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Author's addresses: Boris Krey
E-mail: boris.krey@soi.unizh.ch

Peter Zweifel
E-mail: pzweifel@soi.unizh.ch

Publisher Sozialökonomisches Institut
Bibliothek (Working Paper)
Rämistrasse 71
CH-8006 Zürich
Phone: +41-1-634 21 37
Fax: +41-1-634 49 82
URL: www.soi.unizh.ch
E-mail: soilib@soi.unizh.ch

Efficient Electricity Portfolios for Switzerland and the United States

Boris Krey and Peter Zweifel*
Socioeconomic Institute, University of Zurich

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ABSTRACT: This study applies financial portfolio theory to determine efficient electricity-generating technology mixes for Switzerland and the United States. Expected returns are given by the (negative of the) rate of increase of power generation cost. Volatility of returns relates to the standard deviation of the cost increase associated with the portfolio, which contains *Nuclear*, *Run of river*, *Storage hydro* and *Solar* in the case of Switzerland, and *Coal*, *Nuclear*, *Gas*, *Oil*, and *Wind* in the case of the United States. Since shocks in generation costs are found to be correlated, the seemingly unrelated regression estimation (SURE) method is applied for filtering out the systematic component of the covariance matrix of the cost changes. Results suggest that at observed generation costs in 2003, the maximum expected return (MER) portfolio for Switzerland would call for a shift towards *Nuclear* and *Solar*, and therefore away from *Run of river* and *Storage hydro*. By way of contrast, the minimum variance (MV) portfolio mainly contains *Nuclear* power and *Storage hydro*. The 2003 MER portfolio for the United States contains *Coal* generated electricity and *Wind*, while the MV alternative combines *Coal*, *Nuclear*, *Oil* and *Wind*. Interestingly, *Gas* does not play any role in the determination of efficient electricity portfolios in the United States.

Keywords: energy electricity, portfolio theory, efficiency frontier, seemingly unrelated regression estimations (SURE)

JEL: C32, G11, Q49.

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*Socioeconomic Institute, University of Zurich, Hottingerstrasse 10, CH-8032 Zurich, Switzerland.
Tel. (B. Krey): +41-1-634 06 08; Fax: +41-1-634 49 87. Email addresses: (B. Krey) boris.krey@soi.unizh.ch, (P. Zweifel) pzweifel@soi.unizh.ch.

1 Introduction

As most industrial countries, Switzerland and the United States face great challenges in the provision of energy arising from increased demand by emerging economies and dwindling domestic resources. Both countries are expected to face substantial energy shortfalls during the next twenty years. According to the U.S. National Energy Policy Development Group (NEPG), the projected gap amounts to nearly 50 percent of 2020 demand. Over the next ten years, demand for electricity in particular is predicted to increase by about 25 percent, calling for more than 200,000 MWe of new capacity (National Energy Policy, NEP, 2001). As for Switzerland a study conducted by the Paul Scherrer Institute estimates a power shortfall of almost 20 percent by 2020 given a (slow) demand increase of 15 percent, and more than 40 percent given a surge in demand of 30 percent (Gantner, 2000). The experiences of California in 2001 and Italy in 2003 demonstrate the high costs of power shortages to the economy.
The solution available to the two countries are the same, too: import more power (from Canada and France, respectively); improve energy efficiency even more than expected; and increase domestic supply. However, new, more efficient technology should also contribute to enhanced diversification of energy supply. Investors (the government, municipalities, private and public utilities) need to know whether the current mix of power generating technologies in Switzerland and the United States is efficient from an investor's point of view. Can Swiss and U.S. investors do better by modifying the current electricity mix? If so what are the attractive technologies from an investor's point of view?

Financial investors take great interest in reducing their exposure to the ups and downs of the market by holding a diversified portfolio of securities. By examining the variances (standard deviations), covariances, and expected returns between assets, Markowitz (1952) constructed the set of efficient portfolios. An efficient portfolio does not create unnecessary risk for a given expected return, or put the other way around, it maximizes expected return for a given amount of risk, measured by the standard deviation of portfolio returns.
However, in the case of both Switzerland and the United States, who are net importers, power constitutes a liability rather than an asset since payments must be made to foreign suppliers. The (negative) rate of return on the power portfolio then becomes the rate of increase of the energy bill - which now is to be minimized rather than maximized. What is unchanged is the objective to minimize the volatility of the increase in the bill.

Indeed, the objectives of Swiss energy policy as laid down in section 6, art. 89 octies of the constitution support the asset-liability management approach to energy advocated here. The provision of energy should be i) sufficient, ii) diversified, iii) secure, vi) economical and v) environmentally compatible. The objectives of the National Energy Policy Group (NEPG) where established by U.S. President George W. Bush in 2001, viz. "to promote dependable, affordable and environmentally sound production and distribution of energy for the future" (NEP, 2001). Dependable energy is generated if it is sufficiently available, secure and diversified. Affordable energy is guaranteed if the generation is economical. Finally, both countries take great interest to provide energy in an environmentally preserving way.

The asset-liability management approach advocated here can easily accommodate these objectives. As to sufficiency, a shortfall in supply would result in an increase of the electricity bill in view of inelastic demand. Diversification and security are the very topic of the portfolio approach, as is the quest for economical technologies (which limit the increase in the energy bill). Finally, for compatibility with the environment, all it takes is to include a surcharge for negative externalities in the costs that enter the calculation. For example, if additional use of some energy technology causes a particularly high amount of pollution, this surcharge causes its cost increase to be higher. In sum, the objectives of both the Swiss constitution and those guiding NEPG in the United States are served by the construction of efficient power portfolios.

One may ask why a comparative analysis between Switzerland and the United States should be of any interest. From an investor's point of view, the countries may present different prospects in terms of their expected returns and risks associated with their electricity markets. Investors in Swiss electricity production should be particularly interested to know how gas performs in the U.S. electricity portfolio. In 2003, about 17 percent of the total U.S. electricity mix was generated by gas, while in Switzerland no electricity generating gas power plants were installed (see Figures 1 and 2).

