2005).

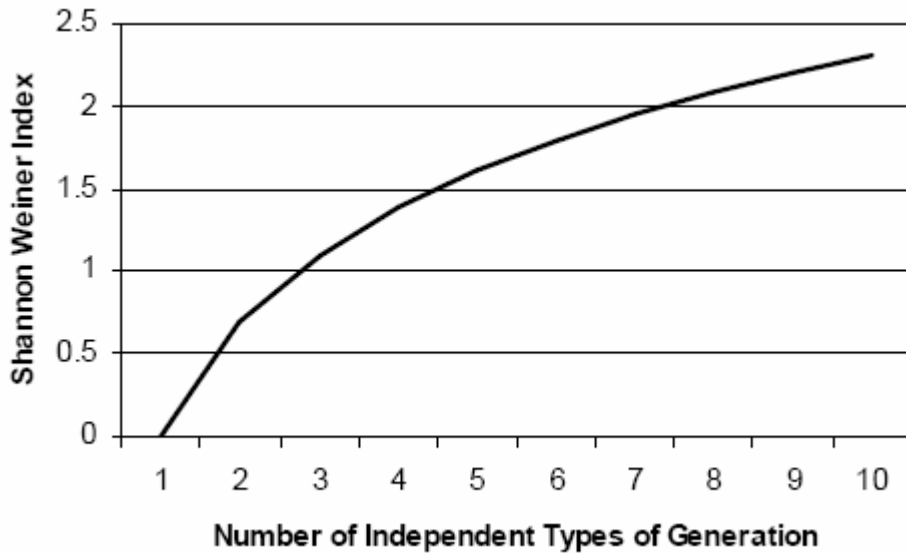


Figure 2.1: Shannon-Wiener Index

Doherty (2005) uses both the SWD index as well as mean-variance portfolio analysis in examining the optimal fuel portfolio plant mix for electricity generation for an all-Ireland market in 2020. These are run under different fuel and carbon price scenarios with the results being shown in figures 2.2 and 2.3. Doherty's results demonstrate that even when applying two different approaches to the same portfolio, when they are applied to a scenario with limited options they produce similar outcomes.

The graphs plot the cost of electricity from a particular portfolio of generation plants on the x-axis against the standard deviation of the electricity cost and the Shannon-Wiener index on the y-axis. In both cases, the efficient frontier charts the points along which all the optimal portfolios are located. For instance, portfolio B exhibits the least cost scenario and results in a relatively low level of fuel diversity and possibly high levels of exposure to gas price hikes. Portfolio A can be considered inferior as it offers neither lower costs nor lower risk to B. Portfolios C and D contain greater levels of fuel diversity with only minimal increases in costs.

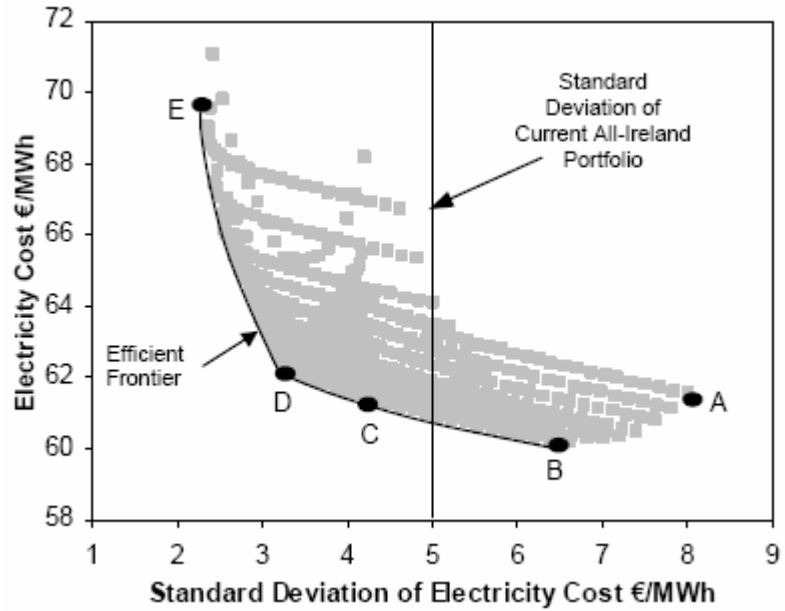


Figure 2.2: Mean-variance portfolio analysis (Doherty, 2005)

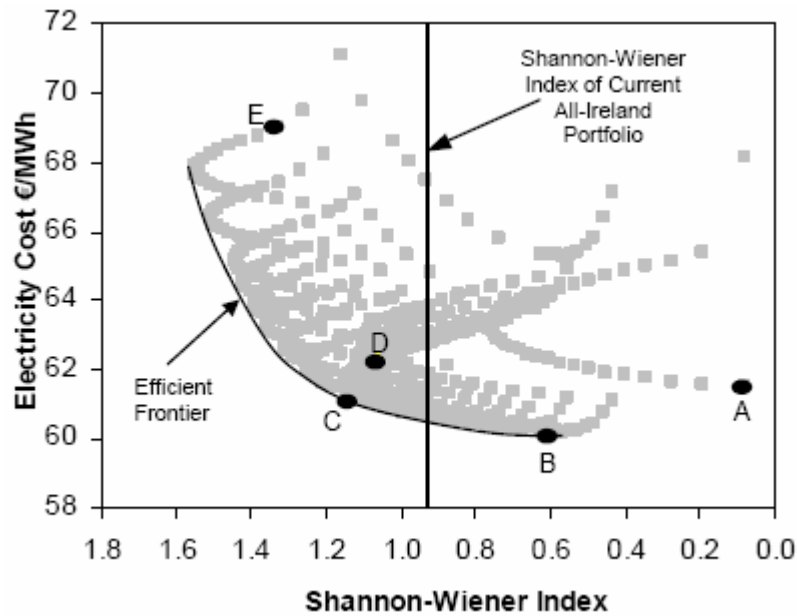


Figure 2.3: Shannon-Wiener index portfolio analysis (Doherty, 2005)

Doherty in his work also utilises a linear programming portfolio optimisation algorithm to locate the mix of generation technologies that, for a given set of inputs, results in the load being met at least-cost. Issues of plant utilization, load duration and generation adequacy are included in the analysis. However, temporal system aspects and unit start-up factors are not included. The algorithm optimizes the installed capacity of each type of generation in the portfolio and optimizes how they are utilized with respect to the load duration curve.

Doherty (2006) most recently made an assessment of the generation plant portfolio for the all-island system in 2020 by using such an algorithm. This work was performed within the confines of the All-Island Grid Study. As the study is still ongoing and confidential at this stage it was not deemed appropriate to reference any of the results.

The ESRI also used the concept of modern portfolio theory in looking at optimal plant mixes for an Irish system (ESRI, 2005). The analysis looked at a range of plant technologies and was performed under different carbon price scenarios. The model was run unconstrained and used standard deviation and the time weighted average price as measurements of risk and cost respectively. Only the fuel cost element in the final cost of electricity was included. The results indicated that risk is minimised at a price level of €68/MWh. In all cases, each of the portfolios is dominated by wind power as unlike conventional plant it does not suffer the vagaries of fuel price volatility and can to a large degree maintain a constant output price level.

The analysis also showed that if the lowest possible cost is the driving factor, and risk and carbon prices were not a concern, then coal and peat would feature strongly in an optimal plant portfolio. However, where carbon prices are included then first peat above a CO₂ price of €10/tonne and then coal at CO₂ price above €30/tonne become uncompetitive and wind begins to become an attractive option beyond a carbon price of €40/tonne.

A further measure of diversity assessment is the Herfindahl Hirschman Index (HHI). This index measures the degree of market concentration in a particular sector. Assuming that p_i is the market share assumed by the i th firm, or the proportion of generation met by one particular fuel source, then the index is calculated according to:

$$H = \sum_{i=1}^I p_i^2$$

where p_i is expressed as a percentage. The HHI takes into account both the relative size and distribution of each source, increasing as the number of firms falls and the disparity in the size of those firms increases. The maximum value of the index is 10,000 in the case of a monopoly, falling towards zero as the market evolves towards a situation of perfect competition. The figure below shows the value taken by the index as the number of sources of generation increase (Grubb, 2005).



Figure 2.4: Herfindahl Hirschman Index (Grubb 2005)

However, McCarthy (2005) observes that although the HHI is an internationally recognised standard, as a static measure it does not represent the real-time aspect of electricity markets. Therefore, McCarthy also uses a more dynamic measure known as the Residual Supply Index (RSI)² to determine the potential for an abuse of market power by a generator. The RSI for a company X measures the percent of supply capacity remaining after subtracting company X's capacity of supply (less contract obligations). An RSI of approximately 120 percent represents a market price outcome close to the competitive benchmark. Anything less than this percentage would infer some form of market power, even if companies were only producing a small amount of output.

A further method of measuring the effects associated with greater diversity is through the use of real options analysis. This approach allows for adjustment in the timing of the investment decision, and is particularly well suited to evaluate investments with uncertain payoffs and costs. For instance, in cases where fuel or carbon prices increase more rapidly than expected, then the project can be deferred or a different technology chosen.

By simulating many realisations of stochastic gas, electricity, and carbon prices and their associated net present value (NPV), the option value of a particular technology can be seen as the difference between the expected NPV of the alternative scenarios (Roques et al, 2005).

Roques (2006) also uses MVP theory to consider optimal portfolio mixes in the UK from a utility perspective rather than the traditional societal approach. Private generators operating in a liberalised electricity market cannot be expected to compare different generating technologies on their production costs, but rather on their expected risks and returns. This requires taking into account not only fuel price risks, but also electricity and carbon price risks.

The results of the analysis indicate that the benefits of increased correlation brought about from a greater share of gas-fired plants 'in the fuel mix and therefore reduced volatility between electricity and gas prices, outweighs the risk-reducing benefits of greater diversification in other technologies. This then bears the question as to whether or not some type of policy instrument should be used in order to incentivise market behaviour that would lead to a more socially optimal outcome. Such measures may include the imposition of taxes differentiated by technology or a 'diversity obligation' quota system requiring suppliers to source their electricity from different sources.

Finally, a completely alternative view put forward is that current energy market models are overlooking the real drivers in national energy policy planning for the future (NREL, 2005). Today, as in the past, there is a host of natural, social, political, and technological drivers outside the scope of energy models that are the true determinants of the future. These factors can't simply be inserted into such deterministic models because they are highly uncertain, even unlikely, but still possibilities with potentially huge consequences.

Although there is no way to remove all the uncertainties associated with the future, there are alternatives other than scenarios for analysing them. One such alternative is currently being developed in the U.S. and is known as the Stochastic Energy Deployment Systems model (SEDS).

SEDS can be operated in either a deterministic mode or a stochastic mode. When operated deterministically SEDS uses a single value instead of the input probability distributions for the uncertain parameters. These deterministic SEDS runs can be extremely quick and informative in terms of how the model responds to different inputs and assumptions. When operated stochastically, SEDS makes a number n^3 of sweeps through time with each sweep beginning in 2005 and extending in 5 year increments out to 2050 (NREL, 2005).

² $RSI_x = (\text{Total Capacity} - \text{Company's } X\text{'s Relevant Capacity}) / \text{Total Demand}$.

³ The user can input the number of sweeps through time, with more sweeps producing a more statistically accurate picture. The current default number of sweeps is 200.

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In summary, although it can be seen that there are many different theoretical approaches to measuring fuel diversity, this study has concentrated on using just one, MVP. The strength of MVP analysis rests on the presumption that the past is a reliable guide to the future. This is not to say that unexpected events will not happen – only that the effect of these events are already known from past experience (Awerbuch, 2004). It therefore serves as a good starting point in examining the application of portfolio analysis to the Irish electricity system.