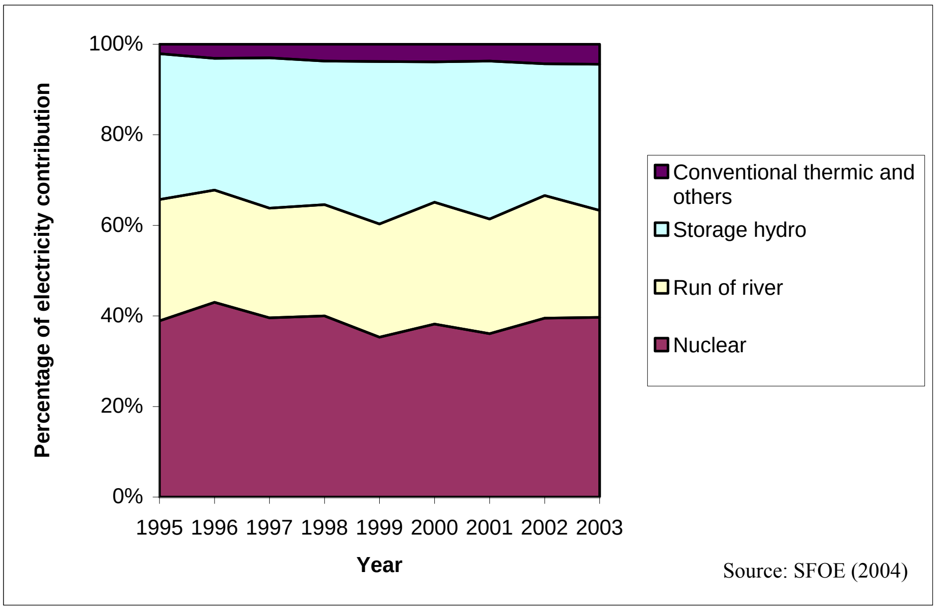

Figure 1 Swiss mix of power generation, 1995 – 2003

Accordingly, there is debate in Switzerland to substantially increase the share of gas-generated electricity as an alternative to nuclear and electricity imports. As to the United States, about 90 percent of all new electricity plants currently under construction will be fuelled by natural gas (NEP, 2001).

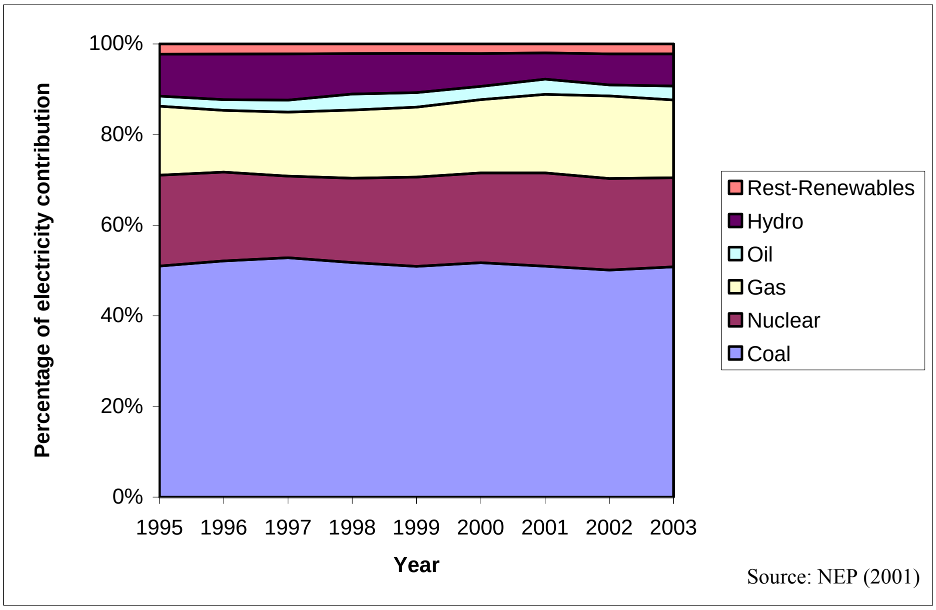

Figure 2 U.S. mix of power generation, 1995 – 2003

While natural gas has many advantages (lower capital costs, shorter construction times, higher efficiencies and lower emissions compared to coal), an over-reliance on imported gas leaves generators vulnerable to price spikes and supply disruptions. While affecting European countries rather than the United States, Russian state owned Gazprom raised the specter of gauching and squeezing, a behaviour that may serve as a model for suppliers of gas worldwide (Economist, 2006).

This paper is structured as follows. Section 2 is devoted to a review of the literature. The portfolio approach has been applied to energy sources of the United States and the European Union. In the present paper, Markowitz theory is applied to Swiss and U.S. electricity supply in section 3. In order to meet the growing demand for power from domestic sources Switzerland and the United States would have to increase production capacities. The question addressed here is what mix of electricity-generating technologies is most efficient from an investor's point of view. The task at hand is to construct electricity portfolios that minimize the increase of generation costs for a given amount of volatility. However, the outcome depends crucially on estimated variances and covariances (the covariance matrix henceforth) that should be stable. The econometric techniques available for filtering out the systematic, time-invariant components of the covariance matrix are described in section 4.

The methodological innovation introduced in this study consists in recognizing that there are common shocks impinging on the generation costs of the energy sources. Taking this correlation into account in the estimation of the covariance matrix (using so-called seemingly unrelated regression estimation, SURE) can give rise to important gains in the efficiency of estimation. To the best of the authors' knowledge, SURE has not been applied yet to the estimation of the covariance matrix pertaining to energy generation costs. Section 5 illustrates the SURE-based construction of efficient power generation frontiers for Switzerland and the United States. It will be shown that the mix of technologies importantly depends on whether one prefers the maximum expected return (MER) or the minimum variance (MV) portfolio. Conclusions are offered in the final section, 6.

2 Review of the literature

Portfolio theory and the concept of diversification have proved useful in areas other than corporate and personal investment. This review of the literature will exclusively focus on applications to energy.

Bar-Lev and Katz (1976) examine fossil fuel procurement to determine the extent to which the U.S. utility industry has been an efficient user of scarce resources. They derive a Markowitz-efficient frontier of fuel mixes which minimize the expected increase of fuel cost at a given risk (see section 3 on portfolio theory). Their results show that while generally utilities are efficiently diversified, their portfolios are characterized by both high (negative) rates of return and high risk. Furthermore, the authors suggest that regulation causes utilities to opt for high-risk alternatives. Utilities could move towards the efficient frontier by purchasing more higher-priced fuels that however exhibit smaller price fluctuation. A major problem with the approach of Bar-Lev and Katz is that it does not account for varying covariances in energy prices over time.

Humphreys and McClain (1998) introduce a time-varying covariance matrix (i.e. variances and covariances in their construction of an efficient portfolio of U.S. energy sources). Thus, estimated variances and covariances are derived from so-called generalized autoregressive conditional heteroscedastic (henceforth: GARCH) models. GARCH modelling allows to filter out systematic changes in volatility in response to price shocks. Without filtering, these shocks may result in unstable estimates of the covariance matrix. The results indicate that while the electric utility industry is operating close to the MV portfolio, a shift towards coal would still reduce overall price volatility at a given rate of return in cost. With the inclusion of expected externality costs, the shift away from oil remains but favors natural gas instead of coal.