2.3 Application of MVP to Energy System Planning⁴

Applications of MVP in the remainder of this study relate to its use in the power generation sector at an aggregated national level, in this case the Republic of Ireland (RoI). These applications enable policy makers and electricity supply system analysts to consider the mix of power generation technologies from a wider societal perspective. A key distinctive feature of the portfolio analysis approach, compared to conventional least-cost power system expansion planning, is that it allows for the incorporation of risks surrounding the electricity mix portfolios. A major electricity cost component is fuel cost. In the electricity supply systems of many countries fossil-fuel-based generating technologies - notably natural gas, coal, and oil – hold a dominant position. Serious risk to supply security may be a consequence of this dependence (Jansen, 2006).

MVP analysis for the power generation sector provides a consistent framework to gain better insight into the portfolio (cost) risk, associated with alternative technology deployment portfolios. The MVP analysis framework, to be further elaborated hereafter, is predicated upon a set of assumptions on technology unit costs, their mutual co-variation relationships, and the risks associated with these costs (Jansen, 2006).

Distinctive features of the MVP approach are that it makes consistent *quantitative* allowance for:

- Risk attached to the power generation technologies;
- The societal benefits associated with the risk-mitigating *portfolio effect*. For example, the cost risk of gas-based generating technologies is far from perfectly correlated with the cost risk of renewables-based technologies. With liberalised energy markets tending to favour the deployment of fast-build and efficient CCGT technology, it would appear highly desirable to include the portfolio effect into a *quantitative* framework to analyse the generating mix from the societal perspective;
- Volumetric risks associated with supply-side factors. Such factors include the supply variability relating to so-called intermittent renewable resources (wind, solar).

By including portfolio (cost of electricity) risk, the MVP approach set out in this report enables policy makers to integrate the three core energy policy goals (price efficiency, supply security, environmental integrity) into one quantitative framework. The proposed approach enables policy makers to monitor electricity cost risk developments using energy supply security as a benchmark.

⁴ This section draws heavily on the study, 'Application of portfolio analysis to the Dutch generating mix', (Jansen, 2006).

2.4 The ECN AIMMS MPT Model

This section draws heavily on the study, 'Application of portfolio analysis to the Dutch generating mix', (Jansen, 2006). Further information on the mathematical description and algorithms of the model can be found in Appendix E.

The ECN AIMMS model adopts a number of refinements made to the theoretical framework. These relate to:

- Introduction of a risk-cost efficient frontier
- Use of energy-based as distinct from capacity-based portfolios
- Expressing risk in terms of costs (however, in the current report risk is expressed in relative terms as a percentage)
- Introduction of a consistent framework for determining the risk of COE for individual technologies
- Incremental technology deployment analysis

ECN proposed the transformation from a risk-return to a risk-cost efficient frontier for electricity mix applications due to the following reasons:

- 'Return' has quite a different meaning than just the reciprocal value of cost per unit of energy;
- Unlike propositions made by Berger (2003) and Awerbuch and Berger (2003) the reciprocal of portfolio cost is not the same as portfolio return;
- The conversion from portfolio cost to a parameter defined as its reciprocal ('portfolio return') makes the link to portfolio risk problematic.

3 Irish Electricity Generating Mix in 2020

3.1 Introduction

This report uses the two energy forecast scenarios presented for the Irish economy by the ESRI and SEI. These scenarios can be translated into a high energy forecast (HEF) and Low Energy Forecast (LEF). These growth pathways are closely aligned, *inter alia*, to the future development of the US economy.

3.2 Scenarios and Input Assumptions

Technology costs have been chosen in accordance with the input data provided. Parameters such as CO₂ and fuel price levels as well as sensitivity cases have been selected and can be subject to some debate. A full breakdown of all cost inputs can be found in Appendix A.

Figure 3.1 shows the cost inputs used for the portfolio analysis broken down by technology type. This graphic demonstrates how the different cost components determine the final cost of electricity. For instance, for fossil fuel based stations the fuel cost component is the dominant factor whereas for renewable plants it is the capital cost. One important element to note here is that an intermittency penalty of €6/MWh is applied to those technologies such as wind where output is variable. It is included under the variable operating cost component. This accounts in some way for the cost of supplying back-up in cases where variability reduces electrical output.

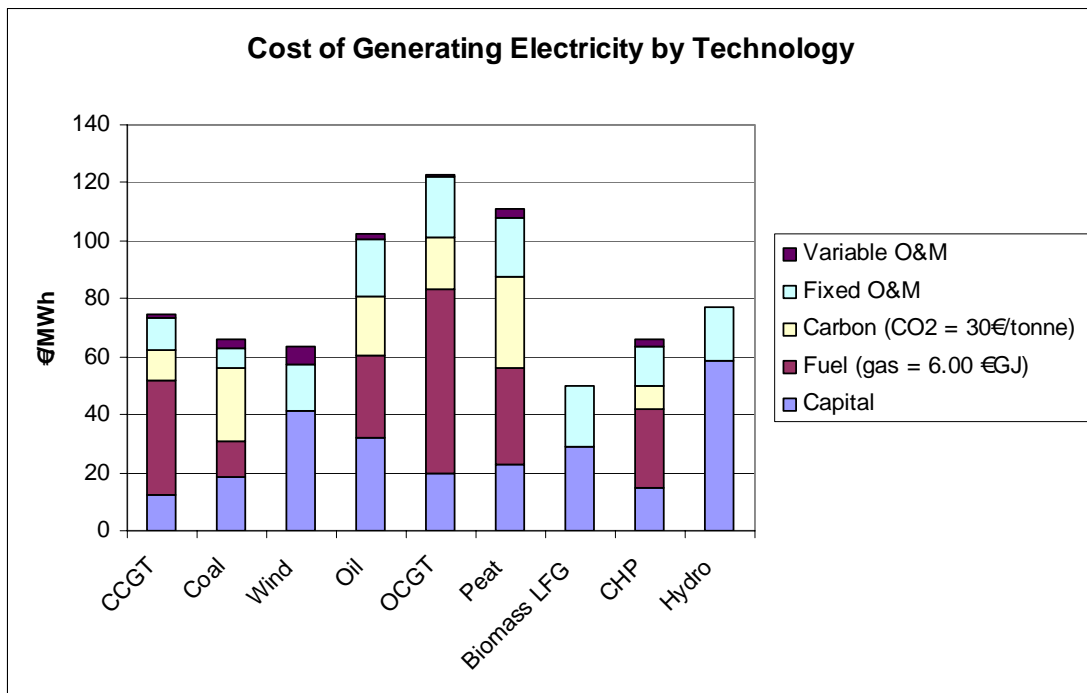


Figure 3.1: Cost of Generating Electricity by Technology

Risk estimates are derived following a pre-defined methodology and projections of long-term cost and risk for generating options. All the technologies included in this study are considered existing technologies and as a result the investment risk for such plants is set to zero.

Furthermore, fuel correlations and technology parameter correlations are indicative and based on expert judgements. Technology risk values used in this study are displayed in full in appendix A along with all other input assumptions.

As discussed, the model considers both a high and low growth scenario. These growth scenarios are translated into a high energy demand forecast and a low energy demand forecast.

Constraints imposed on the model relate, *inter alia*, to the assumed technical potentials of the distinct renewable generating technologies. These constraints are derived from the resource potentials outlined in the document – Renewable Electricity - A '2020 Vision' (SEWG, 2005).

All technology cost assumptions are the same for both HEF and LEF. However, total electricity demand is assumed higher under HEF than under LEF. Other assumptions are listed in subsequent sections. The feasible range of generating capacities, so-called *energy bounds* (see Annex H), are largely identical in energy terms. The bounds do however differ relatively, due to the higher energy demand in the HEF scenario.

3.3 High Energy Forecast (HEF) Scenario

In the *High Growth* scenario it is assumed that the US economy continues to grow rapidly without any process of adjustment to offset the rising balance of payments deficit. This scenario is a reasonable basis for predicting the likely outturn in Ireland out to around 2010. However, it is probably not a reasonable basis for forecasting Irish growth out to 2020, as it is almost certain that market forces will have produced an adjustment to move the US economy back on to a more sustainable growth path.

Figure 3.2 shows the forecast fuel mix for electricity production in Ireland under the HEF scenario. The graphic shows that 72% of electricity production will be supplied by gas-fired plant in 2020. The contribution from renewables will also continue to grow and by 2020 will have reached a point where it accounts for 18% of total electricity supply.

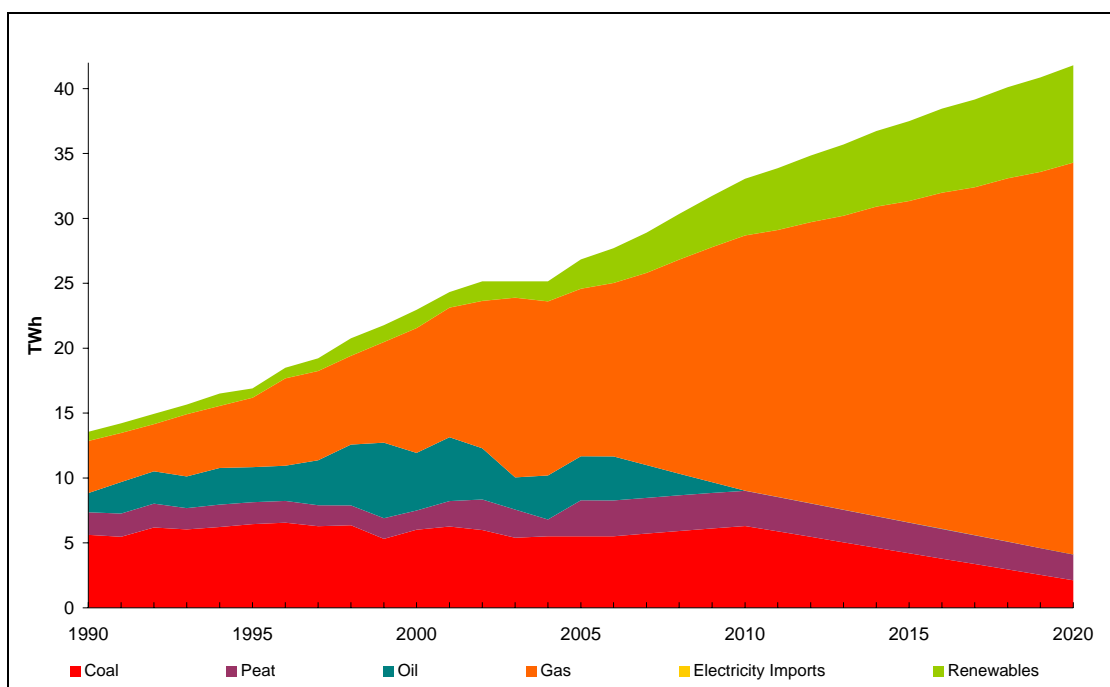


Figure 3.2 Forecast Electricity Generation by Fuel under HEF

3.3.1 HEF Portfolio Analysis Model Results

Figure 3.3 and Table 3.1 show the results of the portfolio analysis under the High Energy Forecast scenario. The AIMMS model scans portfolio cost levels in order to locate the portfolio mix with the lowest possible risk. Starting at the maximum value of portfolio cost, the model minimises risk while stepwise lowering the portfolio cost level until the minimum value has been reached. The methodology for the determination of the cost of electricity is shown in appendix E. It includes investment and operating costs as well as fuel costs.

Each time the model returns five different sets of points, four of which are situated along the efficient frontier. From the analysis the following observations can be made:

- The **'target mix'** represents the business as usual scenario without taking the portfolio analysis into account. In this case it represents the SEI/ESRI forecast energy mix for the Irish electricity system in 2020. At such point we will be over 70% dependent on gas-fired plant for our electricity requirements. Not surprisingly, such a high dependency on any one fuel source has a high risk factor attached. In addition, the cost of such a portfolio is high with gas prices forecast to increase considerably in the future. As a result, our analysis results indicate that such a fuel mix would constitute a portfolio cost of €74/MWh and a portfolio risk of 0.17%.
- **Mix P** represents the portfolio with the lowest possible risk, taking into account the technology data and the bounds set to the generating assets. Such a portfolio would generally consist of a diversity of fuel sources in order to mitigate against over dependency on any one type of generation. In this case the system would consist of more coal powered generation (26.1%) as well as a greater use of renewable energy sources such as wind (19.5%) and biomass (4.9%). The other interesting aspect of this portfolio result is that it can not only reduce Ireland's risk exposure but that it can also achieve this benefit at a lower cost of electricity.
- **Mix N** represents the point on the efficient frontier with a cost level equal to that of the target mix. It is used to demonstrate how it is possible to have the same cost profile as the target mix but achieve a lower level of risk exposure. In this case the risk factor decreases by 41%. Again, more coal and renewables are used to meet the electricity requirement and in so doing displace gas from the system. Indeed, the deployment of renewables such as wind in such portfolios indicates its current cost attractiveness *vis-à-vis* other technologies, even after an intermittency penalty of €6/MWh is applied.
- **Mix S** is the point on the efficiency frontier with a risk level equal to that of the target mix. It demonstrates how the same risk profile can be achieved at a much lower cost level. This is through the deployment of those technologies that offer the same risk exposure but are more cost effective. In this case a cost reduction of €9/MWh is achieved mainly through deployment of coal and biomass plants.
- **Mix Q** is the point on the efficiency frontier with the lowest portfolio cost. The results show that the cost of electricity in this instance would be €65/MWh. The benefit of this portfolio is that it can achieve the same cost profile as 'Mix S' but at lower risk. This is due to having a more diversified portfolio containing those technologies within similar cost ranges.

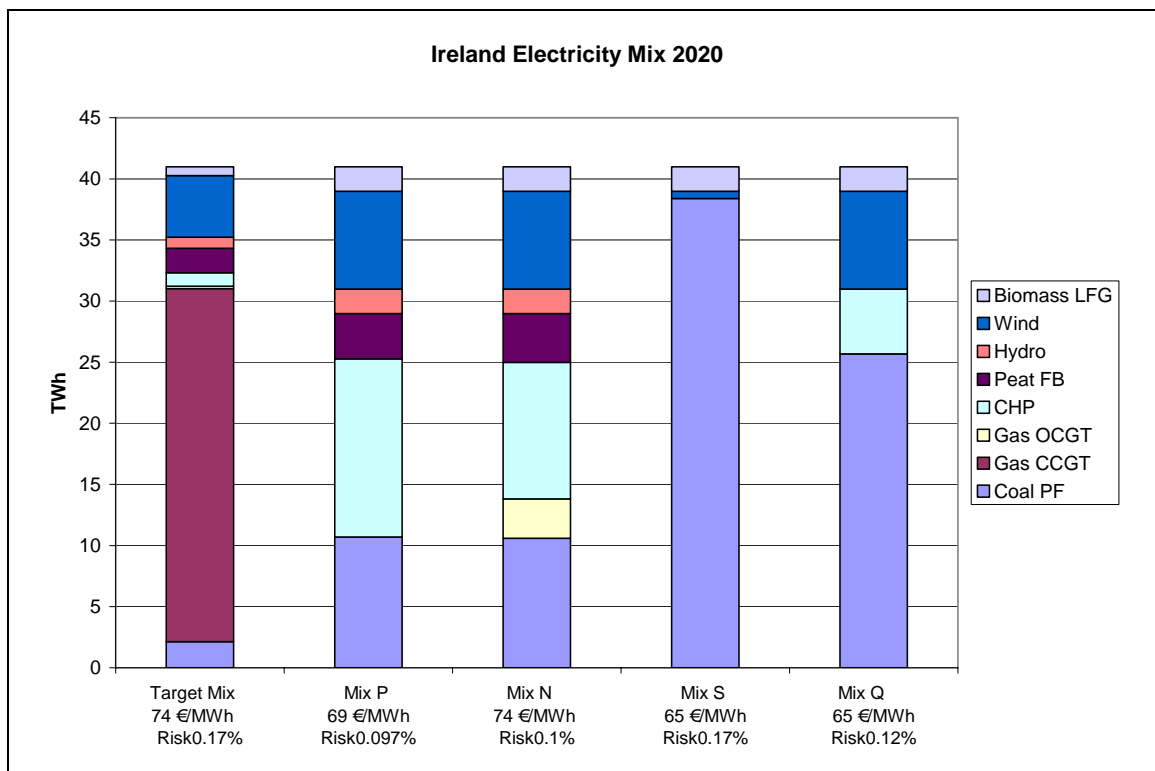


Figure 3.3 Portfolio Analysis Results for HEF Scenario

Table 3.1: Portfolio Analysis Results for HEF Scenario

		Target Mix	Mix P	Mix N	Mix S	Mix Q
Portfolio cost	[€/MWh]	74.0	69.0	74.0	65.0	65.0
Portfolio risk σ	[%]	0.17	0.097	0.1	0.17	0.12
Gas CC	[%]	70.5	0.0	0.0	0.0	0.0
Gas OC	[%]	0.5	0.0	7.9	0.0	0.0
Coal PF	[%]	5.2	26.1	25.8	93.7	62.7
Peat FB	[%]	4.9	9.1	9.8	0.0	0.0
Wind	[%]	12.3	19.5	19.5	1.4	19.5
Hydro	[%]	2.2	4.9	4.9	0.0	0.0
CHP	[%]	2.7	35.6	27.3	0.0	12.9
Biomass	[%]	1.7	4.9	4.9	4.9	4.9

From a policy makers perspective portfolio 'Mix P' looks particularly attractive. It's less costly and risky than the target mix and is a well diversified portfolio spreading the risk among a number of different generation technologies. However, it is important to bear in mind when considering such results that the model makes no attempt at factoring in the system requirement for flexible or mid-merit plant. In certain cases then the model can be considered an abstraction and returns portfolio options that are slightly detached from reality and the need to maintain system security balance.

Efficient Frontier

One of the key outputs of any portfolio analysis is the construction of an efficient frontier. The efficient frontier is the location of all efficient (optimal) generating portfolios. Efficient generating mixes are optimal in the sense that further cost reductions can only be attained by accepting higher risk. Efficient generating portfolios and their technology components provide a benchmark against which projected *business-as-usual* (BAU) generating mixes can be evaluated (Awerbuch, 2004).

Figure 3.4 shows the efficiency frontier for Ireland under the HEF scenario. The x-axis plots the cost of electricity for a particular portfolio and the y-axis shows portfolio risk as measured by the standard deviation of technology generating costs. The frontier clearly shows how the forecast mix for Ireland in 2020 is sub-optimal. In all cases either a lower level of cost or risk can be attained by choosing those portfolios situated along the efficiency frontier.

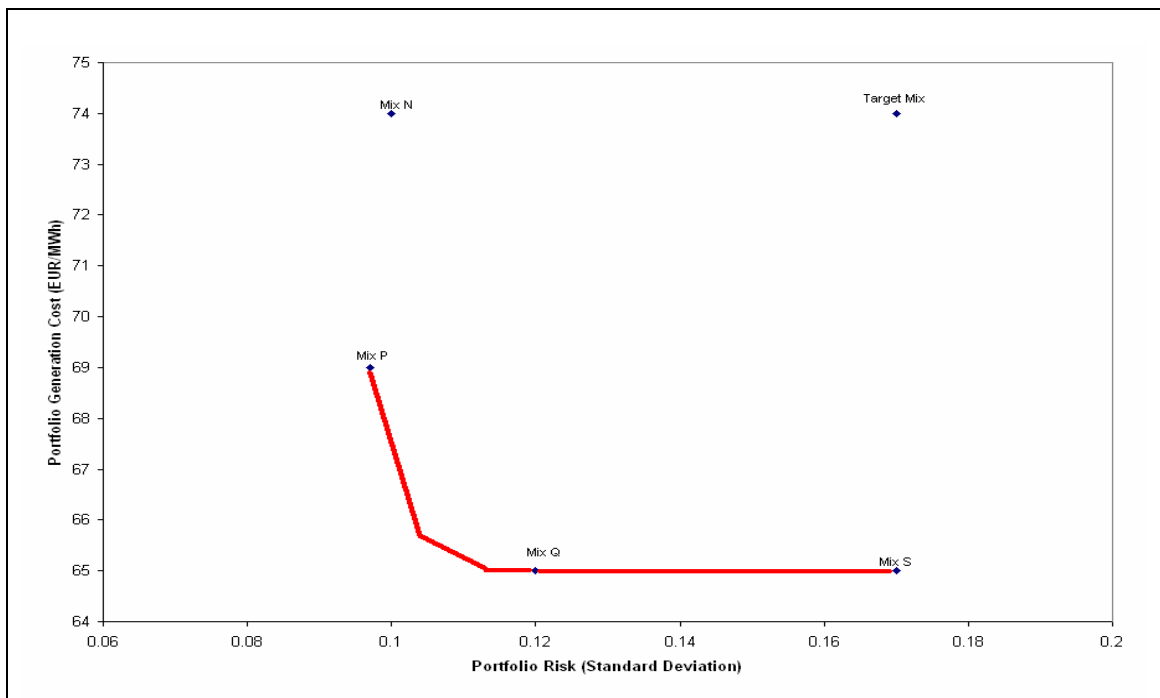


Figure 3.4 Efficient Frontier for HEF

3.4 Low Energy Forecast (LEF) Scenario

The ESRI *low growth* scenario assumes a macroeconomic climate in which market forces produce an adjustment in the US and the world economies, beginning in 2007, to move the US back onto a sustainable growth path. The result of this adjustment process is that US and world growth will be significantly slower in the subsequent five years than in the high growth scenario. Due to the openness of the Irish economy, it will result in significantly lower growth in Ireland than in the alternative scenario where the US does not adjust.

Figure 3.5 provides the forecast electricity production by fuel type under this scenario. It is forecast that gas-fired plant will be supplying around 70% of total electricity demand by 2020. Renewable energy sources will continue to play an increasing role in the electricity fuel mix and by 2020 will constitute 20% of total supply.

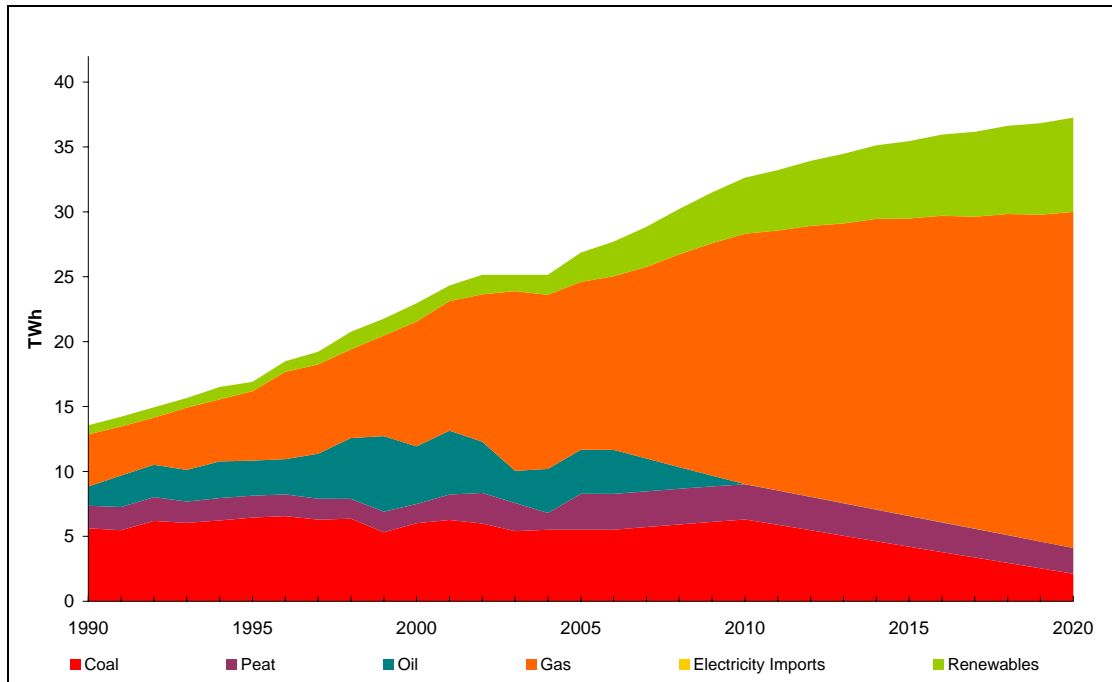


Figure 3.5 Forecast Electricity Generation by Fuel under LEF

3.4.1 LEF Portfolio Analysis Model Results

Figure 3.6 and Table 3.2 show the results of the portfolio analysis under the Low Energy Forecast scenario. From the analysis the following observations can be made:

- The **'target mix'** is the same as under the HEF scenario though electricity production levels are less due to lower energy demand. In this case Ireland will be over 70% dependent on gas-fired plant for its electricity requirements. Once again the results indicate that such a fuel mix would consist of a portfolio cost of €74/MWh and a portfolio risk of 0.16%.
- **Mix P** shows a portfolio cost of €70/MWh and a risk of 0.092%. This low risk portfolio consists of a variety of technologies, though principally coal, gas and wind plant. Once again the portfolio analysis indicates that such a portfolio mix can not only reduce our risk exposure but also that it can be achieved at a lower cost of electricity.
- **Mix N** is on the efficient frontier with a cost level equal to that of the target mix and a risk level of 0.095%. This portfolio demonstrates how more coal, renewables and to a lesser extent peat, can be used to meet the electricity requirement and at the same time reduce risk.
- **Mix S** can achieve the same risk profile as the target mix, but at a cost of electricity that is €9/MWh cheaper. This is through deployment of coal plant and renewable technologies such as wind and biomass landfill gas.
- **Mix Q** has an equally low portfolio cost level of €65/MWh. In this case risk is diversified away through deployment of coal, gas and renewable technologies.

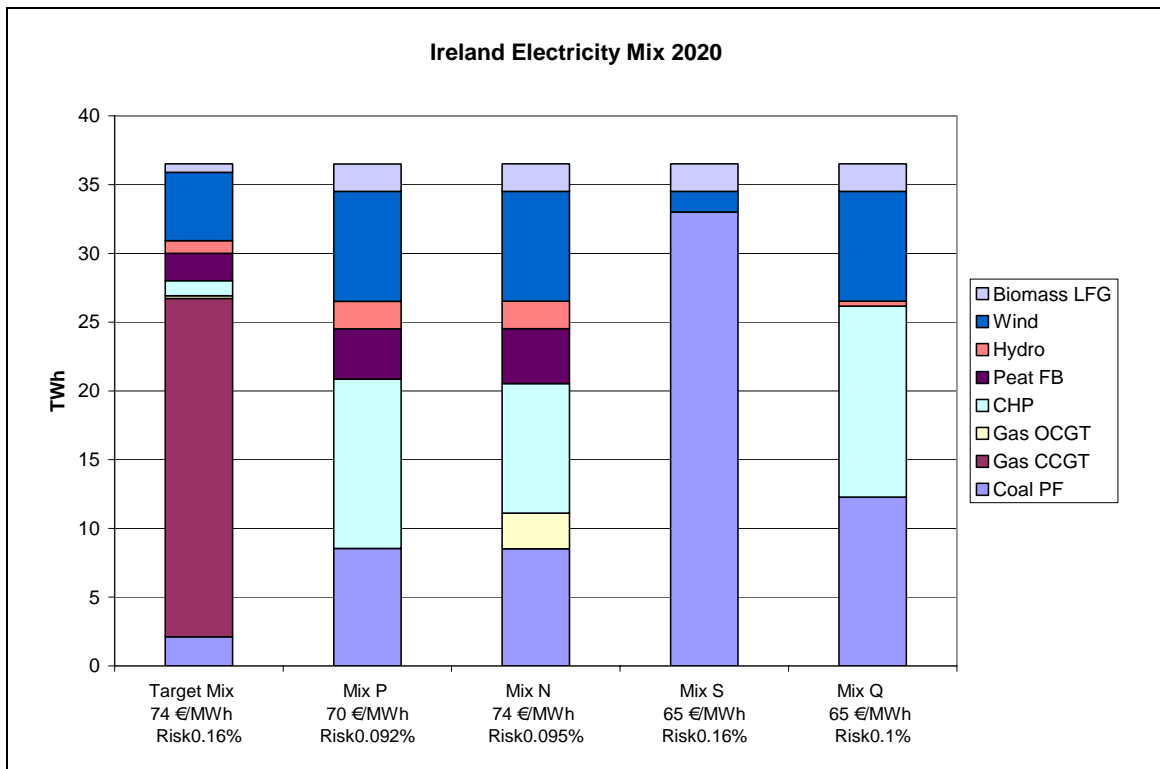


Figure 3.6 Portfolio Analysis Results for LEF Scenario

Table 3.2 Portfolio Analysis Results for LEF Scenario

		Target Mix	Mix P	Mix N	Mix S	Mix Q
Portfolio cost	[€/MWh]	74.0	70.0	74.0	65.0	65.0
Portfolio risk σ	[%]	0.16	0.092	0.095	0.16	0.1
Gas CC	[%]	67.4	0.0	0.0	0.0	0.0
Gas OC	[%]	0.5	0.0	7.1	0.0	0.0
Coal PF	[%]	5.8	23.4	23.3	90.4	33.6
Peat FB	[%]	5.4	10	11.0	0.0	0.0
Wind	[%]	13.6	21.9	21.9	4.2	21.9
Hydro	[%]	2.5	5.5	5.5	0.0	1.0
CHP	[%]	3.0	33.7	25.8	0.0	38.0
Biomass	[%]	1.7	5.5	5.5	5.5	5.5

Efficient Frontier

The efficient frontier under the Low Energy Forecast scenario resembles that of the High Energy Forecast. Any of the portfolio options located along the efficiency frontier are more optimal than that of the target mix.

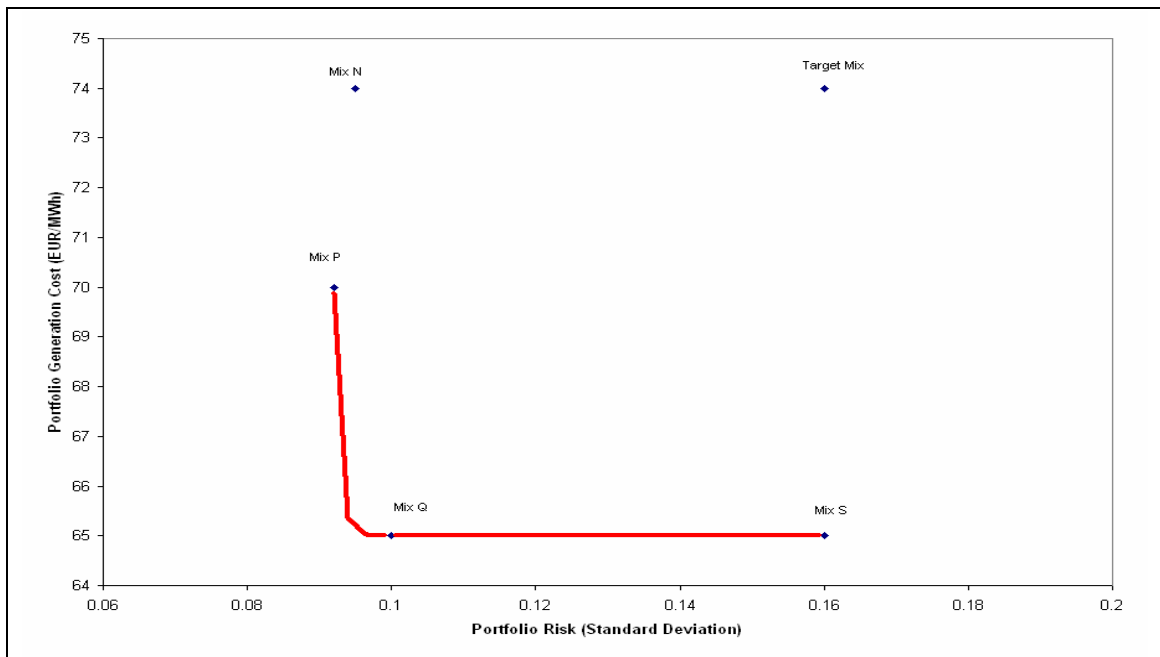


Figure 3.7 Efficient frontier for LEF

3.5 Conclusions

In this section, MVP analysis has been undertaken for two likely growth scenarios. Both scenarios were developed by the ESRI in their assessment of the Irish economy. Firstly, under a High Energy Forecast (HEF) scenario and then also under a Low Energy Forecast (LEF) scenario. Both scenarios assume a carbon price of €30/t in 2020 and the same fuel price trajectory⁵. Differences in the two scenarios relate to the overall growth in energy demand as an indirect output of macroeconomic drivers.

Results of the portfolio analysis indicate that:

- In both scenarios, the base variant is not very efficient and in some cases diversification can lead to a risk reduction of the magnitude of 41% at no additional cost. Cost of electricity generated may be lowered by a factor of between €5/MWh - €9/MWh depending on the cost-risk profile selected.
- Use of renewable energy sources can greatly enhance the cost risk profile of the portfolio. This arises as many renewable technologies such as onshore wind and landfill gas are already at a stage of market maturity where they can compete with conventional generation sources. In addition, they are exempt to the vagaries of the fuel price market and its associated unpredictability.
- Even at a carbon price of €30/t, coal plants still feature largely in providing a hedge against over-dependency on one fuel source for electricity generation. Its attractive cost characteristics ensure that it features strongly in those portfolios targeted at least cost. Unlike renewables, the model assumes that there exists no bounded constraints on coal plants in meeting Ireland's electricity requirement.

⁵ The authors are aware that the price of carbon has recently fallen sharply but believe that a price level of €30/tonne is still sustainable within the timeframe of this study.

4. Sensitivity Analysis

4.1 Introduction

As noted earlier, there are considerable uncertainties in quantifying costs to 2020, and even more uncertainty in completely understanding the risks. It is therefore important to interpret the results of the MVP analysis with this in mind. This section applies some sensitivity cases, evaluating the sensitivity of the outcomes as a result of variations in some of the input parameters.

Firstly, CO₂ price variations are investigated as there is still much uncertainty as to what the price level will be in 2020. The sensitivity then addresses the effects of a change in gas prices on the results. As current and future Irish generating mixes are forecast to have large shares of natural gas, this is a potentially important factor. The sensitivity analysis concludes with a high cost of capital (WACC) scenario and the effect this has on the portfolio mix.

The sensitivities are all run under the High Energy Forecast scenario. As there is a large combination of sensitivity scenarios that could be run, it was considered that only the most likely runs would be performed. For instance, it is unlikely that a high carbon price and low gas price scenario would ever materialise owing to the effect that carbon prices are having on gas prices.

4.2 Sensitivity to CO₂ price variations

The sensitivity of the results presented in the previous section are examined under a range of different carbon price scenarios. The full set of results for the sensitivity analysis runs are displayed in Appendix B.

Figure 4.1 shows the effects on the portfolio analysis results when a high gas (€12/GJ) and carbon regime (€50/t) is in operation. The results demonstrate that capacity constraints or ‘energy bounds’ (attempted to be imposed on the model as realistically as possible given currently available information) rather than technology cost factors appear to limit the penetration of renewables under such market conditions. The model chooses to deploy the maximum amount of renewables at its disposal in all but one of the portfolio cases owing to the fact that these energy sources are not subject to fuel and carbon price impacts.

As would be expected, the portfolio cost has gone up significantly in all cases. For example, the ‘target mix’ has now increased from a cost level of €74/MWh to €110/MWh.