The study by Humphreys and McClain provides evidence suggesting that the price changes are characterized by skewness and excess kurtosis, implying that conditional densities likely are not normal. However, under these conditions GARCH does not provide useful inferences and should be replaced by an alternative approach. In addition, possible correlations between price shocks are not specifically considered.

Yu (2003) presents a short-term market risk model again based on the Markowitz mean-variance approach, where the covariance matrix reflects different developments of fuel prices across regional electricity markets. Yu includes transaction costs and other constraints such as minimum contracting quantities that limit wheeling, resulting in a mixed integer programming problem. An interesting observation is that the resulting efficient frontier is neither smooth nor concave from below anymore, contrary to the illustration of Figure 3 below.

However, Yu does not control for non-normal conditional densities, which might lead to biased regression results that will result in faulty predictions of future price changes. In addition, the study does not provide evidence concerning possible correlations between shocks impinging on prices. Such correlations should be of great concern in this study since Yu uses data from many regions, which may be subject to similar shocks (notably weather, as evidenced by the electricity price hikes in California that were mainly caused by dry and hot weather in the states of Washington, Utah, Nevada, and Arizona (Cicchetti et al., 2004)).

Berger et al. (2003) analyze existing and projected generating mixes in the European Union (EU). They compare existing risk-return properties to a set of efficient portfolios that minimize generation costs at a given level of market risk. In general, the results indicate that the existing and projected EU generating mixes are sub-optimal from a risk-return perspective. The analysis further suggests that portfolios with lower cost and risk can be developed by including greater amounts of renewables (which typically have high fixed but low variable costs, such as wind).

The study by Berger et al. does not take account of external costs. Thus, generation costs for fossil-fuel generated electricity might be underestimated. Most of the generation cost data are proxies. For example, fixed and variable costs of operation and management (O&M) are approximated by using historical business data such as the S&P 500, Morgan Stanley MCSI Europe index, and treasury bills. However, the report does not publish results of commonly known statistical tests showing (i) whether the correlation of the proxies with the endogenous variables are high (e.g. Shea partial r-squared test, F-test of excluded instruments), and (ii) whether the disturbance terms are orthogonal (Sargan test). There is strong support in the econometric literature of the view that weak proxies lead to unreliable results (Greene, 2003, ch. 5). As is true of the other studies, Berger et al. fail to consider correlations of shocks impinging on generation cost. It seems reasonable to generally assume these shocks to be strongly correlated.

Summing up this review, the idea of refining econometric methodology using SURE to obtain reasonably time-invariant covariance matrices as an input to the determination of efficient electricity-generating energy portfolios appears to be a promising approach.

3 Portfolio theory

Rational holders of a portfolio of liabilities seek to minimize the expected increase of its value at a given risk or alternatively seek to maximize its expected negative increase (i.e. decrease) at a given risk. The expected (negative) return of such a portfolio depends on the expected returns of the individual liabilities and the percentage of funds invested in each, while the risk of the portfolio depends on the covariance or correlation matrix of the individual returns. The expected return on a portfolio p consisting of m risky liabilities is given by

$$E(R_p) = \sum_{i=1}^{m} w_i E(R_i) \tag{1}$$

where $E(R_i)$ is the expected percentage increase of liability i and w_i is the share (weight) of liability i in the total. The year 2003 portfolio for Switzerland (*CH2003*) consists of four electricity liabilities, viz. *Nuclear*, *Run of river*, *Storage hydro*, and *Solar* (as described in section 4.2). Therefore,

$$E(R_p, CH2003) = w_1 E(R_1) + w_2 E(R_2) + w_3 E(R_3) + w_4 E(R_4) \tag{2}$$

The volatility (reflected by the standard error) of the portfolio's rate of return involves not only the respective variances but all the covariances as well. Therefore, one has

$$\sigma_p(CH2003) = \begin{pmatrix} w_1^2\sigma_1^2 + w_2^2\sigma_2^2 + w_3^2\sigma_3^2 + w_4^2\sigma_4^2 + 2w_1w_2\rho_{12}\sigma_1\sigma_2 + 2w_1w_3\rho_{13}\sigma_1\sigma_3 \\ + 2w_1w_4\rho_{14}\sigma_1\sigma_4 + 2w_2w_3\rho_{23}\sigma_2\sigma_3 + 2w_2w_4\rho_{24}\sigma_2\sigma_4 + 2w_3w_4\rho_{34}\sigma_3\sigma_4 \end{pmatrix}^{\frac{1}{2}}, \tag{3}$$

$$\text{where } \rho_{ij} = \mathbf{cov}_{ij} / (\sigma_i \sigma_j), \quad i,j = 1,...,4.$$

The year 2003 portfolio for the U.S. contains five liabilities, viz. *Coal*, *Nuclear*, *Gas*, *Oil* and *Wind* (again as outlined in section 4.2). Equations (2) and (3) are modified accordingly. Figure 3 illustrates. Compared to the standard case of a portfolio of assets, one adjustment is necessary for making it applicable to the case of electricity generation technologies. The objective now becomes to minimize the expected rate of increase of the cost of electricity generation subject to a given amount of volatility in this increase. In keeping with eqs. (2) and (3), $E(R_p)$ is defined as the rate of increase per unit of electricity-generating cost. The horizontal axis depicts risk as measured by the standard deviation σ_p, while the vertical axis displays the expected (negative) returns of the liability portfolio measured in U.S. cents/kWh electricity.

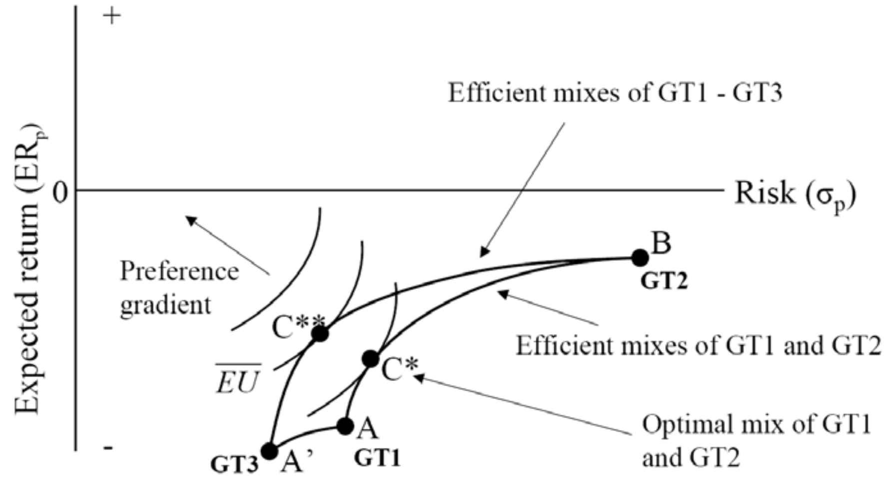

Figure 3 Efficient portfolio of generation technologies (GT)