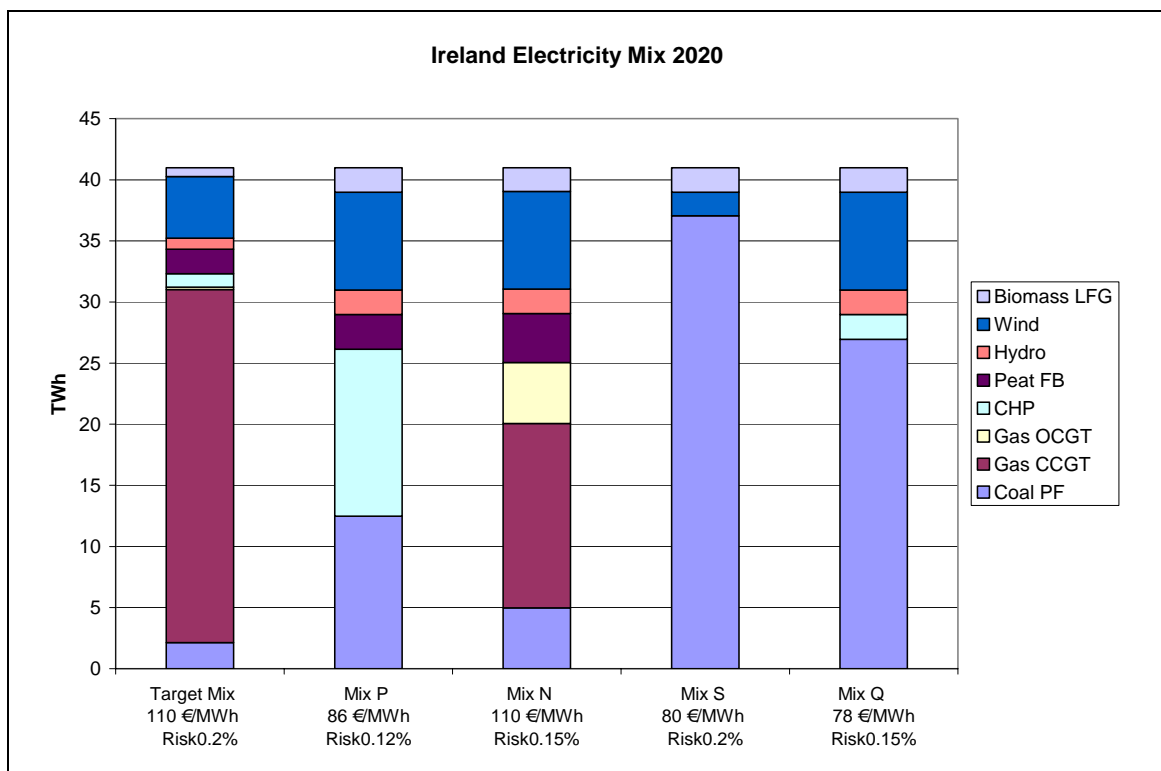


Figure 4.1 Portfolio analysis results for Ireland under a high carbon and gas price scenario

4.3 Sensitivity to gas price variations

Whereas increasing the carbon costs has an impact on all fossil fuel based technologies, increasing the gas price level only impacts on gas-fired plants. Such plants include CCGT baseload, peak load plants (OCGT) and CHP. As our dependency on these gas options is of considerable importance in both scenarios (72% and 69%), the expected portfolio cost will increase considerably.

The sensitivity to the gas price is evaluated using the HEF scenario as a reference. In this reference case the gas price is calculated at €6.00/GJ. The 'high gas' case has a gas price of €12.00/GJ. As always these figures are open to contention. However, these price ranges are comparable to those used in other more recent studies as well as in the calculation of the Best New Entrant (BNE) price (CER, 2005).

Figure 4.2 shows the results of the portfolio analysis when a high gas case is deployed and carbon is set at a price level of €30/t. Due to the important shares of gas under both our reference scenarios, the expected portfolio cost and risk increase considerably. For instance, the cost of electricity under the 'target mix' increases from €74/MWh to €103/MWh and risk from 0.17% to 0.21%. However, the two mixes with cost minimisation as their goal (Mixes S&Q) are left unaffected owing to the complete absence of gas in such portfolios. This demonstrates how coal, as well as renewable technologies, can help insulate generation portfolios from gas price swings.

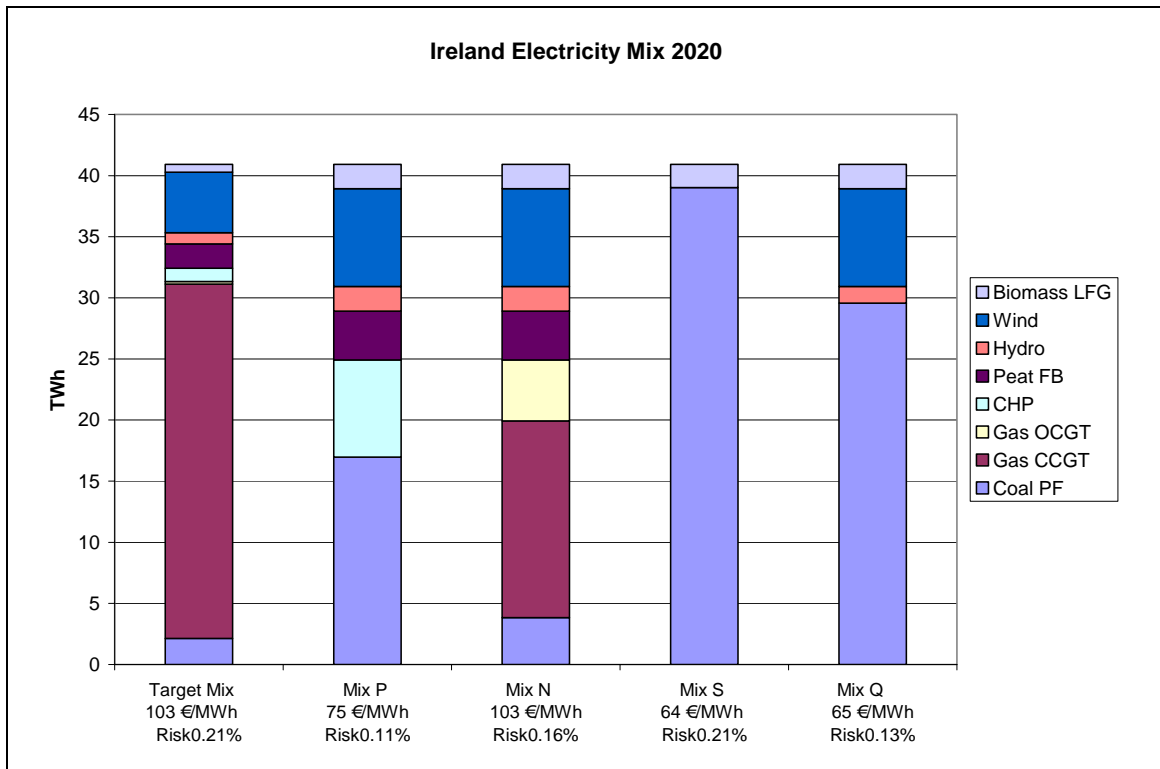


Figure 4.2 Portfolio Analysis Results for Ireland under 'High Gas' and Mean Carbon Sensitivity.

4.4 Sensitivity to the cost of capital

The rate of return earned by a project developer must be sufficient to cover the risk of entering the Irish electricity generation sector. This return is calculated according to the weighted average cost of capital (WACC). This study uses a WACC figure of 7.00% for conventional generation technologies. This is consistent with the figure used in calculating the BNE price for 2006. For renewable technologies it has been decided to employ higher WACC figures owing to the higher risk premium attached to such projects. For wind a figure of 7.7% is used and for biomass landfill gas a WACC of 10.8% is considered appropriate.

The sensitivity analysis considers a high WACC scenario where an increase of 3% in the cost of capital is applied to all technologies. All WACC rates per technology are displayed in appendix A.

The results show the effect that increasing the WACC rate has on all technologies in the portfolio analysis. As can be seen, renewable technologies now feature less strongly in the least cost portfolio options as generally they are regarded as being more capital intensive. The role of CHP in such portfolios increases dramatically at the expense of more capital intensive coal plant.

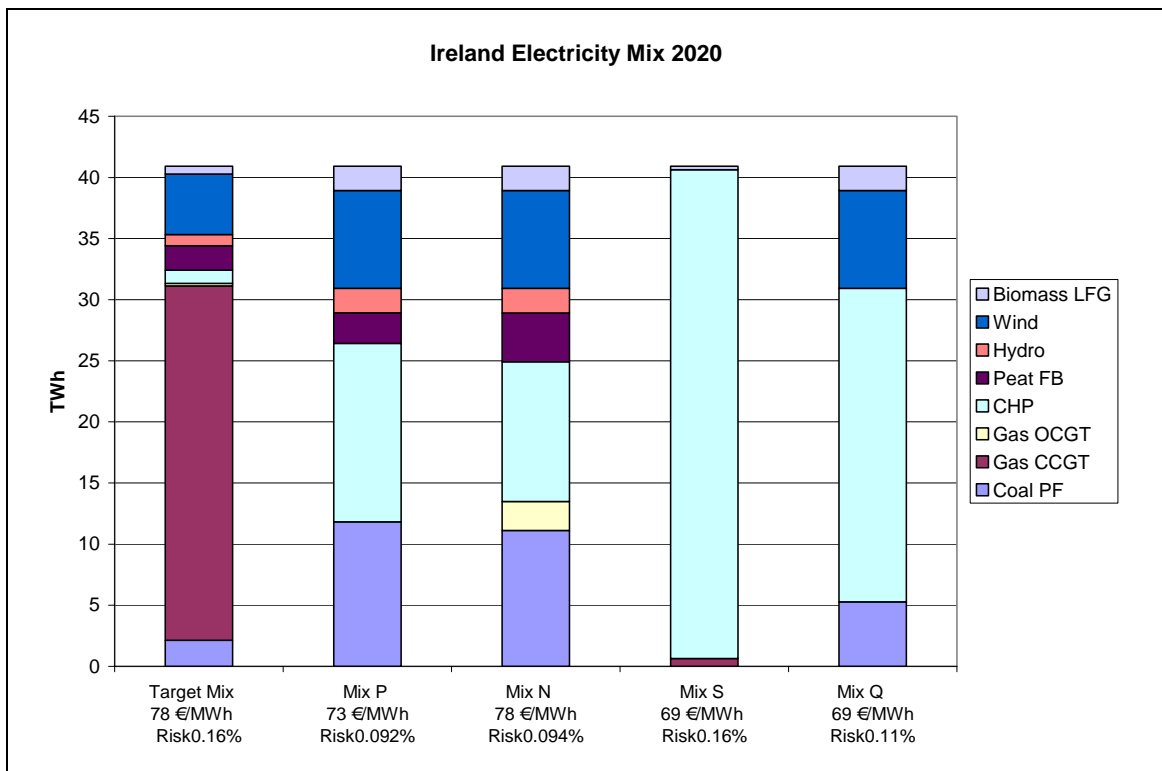


Figure 4.3 Portfolio Analysis Results for Ireland under Mean Carbon and Gas Price Scenario and High WACC.

4.5 Sensitivity to high carbon risk premium

Much has been made by carbon market analysts about the fuel switching capabilities of generators at times of high gas prices. This leads to an increase in coal fired plant and a rise in the carbon price as operators must enter the trading market to cover any shortfall in emission allowances. This observed effect means that the relationship between gas and coal prices has become inextricably linked through the advent of the carbon market. As a result, the ability of coal to reduce security of supply risk may be overestimated unless this observed relationship is taken into account.

Figure 4.4 shows the effects on the portfolio analysis results when a carbon risk premium is applied to reflect this behaviour. It is modelled under the same gas and carbon price parameters as figure 4.1. The two most interesting observations can be found in portfolio mixes S & Q. In portfolio mix S, the model maintains risk at the same level as before and does so by reducing the amount of coal in the mix and replacing it with more renewables and CHP. For mix Q, the least cost portfolio, the model preserves the prevailing portfolio cost level, but this is achieved through acceptance of a higher risk level. In this case, when compared to figure 4.1, risk has increased by a margin of around 86%.

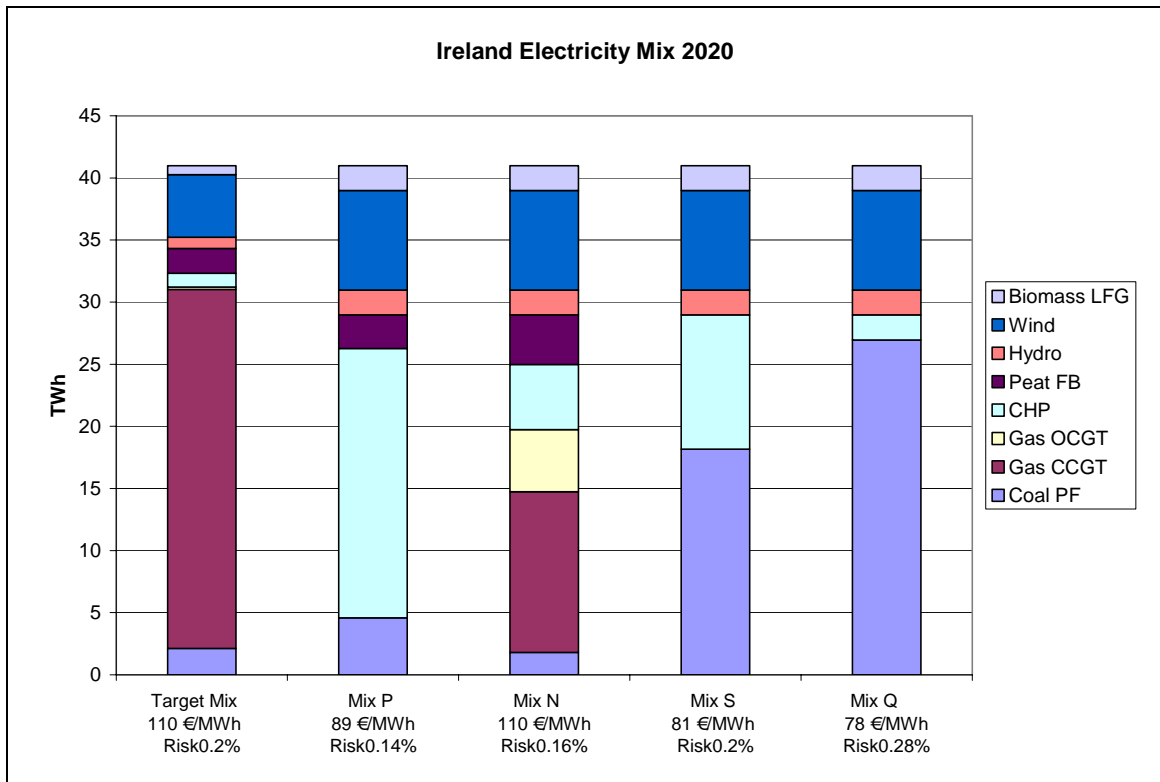


Figure 4.4 Portfolio Analysis Results for Ireland when a High Carbon Risk Premium is Applied.

4.6 Conclusions

In this section, the effects of variations in a number of key input parameters on the cost and risk of the generating mixes have been investigated. Due to the inherent uncertainty surrounding some of the cost inputs, it is critical that a sensitivity analysis is performed.

One such sensitivity needs to be performed around the future price of carbon. The price of carbon is a critical input at which a country's security of supply position can be improved through moving towards an increasing share for renewables based portfolio options. The analysis shows that under conditions of high carbon and gas prices, the case for renewables based portfolios becomes very compelling. The only inhibiting factor in such cases is the energy bounds or constraints imposed upon renewables.

Due to the large share of natural gas in the Irish generating mix, a sensitivity analysis in which the price of gas doubles results in expected portfolio cost and risk increasing considerably. However, this proves not to be the case for those portfolios with least cost as their single objective. This is due to the prominent role of coal in such portfolios which remains unaffected by gas price swings.

Finally, the sensitivity analysis shows that renewable technologies are more sensitive to changes in the cost of capital. This is because some renewable technologies such as wind are quite capital intensive and are therefore more responsive to the WACC rate. Coal plants are supplanted by less capital intensive CHP technologies in the least cost portfolio options.

5 Conclusions

5.1 Analysis of generating mix scenarios in Ireland

In this study, MVP analysis has been performed with respect to projected generating mixes in Ireland for the year 2020. The analysis looked at different scenarios and sensitivities, with special reference to renewable electricity development.

MVP shows the potential role for renewables-based technologies in mitigating the impact of long-term energy supply security risk to a specific national or regional electricity supply system.

5.1.1 Key results of the analysis

The analysis demonstrates that for both of the forecast target portfolios for the year 2020, none is efficient in the sense deployed in this study. For each portfolio, reductions in either cost or risk or both is attainable. In most cases, risk reductions and cost reductions can be obtained by increasing the share of renewable generating options (notably wind power and biomass). These opportunities can be quantified as a 43% risk reduction and a 12% cost reduction (Tables 5.1 and Table 5.2).

Table 5.1 Potential diversification effect HEF

	Reference Case	Minimum	Reduction [%]
Portfolio risk σ [%]	0.17	0.097 (mix P)	43
Portfolio cost [€MWh]	74	65 (mix S/Q)	12

Table 5.2 Potential diversification effect LEF

	Reference Case	Minimum	Reduction [%]
Portfolio risk σ [%]	0.16	0.092(mix P)	43
Portfolio cost [€MWh]	74	65 (mix S/Q)	12

The outcome of the analysis is very sensitive to CO₂ and gas price assumptions. In the high gas and CO₂ price scenario, with prices of €12/GJ and €50/tonne, the renewable options become very attractive. The relative importance of gas-fuelled power plants in the forecast scenarios (72% in HEF and 69% in LEF) poses a quite serious cost risk for the Irish electricity sector. Renewables can considerably reduce and mitigate this cost risk on the generating portfolio.

5.2 Further work

This study has only provided a first step in considering the application of portfolio analysis theory to the Irish electricity system. The results indicate that the procedure is robust and therefore could be expanded upon and used as a viable support tool in assisting policy makers in their attempts at energy policy design.

It is recommended that for future work the following areas be considered as priorities:

- As Ireland is currently in the process of transition to an all-island single electricity market, future work should take cognizance of this fact by incorporating an all-island dataset into the model analysis;
- The analysis should be extended to include a longer time horizon. A timeframe of 2030 would appear appropriate as this would provide policy makers and grid system operators with enough advanced warning to apply any of the model results. It would also allow for the possible inclusion of new technologies such as modern nuclear plant and coal capture and storage technology.
- The model at present is only applicable to the electricity sector. It should be considered adapting the model from the electricity sector to other sectors such as transport. This would enable policies supporting the use of biofuels to be assessed;
- The application of the model to distributed power systems and micro grids may provide some interesting insights;
- The outputs arising from the portfolio analysis could be considered within the context of providing a useful metric for SEI's annual Security of Supply Metrics publication;
- Allowances should be made for the cost impacts of greater penetration of intermittent renewable resources. This warrants, *inter alia*, a segmentation of the power market into peak, mid-merit, base load plant and specification of contributions to ancillary power provision services;
- Expanding the environmental externalities cost component for inclusion of the cost of non-GHG polluting emissions such as NO_x and SO₂ would seem appropriate in light of the NEC Directive;
- Greater consideration in the analysis be given to the impact of carbon price risk and its associated interrelationship with the plant fuel mix;

References

- Awerbuch, S. and M. Berger (2003): *'EU Energy Diversity and Security: Applying Portfolio Theory to Electricity Planning and Policy-Making'*, Paris: International Energy Agency, February 2003.
- Awerbuch, S., A.C. Stirling, J.C. Jansen and L.W.M. Beurskens (2004): *'Portfolio and Diversity Analysis of Energy Technologies Using Full-Spectrum Uncertainty Measures'*, Pre-Conference Draft, April 15-16, 2004.
- Awerbuch, S., J.C. Jansen and L.W.M. Beurskens (2004): *'Building Capacity for Portfolio-Based Energy Planning in Developing Countries'*, Final Report, Submitted to The Renewable Energy & Energy Efficiency Partnership (REEEP), and UNEP, London-Paris: August 2004.
- Awerbuch, S., J.C. Jansen and L.W.M. Beurskens (2006): *'The Role of Wind Generation in Enhancing Scotland's Energy Diversity and Security'*, University of Sussex, UK.
- Berger, M. (2003): *Portfolio Analysis of EU Electricity Generating Mixes and its Implications for Renewables*, Ph.D. Dissertation, Technischen Universität Wien, Vienna, Mar.
- Bergin, A., Fitz Gerald, J., Keeney, M., O'Malley, E. and Scott, S. (2005), *'Aspects of Irish Energy Policy'*, [Online]. Available: <http://www.esri.ie>.
- Bodie, Z., A. Kane and A.J. Marcus (2002): *Investments*, Fifth edition, McGraw-Hill.
- Brealey Richard A., Myers Stewart C. (2003), *'Principles of Corporate Finance'*, International Edition, McGraw Hill.
- Commission for Energy Regulation (2005), *'Best New Entrant Price 2006'*, [Online]. Available: <http://www.cer.ie>.
- Doherty, R., *'New Methods for Planning and Operating Modern Electricity Systems with Significant Wind Generation'*, Ph.D. Thesis, University College Dublin, 2005.
- Doherty, R., Outhred, H., O'Malley, M. (2005): *'Generation Portfolio Analysis for a Carbon Constrained and Uncertain Future'*, Future Power Systems, 16-18 Nov, pgs. 1-6.
- Doherty, R., (2006): *'Assessment of Suitable Generation Portfolios for the All-Island System in 2020'*, All-Island Grid Study Work-Stream 2A, 2006.
- Fabozzi, Frank J., Francis Gupta and Harry Markowitz (2002): *'The Legacy of Modern Portfolio Theory'*, Journal of Investing, Fall 2002, 7-22.
- Grubb, M., Butler, L., Sinden, G (2005) *'Diversity and Security in UK Electricity Generation: The Influence of Low Carbon Objectives'*, Cambridge Working Papers in Economics 0511, Faculty of Economics (DAE), University of Cambridge.
- Hobbs, B.F., Meier, Peter (2000) *'Energy Decisions and the Environment: A Guide to the Use of Multicriteria Methods'*, Kluwer Academic Publishers
- J.C. Jansen, L.W.M. Beurskens and X. van Tilburg (2006): *'Application of Portfolio Analysis to the Dutch Generating Mix'*, ECN-C--05-100, February 2006. Available for download at <http://www.ecn.nl/library/reports/2006/c05100.html>
- L.W.M. Beurskens and J.C. Jansen (2005): *'User Manual to the Online Portfolio Analysis Tool'*, ECN.
- McCarthy, Niamh (2005): *'Market Size, Market Structure and Market Power in the Irish Electricity Industry'*, ESRI Working Paper No. 168.

Markowitz, Harry (1952): '*Portfolio selection*', *Journal of Finance*, 7(1), 77-91.

Moore J.H. and L.R. Weatherford (2001): *Decision modelling with Microsoft Excel*. Sixth edition. Pearson/Prentice Hall.

NREL, '*SEDS User Manual*', [Online]. Available: <http://www.nrel.gov>.

Roques, Fabien, David Newbery, William Nuttall, Stephen Connors, Richard de Neufville (2005): '*The Diversification Value of Nuclear Power as part of a Utility Technology Mix when Gas and Carbon Prices are Uncertain*', University of Cambridge, UK.