For illustration, let there be only two electricity generation technologies, GT1 and GT2. By assumption, GT1 has little volatility in terms of an increase in generation costs; on the other hand, the expected future increase in generation costs is substantial (point A). By way of contrast, GT2 is more risky, but on expectation its increase in cost is much less (point B). Due to the correlation terms contained in eq. (3), the efficient frontier linking points A and B (i.e. combining the two technologies) is the segment of an ellipse. Thus, if the correlation between two generation technologies is less than perfect $\left(-1 < \rho_{12} < 1\right)$, the efficient frontier between points A and B runs concave. The lower the correlation coefficient, the stronger this portfolio effect will be. This means that by adding GT2 with its high volatility but low expected generation cost increase to the portfolio, the country may profit from a diversification effect. Note that if returns of A and B move in a perfectly opposite way $\left(\rho_{12} = -1\right)$, then it will be possible to construct a portfolio with no volatility at all (Berger et al., 2003). Such a portfolio would always yield the same expected return, since when returns of B were higher than expected, returns of A would be below expectation by an equal amount.

Now let there be a third technology (GT3), symbolized by point A'. This creates additional opportunities for diversification. One alternative is between GT1 and GT3, giving rise to the partial efficient frontier AA'. Now the two portfolios consisting of GT1 and GT2 and GT2 and GT3 respectively can be combined to yield the envelope of AA' and AB, i.e. A'B. Clearly, this overall portfolio offers a still greater diversification effect than the two component portfolios.

In order to predict the optimal portfolio (to be selected among the efficient ones), knowledge of the decision maker's preferences would be necessary. Along an indifference curve, expected utility (EU) is held constant. The preference gradient indicates a risk-averse decision-maker who likes a higher expected return but dislikes volatility. Evidently, the optimum allocation of liabilities is given by the highest-valued indifference curve that is still compatible with the efficient frontier. For the frontier composed of GT1 and GT2 (boundary AB), this optimum is depicted by point C*. If GT3 is indeed available, C** becomes the new optimum, with a slower increase of the value of the liability portfolio and at the same time less volatility. Clearly, C** lies on a higher-valued indifference curve than C*, demonstrating the future contribution to welfare that can be expected from the availability of additional energy technologies thanks to improved diversification.

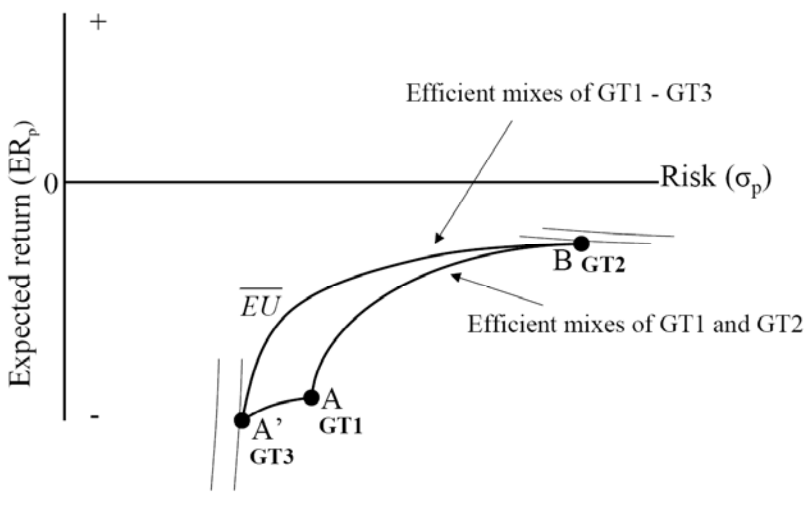

Figure 4 Optimal portfolios in two extreme cases

Figure 4 displays optimal portfolios for two extreme cases with regard to the degree of risk aversion assumed. A very risk-averse decision maker is predicted to prefer point A', i.e. the minimum variance (MV portfolio). By way of contrast, an almost risk neutral decision maker will opt for point B, i.e. the maximum expected return (MER) portfolio. Comparing these two extreme solutions permits to assess the influence of the degree of risk aversion (which is not known by policy makers or the population with regard to the provision of electricity) on the optimal portfolio of power generation technologies.

4 Econometric analysis

4.1 Seemingly unrelated regression estimation (SURE)

From eq. (3), we know that the portfolio risk σ_p depends on individual standard errors of σ_i and the correlations between the electricity-generation return variables ρ_{ij}. As argued in section 2, it is important to derive estimates of the covariance matrix (i.e. of σ_i and σ_{ij}) that are reasonably time-invariant. In each time series of electricity cost changes considered, this calls for the estimation of residuals $\hat{u}_{i,t}$ that e.g. do not contain a systematic shift. Such residuals can be computed from the following regression,

$$R_{i,t} = \boldsymbol{\alpha}_0 + \sum_{j=1}^{m} a_{i,t-j} \cdot R_{i,t-j} + u_{i,t}; \tag{4}$$

where $R_{i,t}$ is the percentage change (return) in electricity-generation cost for technology *i* at time period *t*, α_0 is a constant, $\boldsymbol{\alpha}_{i,t-j}$ is the coefficient of the lagged return electricity-generation cost variable(s) of electricity source *i* at time period *t-j*, and $u_{i,t}$ is the error term for technology *i* at time period *t*.

If the shocks $u_{i,t}$ causing volatility in $R_{i,t}$ were uncorrelated across technologies, one could estimate the expected return for each electricity-generating technology separately for deriving residuals. However, the error terms are significantly correlated (as will be shown in section 5.1). This constitutes information that can be exploited for improving the efficiency of estimation, typically resulting in sharper estimates of the parameters $\boldsymbol{\alpha}_{i,t-j}$, of the residuals $u_{i,t}$, and hence of the σ_i and σ_{ij} making up the covariance matrix. The econometric method available is called seemingly unrelated regression estimation, or SURE for short.

The SURE model consists of *m* regression equations (*m* = the number of different electricity-generation technologies), each of which satisfies the assumptions of the standard regression model. Equation 5 displays the set of equations that make up SURE in the in the year 2003 portfolio for Switzerland[1].

$$\begin{aligned}
R_{Nucl,03} &= const\,\mathbf{b}_{0Nucl,03} + \mathbf{x}_{Nucl,02}\mathbf{b}_{1Nucl,02} + \mathbf{x}_{Nucl,01}\mathbf{b}_{2Nucl,01} \\
&\quad + \mathbf{x}_{Nucl,00}\mathbf{b}_{3Nucl,00} + \mathbf{x}_{Nucl,99}\mathbf{b}_{4Nucl,99} + trend\,\mathbf{b}_{5Nucl} + \boldsymbol{\varepsilon}_{Nucl,03} \\
R_{Ror,03} &= const\,\mathbf{b}_{0Ror,03} + \mathbf{x}_{Ror,02}\mathbf{b}_{1Ror,02} + trend\,\mathbf{b}_{2Ror} + \boldsymbol{\varepsilon}_{Ror,03} \\
R_{Hs,03} &= const\,\mathbf{b}_{0Hs,03} + \mathbf{x}_{Hs,02}\mathbf{b}_{1Hs,02} + trend\,\mathbf{b}_{2Hs} + \boldsymbol{\varepsilon}_{Hs,03} \\
R_{Sol,03} &= const\,\mathbf{b}_{0Sol,03} + \mathbf{x}_{Sol,02}\mathbf{b}_{1Sol,02} + \mathbf{x}_{Sol,01}\mathbf{b}_{2Sol,01} \\
&\quad + \mathbf{x}_{Sol,00}\mathbf{b}_{3Sol,00} + \mathbf{x}_{Sol,99}\mathbf{b}_{4Sol,99} + trend\,\mathbf{b}_{5Sol} + \boldsymbol{\varepsilon}_{Sol,03}
\end{aligned} \tag{5}$$

[1] The U.S. equation can be constructed in the same way, but for brevity only the Swiss equations are presented.

Generally, influences such as technological changes, increases and decreases in the cost of inputs used in the production of the technology considered, and natural disasters are hypothesized to influence electricity-generation return. However, estimating such a comprehensive model would be beyond the scope of this study. Therefore, electricity-generating return is determined by the cost changes of previous years plus a constant and a time trend. For example, the cost changes of nuclear energy in Switzerland in the year 2003, $R_{Nucl,03}$, is related to the cost changes in the preceding years $x_{Nucl,02}$, $x_{Nucl,01}$, $x_{Nucl,00}$, $x_{Nucl,99}$, a constant ($const$) and a time trend ($trend$) (see eq. 5). In analogy, relative cost change of nuclear energy in the United States in the year 2003, $R_{Nucl,03}$, is related to the cost change in the preceding year $R_{2,2002}$ a constant ($const$) and a time trend ($trend$) (cf. Table 6).

Dealing with $\varepsilon_{i,t}$ the t_{th} element of ε_i, we assume that the $(\varepsilon_{1,t}, \varepsilon_{2,t}, ..., \varepsilon_{m,t})$ are iid, with $E(\varepsilon_{i,t}) = 0$ and $E(\boldsymbol{\varepsilon}_{i,t}\boldsymbol{\varepsilon}_{j,s}) = \boldsymbol{\sigma}_{ij}$ if $t = s$ and $= 0$ if $t \neq s$. This part of the specification is crucial because it admits nonzero contemporaneous correlations between the error terms of the equations. Written in matrix algebra, the system (5) reads,

$$\begin{bmatrix} R_{Nucl,03} \\ R_{Ror,03} \\ R_{Hs,03} \\ R_{Sol,03} \end{bmatrix} = \begin{bmatrix} X_1 & 0 & 0 & 0 \\ 0 & X_2 & 0 & 0 \\ 0 & 0 & X_3 & 0 \\ 0 & 0 & 0 & X_4 \end{bmatrix} \cdot \begin{bmatrix} b_{Nucl,03} \\ b_{Ror,03} \\ b_{Hs,03} \\ b_{Sol,03} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\varepsilon}_{Nucl,03} \\ \boldsymbol{\varepsilon}_{Ror,03} \\ \boldsymbol{\varepsilon}_{Hs,03} \\ \boldsymbol{\varepsilon}_{Sol,03} \end{bmatrix} \tag{6}$$

where e.g.
$X_1 = [const \ \mathbf{x}_{Nucl,02} \ \mathbf{x}_{Nucl,01} \ \mathbf{x}_{Nucl,00} \ \mathbf{x}_{Nucl,99} \ trend]$ and
$b_{Nucl,03} = [\mathbf{b}_{\mathbf{0}\,Nucl,03} \ \mathbf{b}_{\mathbf{1}\,Nucl,02} \ \mathbf{b}_{\mathbf{2}\,Nucl,01} \ \mathbf{b}_{\mathbf{3}\,Nucl,00} \ \mathbf{b}_{\mathbf{4}\,Nucl,99} \ \mathbf{b}_{\mathbf{5}\,Nucl}]'$,
all other variables are defined in analogy.

Therefore, the vectors of observed cost changes are stacked on top of each other. They are related to the corresponding matrix of explanatory variables $\mathbf{X}_i$. For this reason, the matrix on the right-hand side is diagonal, indicating that e.g. the cost change in the nuclear technology of 2003 is only related to its own history but not to cost changes in the other technologies.

These *m* equations (involving *T* observations each) can be stacked once more. By using **X** as the symbol of the block diagonal matrix in eq. (6), one obtains,

$$\mathbf{R} = \mathbf{Xb} + \boldsymbol{\varepsilon}, \qquad E(\boldsymbol{\varepsilon\varepsilon}') = \boldsymbol{\Omega} \tag{7}$$

The assumption that is specific to SURE is that the covariance matrix is not diagonal,

$$\boldsymbol{\Omega} = E(\boldsymbol{\varepsilon\varepsilon}') = \begin{bmatrix} \boldsymbol{\sigma}_{NuclNucl}I & \boldsymbol{\sigma}_{NuclRor}I & \boldsymbol{\sigma}_{NuclHs}I & \boldsymbol{\sigma}_{NuclSol}I \\ \boldsymbol{\sigma}_{RorNucl}I & \boldsymbol{\sigma}_{RorRor}I & \boldsymbol{\sigma}_{RorHs}I & \boldsymbol{\sigma}_{RorSol}I \\ \boldsymbol{\sigma}_{HsNucl}I & \boldsymbol{\sigma}_{HsRor}I & \boldsymbol{\sigma}_{HsHs}I & \boldsymbol{\sigma}_{HsSol}I \\ \boldsymbol{\sigma}_{SolNucl}I & \boldsymbol{\sigma}_{SolRor}I & \boldsymbol{\sigma}_{SolHs}I & \boldsymbol{\sigma}_{SolSol}I \end{bmatrix}. \tag{8}$$

The seemingly unrelated regression (SURE) model therefore allows to simultaneously estimate the stacked expected returns of all power generation technologies in one regression, controlling for the possible correlation of error terms across equations.