Roques, Fabien (2006): '*Fuel mix diversification incentives in liberalised electricity markets: a Mean-Variance Theory Approach*', University of Cambridge, UK.

Stirling, Andrew (1994): '*Diversity and ignorance in electricity supply investment. Addressing the solution rather than the problem*', *Energy Policy*, 22(3), 195-216.

Stirling, A.C. (1995) 'Diversity in Electricity Supply: a response to the criticism of Lucas et al', *Energy Policy*, Vol.23 (1) pp.8-11.

Stirling, A.C. (1996) 'Optimising UK Electricity Portfolio Diversity, chapter in G. MacKerron and P. Pearson, (eds), *The UK Energy Experience: a model or a warning?* Imperial College Press.

Sustainable Energy Working Group (2005): '*ALL-ISLAND ENERGY MARKET: Renewable Electricity – A 2020 Vision*', Preliminary Consultation Document.

Appendix A Input Assumptions

This appendix presents a concise overview of the assumptions used throughout this study.

Table A.1: Technology specific upper and lower bounds of electricity generation (2020)

[TWh]	Lower bound	Upper bound
Gas CCGT	0	40
Gas OCGT	0	5
Gas CHP	0	40
Coal	0	40
Peat	0	4
Onshore wind	0	8
Biomass LFG	0	2
Hydro	0	2

Table A.2: Estimated fuel costs (2020)

[€/GJ]	Mean	High
Gas	6.00	12.00
Coal	1.34	-
Oil	3.02	-
Peat	3.57	-

Table A.3: Fuel cost correlations

	Gas	Coal	Oil	Peat
Gas	1	0.3	0.75	0.39
Coal	0.3	1	0.28	0.14
Oil	0.75	0.28	1	0.07
Peat	0.39	0.14	0.07	1

Table A.4: Non-fuel cost correlations, expert opinions

	Investment	Variable O&M	Fixed O&M	CO ₂
Investment	0.7	0.1	0.1	0
Variable_OM	0.1	0.7	0.1	0
Fix_OM	0.1	0.1	0.7	0
CO ₂	0	0	0	1

Table A.5: CO₂ costs/emission estimates

	CO ₂ emission [kg/GJ]	Mean [€/tonne]	High[€/t]
Gas	56.1		
Coal	94.7		
Oil	73.3		
Peat	115		
CO ₂ -price HEF		30	50
CO ₂ -price LEF		30	50

Table A.6: Mean Levelised Cost of Electricity Production by Technology*

Plant Type	Investment (€/MWh)	Fuel (€/MWh)	CO ₂ (€/MWh)	Fix_OM (€/MWh)	Var_OM (€/MWh)	Total (€/MWh)
CCGT	12.29	39.27	11.02	10.87	1.0	74.45
Coal	18.57	12.06	25.57	6.64	3.0	65.84
Wind	41.02	0.0	0.0	16.31	6.0	63.33
Oil	32.32	27.88	20.30	20.15	2.0	102.64
OCGT	19.71	63.53	17.82	20.76	1.0	122.82
Peat	22.94	32.95	31.85	20.10	3.0	110.85
CHP	14.53	27.69	7.77	13.24	3.0	66.23
Hydro	58.41	0.0	0.0	18.58	0.0	76.99
Biomass LFG	28.78	0.0	0.0	20.98	0.0	49.76

*Calculated under a CO₂ price of €30/tonne and gas price of €6/GJ.

Table A.7: Technology Risk Breakdown

Technology	Investment (€/MWh)	Fuel (€/MWh)	CO ₂ (€/MWh)	Fix_OM (€/MWh)	Var_OM (€/MWh)
CCGT	0.00	0.40	0.35	0.06	0.29
Coal	0.00	0.38	0.42	0.05	0.24
Wind	0.00	0.00	0.00	0.09	0.00
Biomass LFG	0.00	0.00	0.00	0.03	0.00
OCGT	0.00	0.41	0.40	0.05	0.24
Peat	0.00	0.29	0.45	0.01	0.23
CHP	0.00	0.39	0.30	0.05	0.32
Hydro	0.00	0.00	0.00	0.05	0.00

Table A.8: Cost of Capital Rates Used in the Analysis

[WACC]	Mean rate	High sensitivity
Gas CCGT	7.00	10.00
Gas OCGT	7.00	10.00
Gas CHP	7.00	10.00
Coal	7.00	10.00
Peat	7.00	10.00
Onshore wind	7.70	10.70
Biomass LFG	10.8	13.80
Hydro	7.00	10.00

Appendix B Sensitivity Analysis

Table B.1 Portfolio Analysis Results for Ireland under a High Gas and Mean Carbon Price Scenario*

		Target Mix	Mix P	Mix N	Mix S	Mix Q
Portfolio cost	[€/MWh]	103.0	75.0	103.0	64.0	65.0
Portfolio risk σ	[%]	0.21	0.11	0.16	0.21	0.13
Gas CC	[%]	70.5	0.0	39.3	0.0	0.0
Gas OC	[%]	0.5	0.0	12.2	0.0	0.0
Coal PF	[%]	5.2	41.5	9.4	95.4	72.3
Peat FB	[%]	4.9	9.8	9.8	0.0	0.0
Wind	[%]	12.3	19.5	19.5	0.0	19.5
Hydro	[%]	2.2	4.9	4.9	0.0	3.3
CHP	[%]	2.7	19.4	0.0	0.0	0.0
Biomass	[%]	1.7	4.9	4.9	4.6	4.9

*Gas = €12/GJ, CO₂ = €30/t

Table B.2 Portfolio Analysis Results for Ireland under a High Carbon and Gas Price Scenario*

		Target Mix	Mix P	Mix N	Mix S	Mix Q
Portfolio cost	[€/MWh]	110.0	86.0	110.0	80.0	78.0
Portfolio risk σ	[%]	0.2	0.12	0.15	0.2	0.15
Gas CC	[%]	70.5	0.0	36.8	0.0	0.0
Gas OC	[%]	0.5	0.0	12.2	0.0	0.0
Coal PF	[%]	5.2	30.5	12.1	90.4	65.8
Peat FB	[%]	4.9	7.0	9.8	0.0	0.0
Wind	[%]	12.3	19.5	19.5	4.7	19.5
Hydro	[%]	2.2	4.9	4.9	0.0	4.9
CHP	[%]	2.7	33.3	0.0	0.0	5.0
Biomass	[%]	1.7	4.9	4.7	4.9	4.9

* Gas = €12/GJ, CO₂ = €50/t

Table B.3 Portfolio Analysis Results for Ireland under a Mean Carbon and Gas Price Scenario and High WACC*

		Target Mix	Mix P	Mix N	Mix S	Mix Q
Portfolio cost	[€/MWh]	78.0	73.0	78.0	69.0	69.0
Portfolio risk σ	[%]	0.16	0.092	0.094	0.16	0.11
Gas CC	[%]	70.9	0.0	0.0	1.6	0.0
Gas OC	[%]	0.5	0.0	5.8	0.0	0.0
Coal PF	[%]	5.2	28.9	27.2	0.0	12.9
Peat FB	[%]	4.9	6.1	9.8	0.0	0.0
Wind	[%]	12.1	19.5	19.5	0.0	19.5
Hydro	[%]	2.2	4.9	4.9	0.0	0.0
CHP	[%]	2.7	35.7	28.0	97.8	62.7
Biomass	[%]	1.5	4.9	4.9	0.7	4.9

*Gas €6/GJ, CO₂ €30/t

Appendix C Technology characteristics

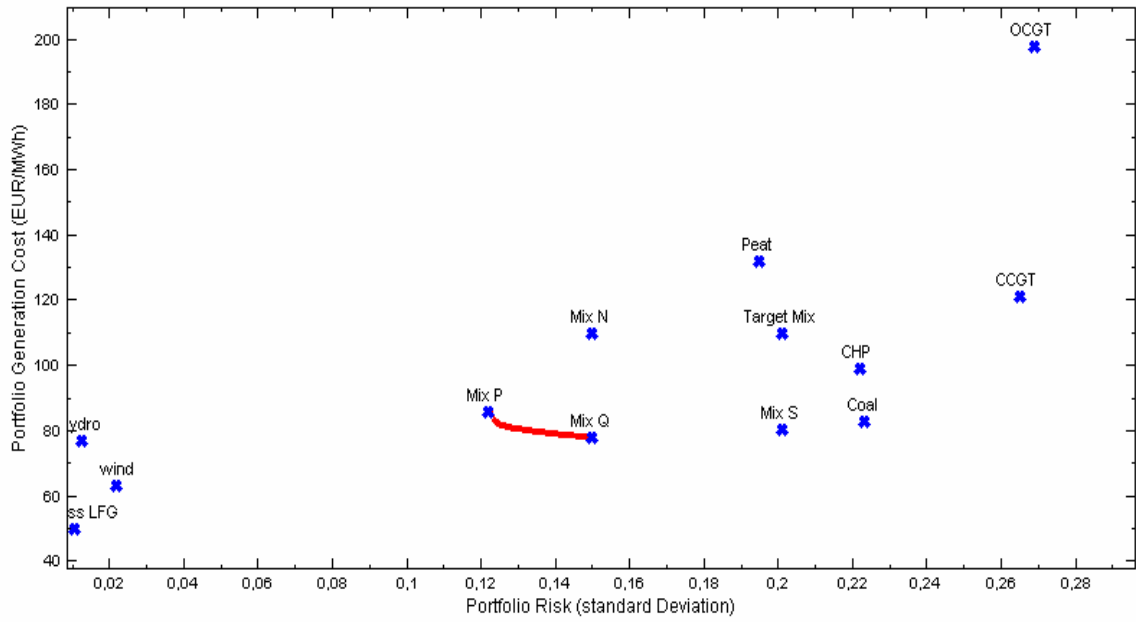


Figure C. 1 Technology characteristics

Appendix D Cost of Electricity⁶

The portfolio analysis undertaken for the Irish generating mix focuses on the target year of 2020. A target year is a year in the future for which a portfolio of electricity generating technologies has been forecast by the government or its agencies under baseline scenario conditions. This future mix is then compared with the mix in place in the base year.

Electricity generation and installed capacity

The target mix for electricity generation (TWh) and installed capacity of generating technologies can be shown in the manner provided in the table below.

Table D.1 Minimum cost and risk portfolios

Power plant category	Total capacity [MW]		Total generation [TWh]	
	Base year	Target year	Base year	Target year
Coal-fired	old plants			
	new plants			
Oil-fired	old plants			
	new plants			
Gas CCGT	old plants			
	new plants			
Wind	old plants			
	new plants			

Note that the distinction between existing plants ('old' plants) and new plants can affect the results. Imagine a future target year, that in part consists of pre-2005 plants, year 2005 being the base year, and on the other hand of plants that have been newly built in the post-2005 period. As pre-2005 plants are already in place, this influences the assumptions on investment risk and investment costs. Taking into account the expected decommissioning of 'old' plants, their total installed power and energy production is likely to be smaller in the target year, compared to the base year.

All the technologies included in this study are considered existing technologies and as a result the investment risk for such plants is set to zero.

Time series of annual fuel prices

A critical component of any risk assessment is the fuel price risk. The basis for setting fuel price risks and correlation factors between distinct fuels are realised values as implied by historical time series. Time series data should at least cover a period of 10 years. Historical values of standard deviations of fuel prices are the basis for fixing expected fuel price volatility. As the only thing that is certain about the future is that everything is uncertain, the analyst can adjust historical values as they deem appropriate.

⁶ This section draws heavily on the study, 'Application of Portfolio Analysis to the Dutch Generating Mix' (Jansen, 2006) and 'User Manual to the Online Portfolio Analysis Tool' (Beurskens, 2005).