4.2 The data

The Swiss data set consists of four variables: *Nuclear*, *Run of river*, *Storage hydro*, and *Solar*. All variables are averaged annual data defined as changes in costs of U.S. cents per kWh electricity[2]. All variables are cost deflated by the Swiss and the U.S. CPI respectively, with 2000 serving as the base year (=100). *Nuclear*[3] covers the time period 1986 to 2003, *Run of river*[4] and *Storage hydro*[5] 1993 to 2003, and *Solar*[6] 1991 to 2003. Data for the U.S. efficient portfolios relate to the change in cost, viz. *Oil*, *Gas*, *Nuclear*, *Coal* and *Wind* power[7], and cover the time period 1982 to 2003. Throughout, private costs comprise (i) fuel costs, (ii) costs of current operations, and (iii) capital user costs. In the case of *Nuclear*, decommissioning and waste disposal costs are also included.

One variant also contains an externality surcharge since electricity generation causes environmental damage. From a society's point of view, the price of a product should reflect external costs to the extent that the marginal benefit of internalization still covers its marginal cost. This means that full internalization almost always entails an efficiency loss because in that event, expected marginal benefits are necessarily zero, while the marginal cost of the internalization effort is substantial (filtering out the last 0.1 percent of toxic substances contained in a body of water causes very high cost). By way of contrast, the surcharges used in this study for Switzerland are taken from Hirschberg (1999), who implicitly assumes 100 percent internalization when dividing estimated total external cost by total final energy produced by the technology considered. No external cost data for the United States were available, therefore external cost data from the UK where used (European Commission, 2003). The UK electricity generation mix and electricity industry are similar to that of the United States, and therefore the UK external cost data should serve as a useful proxy. Furthermore, Swiss and UK external cost data are comparable, both being generated by the same methods.

In terms of categories, external costs related to health and global warming enter calculations. However, no data are available for some other categories such as external costs related to agriculture and forestry. In an attempt to take the uncertainty caused by this gap into account, Hirschberg's and the European Commission’s estimates are used to generate a lower bound and an upper bound of social cost estimates for Switzerland and the United States (Hirschberg, 1999; EC, 2003). However, the difference between the two external cost estimates is expected to have little effect since it is the relative change in cost over time that constitute the input to the portfolio allocation model.

Three of the four generation technologies considered in the Swiss data set are comparable in terms of unit cost. They are in the 1 to 4 U.S. cents/kWh (busbar) range in 2003. By way of contrast, *Solar* initially was markedly more expensive at the beginning of the observation

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[2] The mean value of the exchange rate for the year 2000 was used to convert Swiss cents into U.S. cents, as published by the U.S. Federal Reserve (http://research.stlouisfed.org).

[3] Data sources: KKL (2005), KKG (2005)

[4] Data source: personal correspondence

[5] Data source: personal correspondence

[6] RWE Schott Solar (2005); The year 2000 average exchange rate to convert Euro cents into US cents was used, obtained from the Federal Reserve, USA. RWE Schott Solar data from Germany is used as a proxy for Swiss solar electricity data, since Solar generation technologies in both countries are similar.

[7] Data for *Oil*, *Gas*, *Nuclear* and *Coal* was obtained from the UIC (2005). Wind (State Hawaii, USA (www.state.hi.us) and U.S. Department of Energy (www.energy.gov)). Since the wind data was not available for every year, values for 1983, 1985-1987, 1989-1994, 1996-1999 were generated by cubic spline interpolation.

period. As can be seen in Table 1, generation cost reductions have been modest for *Nuclear*, *Run of river* and *Storage hydro* in the period 1995 to 2003. However, *Solar* has experienced consistently large cost decreases.

Year	Nuclear	Run of river	Storage hydro	Solar
1995	4.97	2.59	5.69	80.76
2003	3.47	1.91	4.04	47.41

Table 1 Cost comparison between 1995 and 2003 of Swiss generation costs taking account of external costs (using high cost scenario), in U.S. cents/kWh

All U.S. generation technologies have comparable unit costs, ranging between 3 and 10 U.S. cents (busbar) in 2003. In contrast to renewables like *Solar* power in the Swiss data set, *Wind* generated electricity in the U.S. is one of the cheapest generation technologies. Table 2 shows that in 2003 *Wind* power was amongst the cheapest, facing less than half of the costs of *Oil* and *Coal*.

Year	Oil	Coal	Gas	Nuclear	Wind
1995	11.27	11.44	6.20	5.77	5.44
2003	10.10	8.99	7.56	3.80	4.35

Table 2 Cost comparison between 1995 and 2003 of U.S. generation costs taking account of external costs (using high cost scenario) in U.S. cents/kWh

Yet, unit costs as such are not relevant for the purpose of this paper. Recall that investors in the capital market are not concerned about the price of a share. An expensive share that has the potential to still increase in value in the future can be part of their efficient portfolio. In short, the expected rate of return is crucial (along with possible diversification effects (see section 3 again). Thus, an investor would want to buy into Swiss *Solar* regardless of its initial unit cost. In view of its consistent decrease of unit cost, Swiss *Solar* should figure prominently in an investment portfolio unless it has extremely unfavorable diversification properties.

However, current users of energy technologies do not adopt an investor's point of view. They would want to satisfy their current needs in terms of primary energy sources at minimum costs. The present paper follows most of the existing literature by adopting the investor's rather than the current user's point of view. It thus seeks to answer the question, How should a policy maker have started restructuring the electricity generating portfolio in the 1980s (assuming he knew the cost changes occurring until 2003) in order to arrive at the MER or the MV portfolio by 2003, depending on his or her risk preferences.

In keeping with the definition of returns in section 3, the historical development of percentage changes in Swiss power generation costs, taking account of high external costs, are shown in Figure 5. The data extend from 1986 to 2003 (*Nuclear*) and 1993 to 2003, respectively (*Run of river* and *Storage hydro*) and 1991 to 2003 (*Solar*). As can be seen from Figure 5, *Run of river* exhibits the strongest fluctuations, particularly in 1999 and 2000, mainly due to changes in financial transactions between key *Run of river* electricity suppliers (Axpo, 2002). In contrast, the change in the generation costs of *Nuclear* deviates little from zero, pointing to stability of real cost over time.