Investment cost

Investment cost per unit of output is a function of:

- I: total investment cost per unit of capacity (kW) at commissioning date of the generating plant
- The real cost escalation factor, which will be tacitly presumed to be 1 unless there are strong reasons to expect a different factor. This is due to the assumption that investment cost will change in line with the general rate of inflation
- r: the real cost of capital, which is a function of the real risk free borrowing rate and the technology-specific and region-specific risk premium. The real risk free rate of borrowing can be estimated from the prevailing effective interest rate on government bonds with a high credit rating. The risk premium for most generating technologies range typically from 4% to 10%. Hence real discount factors used for power generation projects are typically in the range 6%-12%.
- F: the average full load hours per year
- T: the economic life time, after which the generating plant considered will be scrapped.

The investment cost per unit of output can be determined by applying the following formula:

$$\text{INCO} = (I * 1000 * \text{CRF}(r,T))/F$$

where CRF stands for capital recovery factor.

Fuel costs

The fuel cost per MWh is a function of:

- pf: the average price of the fuel (€/toe)
- η : the system conversion factor

This cost can be determined by the following formula:

$$\text{FUEL} = (pf * 3.6) / (\eta)$$

Fixed O&M

The average annual fixed O&M cost, FC, are expressed in €/kW.

The fixed O&M cost per MWh is a function of:

- FC: the average annual fixed O&M cost
- The real cost escalation factor, which will be tacitly presumed to be 1 unless there are strong reasons to expect a different factor. This owes to the assumption that fixed O&M cost will change in line with the general rate of inflation
- F: the average full load hours per year

$$\text{FIOM} = (FC * 1000 * F)$$

Variable O&M

The average variable O&M cost, VC, are expressed in €/MWh

$$\text{VAOM} = VC$$

For the time being, an additional cost of €6/MWh is applied to variable output technologies as an intermittency premium. In future, with a more advanced version of the model, it should be made possible that the intermittency premium be made dependent on the penetration level of the technology concerned. For example, the assumed premium might be a reasonable assumption for wind power at a 20% level, while for lower penetration levels a lower premium would be appropriate.

Environmental adders

Depending on the policy environment in the host country, emission pollutants per MWh of output will add to generating costs. Hereafter, allowance is only made for CO₂ emissions. However, a method for allowance of other emission pollutants is basically the same.

The cost of CO₂ emissions per MWh of output depends on:

- eCO_{2, fuel} : the CO₂ emission factor of the fuel used (tCO₂/GJ fuel)
- pCO₂ : the price of CO₂ (US\$/tCO₂)
- η : the system conversion factor

The cost of this environmental adder per MWh can be determined by the following formula:

$$ENAD = (eCO_{2, fuel} * pCO_2 * 3.6) / (\eta)$$

Unit Technology Cost

For a certain technology in any given year the following then holds:

$$UTCO = INCO + FUEL + FIOM + VAOM + ENAD$$

Appendix E – Description of ECN AIMMS Model⁷

E.1 Introduction

The following sections describe mathematically the ECN MVP model utilised for this study. For a portfolio with two assets, characterised by a certain level of expected HPR and expected risk, the following holds (Bodie, 2002):

$$r_p = w_1 r_1 + w_2 r_2 \quad (E.1)$$

$$\sigma^2 = w_1^2 \sigma_1^2 + w_2^2 \sigma_2^2 + 2w_1 w_2 \rho_{12} \sigma_1 \sigma_2 \quad (E.2)$$

Where

$$\rho_{12} = \frac{\text{cov}(r_1, r_2)}{\sigma_1^2 \sigma_2^2} \quad (E.3)$$

$$\text{cov}(r_1, r_2) = E \left\{ (r_1 - E(r_1)) \cdot (r_2 - E(r_2)) \right\} \quad (E.4)$$

In the formulas above, the following legend applies:

r: expected HPR, a random variable which presumably can be characterised by a probability distribution

w: portfolio weight (with all weights adding up to unity)

σ : risk (standard deviation)

Cov: coefficient of covariance, the extent to which two random variables co-vary;

ρ : coefficient of correlation, the extent to which two random variables co-vary, scaled such that it ranges from -1 (perfectly negative co-variation) through 0 (no relationship) to +1 (perfectly positive co-variation);

p,1,2 indices referring to portfolio, asset 1, and asset 2 respectively

The portfolio risk depends *inter alia* on the co-variation of return on asset 1 and asset 2 respectively:

$$\text{corr}(r_1, r_2) = 1 \Rightarrow \sigma_p = w_1 \sigma_1 + w_2 \sigma_2 \quad (E.5)$$

If the asset returns are perfectly positively correlated, then portfolio risk σ_p equals the weighted average of their standard deviations. If the asset returns are not perfectly positively correlated, then σ_p is less than the weighted average of the standard deviations of the individual asset returns:

$$\text{corr}(r_1, r_2) = 0 \Rightarrow \sigma_p = \sqrt{w_1^2 \sigma_1^2 + w_2^2 \sigma_2^2} \quad (E.6)$$

$$\text{corr}(r_1, r_2) = -1 \Rightarrow \sigma_p = |w_1 \sigma_1 - w_2 \sigma_2| \quad (E.7)$$

It can be proven that if the unweighted average covariance among security returns is zero (i.e. all risk is firm-specific), the portfolio standard deviation can be completely diversified away (Bodie et al., 249-250).

⁷ This section is drawn from the study, 'Application of portfolio analysis to the Dutch generating mix', (Jansen, 2006).

The 2-asset case can be generalised into an n-asset case as follows:

$$r_p = \sum_{i=1}^N w_i r_i \quad (E8)$$

$$\sigma_p^2 = \sum_{i=1}^N \sum_{j=1}^N w_i w_j \rho_{ij} \sigma_i \sigma_j \quad (E9)$$

In matrix notation this breaks down to:

Where:

$\mathbf{1}$ is the unity vector [1..1]^T

\mathbf{w} is the vector of portfolio weights

$\boldsymbol{\sigma}$ is the vector of portfolio risks (std dev)

\mathbf{P} is the matrix of correlations between any two asset returns

Major outputs of MVP analyses on portfolios of a set of risky assets (not comprising a risk free asset) include:

1. A model calculating portfolio returns and risk combinations for varying asset allocations along with the set of minimum risk portfolios at varying returns. Asset allocations are denoted by holding weights, summing up to one;
2. A graph of the '*minimum variance frontier*'. This graph - with risk values on the X-axis and portfolio expected returns on the Y-axis - depicts a set of points, each of which indicates a given portfolio expected return and the minimum standard deviation (e.g. the minimum variance, being the square of the standard deviation) that can be attained for the indicated portfolio expected return. The part of the frontier that lies above the global minimum variance portfolio is called the *efficient frontier*;
3. A diagram showing the composition of the efficient frontier at a wide range of risk values.

These outputs can be generated, based on a simple non-linear optimisation model. For example, for the 2-asset case the model can be formulated as follows (More and Weatherford (2001: 357)):

Minimize:

$$w_1^2 \sigma_1^2 + w_2^2 \sigma_2^2 + 2w_1 w_2 \rho_{12} \sigma_1 \sigma_2 \quad \text{variance of portfolio return} \quad (E10)$$

Subject to:

$w_1 + w_2 = 1$	allocating all funds
$w_1 r_1 + w_2 r_2 \geq b$	lower bound on the expected portfolio return
$w_1 \leq S_1$	upperbound on investment asset 1
$w_2 \leq S_2$	upperbound on investment asset 2
$x_1, x_2 \geq 0$	short selling is not allowed

E.2 Proposed adjustments of the analytical framework

This study uses the methodology employed by the ECN research team. They proposed some adjustments to the analytical framework described by Awerbuch and Berger (2003) and Berger (2003).

Proposed key adjustments concern:

1. Transformation to a risk-cost efficient frontier with energy-based portfolios;
2. Design of a transparent, comprehensive concept of portfolio risk and determination of its parameter values. The framework includes preliminary provisions for environmental costs and intermittency costs;
3. Design of an analysis tool related to incremental technology deployment analysis.

What follows is a brief outline of the adjustments made by the ECN team to the analytical process. More detailed information on the adjustments can be found in (ECN, 2006).

A consistent comprehensive framework for risk assessment

The key feature of the MVP approach to power system optimisation is that not only is the expected portfolio cost (COE) considered. The expected (COE) cost risk is considered to constitute an important second dimension in the optimisation process. To project the comprehensive MWh cost risk, associated with a generating technology, we need assumptions on fuel cost risk and on all other cost components.

Technology risks

The risk measure, standard deviation of annual COE, is used to provide an indication for the downside surprise risk (upside cost risk) associated with the corresponding unit cost. Although changes in annual costs and 'HPRs' often tend to be closely correlated, the respective correlation matrices still tend to differ significantly. Therefore, the analysis opts for a risk measure pertaining to absolute annual cost levels in real terms.

The goal is to derive information on the order of magnitude of COE for specific generating technologies and generating technology portfolios in a certain target year in real terms.

The procedure for projecting the downside risk (upside cost risk) per technology encompasses the following four steps:

1. For each factor j underlying the expected unit cost of a cost category k , establish the boundary (critical value) q_{jk} of the interval of possible factor values. This value is associated with a 2.5% probability that a more extreme value will occur, with corresponding unfavourable impact on the expected unit costs in the category. Typically, this critical value is based on 'expert judgement'. From this critical value q_{jk} and the expected value, we can deduce the risk σ_{jk} such that $P(X > q_{jk}) \leq 2.5\%$, by dividing the difference between the mean and the critical value by 1.96.
2. For each factor k underlying the expected unit cost of a cost category: establish the downside risk σ_{jk}
3. For each of the five cost categories k : establish the composite downside risk underlying the expected unit cost by applying the following 'rule of thumb':

$$\sigma_k = \sqrt{\sum_j \sigma_{jk}^2} \quad (\text{E11})$$

The foregoing estimator has been established by intuition. It has not been analytically proven. Yet, interestingly, an inductive 'proof' by way of Monte Carlo tests indicates that - under the assumption that the underlying cost factors are mutually statistically independent - the foregoing aggregation operation yields a quite reasonable approximation.

4. Establish the downside risk of a technology as a composite of each downside risk of the five cost categories using the following rule:

$$\sigma = \sqrt{\sum_{k=1}^5 \sigma_k^2} \quad (E12)$$

under the condition that all five cost components are mutually statistically independent.

This procedure can be formally proven as follows. Given a certain power generating technology with a portfolio of (five) cost components under the condition that the unit cost of each component can be approximated by a normal distribution, the following holds:

$$E(c) = \sum_{k=1}^5 w_k E(c_k) \quad (E13)$$

$$\sigma^2 = \sum_{k=1}^5 \sum_{l=1}^5 w_k w_l \rho_{kl} \sigma_k \sigma_l \quad (E14)$$

, where:

- c_k : the kWh cost of cost component k of a certain power generating technology in a target year;
- w_k : weight of cost component k in the total kWh cost of this power technology;
- c : the total kWh cost of this power generating technology in a target year;
- σ^2 : the variance of c ;
- ρ_{kl} : the correlation coefficient between the unit cost of cost components k and l ;

As the total kWh cost of a technology is the weighted sum of the kWh cost of all cost components, each weight is:

$$w_k = c_k / c, \quad \forall k \quad (E15)$$

Moreover, as by presumption all cost components are mutually independent, it holds that:

$$\rho_{kl} = 0, \quad \forall l, k \neq l, \text{ while } \rho_{kl} = 1, \quad \forall l, k = l \quad (E16)$$

Hence:

$$E(c) = \sum_{k=1}^5 E(c_k) \quad (E17)$$

And

$$\sigma = \sqrt{\sum_{k=1}^5 \sigma_k^2} \quad (E18)$$

The procedure to aggregate COE risk per technology to portfolio risk σ involves one additional step, step 5:

$$c_p = \sum_{i=1}^N w_i c_i \quad (\text{E19})$$

$$\sigma = \sqrt{\sum_{i=1}^N (X_i \cdot \sigma_i)^2} \quad (\text{E20})$$

Here, X_i is the share of technology i in the portfolio mix.

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