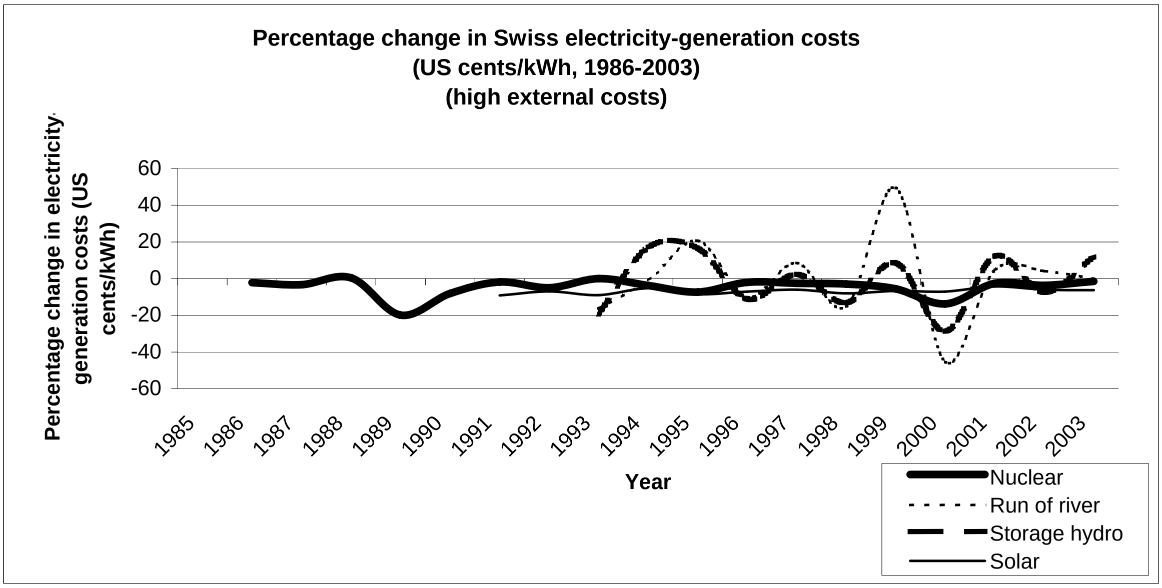


Figure 5 Percentage changes in Swiss electricity-generation costs (U.S. cents/kWh) 1986/1993-2003

The U.S. data cover 1982 to 2003 and contain *Oil*, *Coal*, *Gas*, *Wind* and *Nuclear* power. *Oil*-generated electricity shows large fluctuations in generation costs throughout the observation period. The Persian revolution in the early 1980s and the aftermath of 9/11 cause particularly market cost spikes.

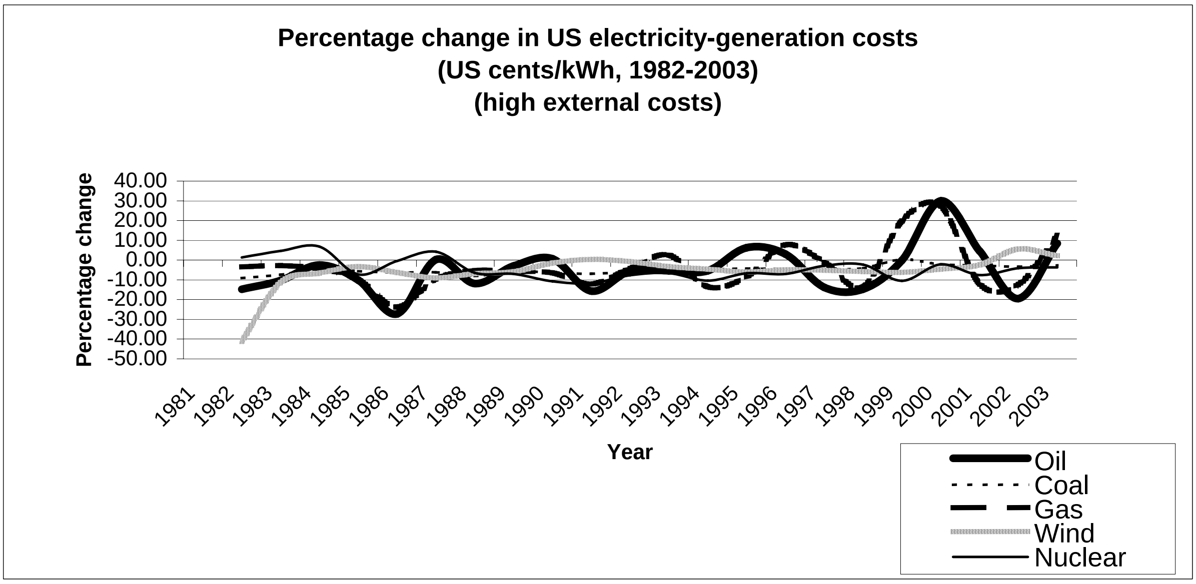


Figure 6 Percentage changes in U.S. electricity-generation costs (US cents/kWh) 1982-2003

Similar cost fluctuations can be found in *Gas* generated electricity, since, amongst many other reasons, *Gas* fuel is heavily correlated with oil fuel (e.g. gas fuel transportation is oil fuel dependent). *Wind* generated electricity remained fairly constant over time.

4.3 Current Swiss and U.S. mix of power generation

Figure 7 displays the 2003 mix of Swiss power generation as it will be used in this study. Switzerland produces electricity using mainly *Nuclear* (40%). *Storage hydro* and *Run of river* account for 32% and 24% respectively, while *Solar* generates a mere 4% of total Swiss electricity. In addition, *Solar* is a proxy for all conventional-thermic and other energy sources that are used in Switzerland but for which data is unavailable.

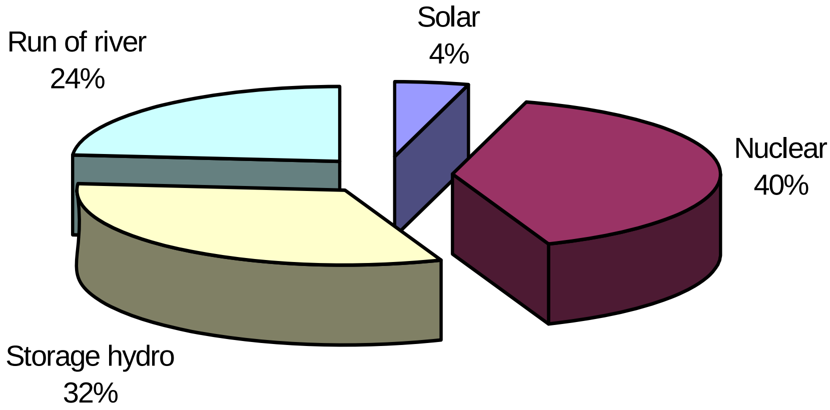


Figure 7 Swiss mix of power generation in 2003

As can be seen in Figure 8, the U.S. mix of power generation technology in 2003 is *Coal* power 56%, *Nuclear* 21%, *Gas* 18% and *Wind* and *Oil*, which generate 5% and 3% respectively. No data was available for *Hydro* generated electricity, that usually makes up around 7 percent of total electricity production (see Figure 2 in section 1). *Wind* is used as a proxy for renewables and a remainder. The Swiss and U.S. power generation mixes of 2003 will be compared with their predicted efficient frontiers in section 5.

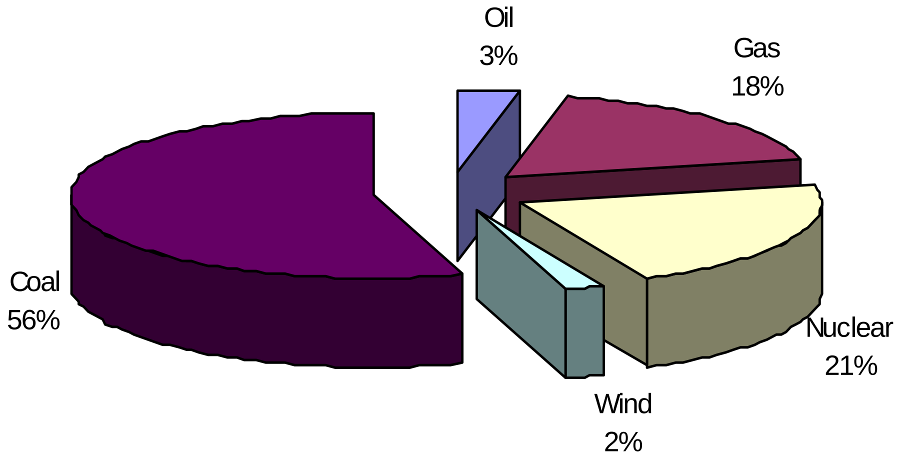


Figure 8 U.S. mix of power generation in 2003

5 Efficient frontiers for Swiss and U.S. power generation

5.1 Time series analysis

5.1.1 Essential pre-tests

The objective is to obtain a stable estimate of the covariance matrix. In order to be able to filter out the systematic (and *trend* stable) component of the covariance matrix, changes in generation costs must form stationary time series. Given nonstationarity, the estimate of the covariance matrix would necessarily shift over time, precluding the estimation of a reasonably stable efficient frontier (Wooldridge (2003), ch. 11).

To test for stationarity and systematic shifts, the augmented Dickey-Fuller (ADF) test was applied. Results indicate at the one percent significance level that all generation cost variables[8] in the Swiss and U.S. data sets are stationary.

To determine the correct lag order for the SURE regressions, several tests were applied, viz. Akaike's information criterion (AIC), Hannan & Quinn information criterion (HQIC), Schwartz's Bayesian information criterion (SBIC), and the likelihood ratio test (LR) (Al-Subaihi, 2002; Liew, 2004). The results for the Swiss data suggests that in the case of all *Nuclear* variables four lags should be applied, while in the cases of *Run of river* and *Storage hydro*, one lag suffices. Tests are inconclusive for *Solar*.

However, Liew (2004) shows that tests for the selection of lags may lack validity if the sample is small. Using a sample size of 25 observations (*Solar* contains even 13 observations only in this study), he predicts that the probability of correctly estimating the true order of an autoregressive process ranges between 58% (Schwartz's Bayesian Information Criterion) and 60% (Hannan & Quinn Information Criterion). Four lags were applied here since the coefficients on the autoregressive variables used in the SURE procedure are in most cases significant (see Table 5). The results for the U.S. data suggest five lags on all *Oil* variables[9], three lags on *Gas*[10] and one lag on *Coal*. One lag was used for *Wind* and *Nuclear*, since considerations of goodness of fit in the SURE results speak in favor of it (see Table 6).

5.1.2 Seemingly Unrelated Regression Estimation SURE

Now that the specifications of the different equations are established, the issue to be addressed becomes the possible presence of correlations across equations. A first indicator is provided by the dependent variables themselves. Table 3a does indicate positive correlations in the Swiss data as expected. For instance, the cost changes of *Run of river* and *Storage hydro* exhibit a positive correlation coefficient of 0.72 regardless of whether the changes of private cost or full social costs are considered (suffix "_h" indicates high costs; "_l" stands for low costs). Table 4a (U.S. data) displays both negative and positive correlations. Positive and high correlation coefficients can be found between *Coal* and *Gas* equal to 0.71 in the private cost case, 0.54 to 0.61 depending on external costs considered). Negative and strong correlations are evident for *Nuclear* and *Coal*. Here again, the correlation in the private cost case is stronger (-0.46) than in the total cost scenarios (-0.24 and –0.35, respectively).

[8] That includes variables without external costs and variables with high and low external costs respectively.
[9] Remember that variables are measured with and without external costs
[10] Two lags in the high cost scenario, as *R*-sq results with two lags are higher than three lags in SURE

However, for estimation purposes it is not the correlations between dependent variables but between residuals $\hat{\varepsilon}_{i,t}$ that are relevant. As evidenced by Tables 3b and 4b, the correlation coefficients do drop somewhat (mainly because common time trends account for some of the correlations). For example, the residuals of Swiss *Storage hydro* and *Run of river* now exhibit correlation coefficients between 0.46 and 0.47 (rather than 0.72), depending of whether externality surcharges are included or not. In the case of U.S., *Coal* and *Gas* correlation coefficients range between 0.4 and 0.54. High correlation coefficients of this magnitude should be accounted for in estimation, and SURE is one way to do this.

	Nuclear	Run of river	Storage hydro	Solar
Nuclear	1			
Run of river	0.2532	1		
St. hydro	0.2703	0.7220	1	
Solar	0.0794	0.1726	0.4689	1

	Nuclear_h	Run of river_h	Storage Hydro-h	Solar_h
Nuclear_h	1			
Run of river_h	0.2532	1		
St. Hydro_h	0.2703	0.7220	1	
Solar_h	0.0794	0.1726	0.4689	1

	Nuclear_l	Run of river_l	Storage Hydro_l	Solar_l
Nuclear_l	1			
Run of river_l	0.2532	1		
St. Hydro_l	0.2703	0.7220	1	
Solar_l	0.0794	0.1726	0.4689	1

Table 3a Partial correlation coefficients of Swiss generation cost changes; no external costs, high and low external cost scenarios (1986/1993-2003)

	Nuclear	Run of river	Storage hydro	Solar
Nuclear	1	-0.0639	-0.1990	0.3996
Run of river	-0.0639	1	0.4622	-0.4486
St. hydro	-0.1990	0.4622	1	0.2232
Solar	0.3996	-0.4486	0.2232	1

	Nuclear_h	Run of river_h	Storage Hydro-h	Solar_h
Nuclear_h	1	-0.1588	-0.2713	0.4096
Run of river_h	-0.1588	1	0.4748	-0.4462
St. Hydro_h	-0.2713	0.4748	1	0.2123
Solar_h	0.4096	-0.4462	0.2123	1

	Nuclear_l	Run of river_l	Storage Hydro_l	Solar_l
Nuclear_l	1	-0.0639	-0.1990	0.3999
Run of river_l	-0.0639	1	0.4622	-0.4484
St. Hydro_l	-0.1990	0.4622	1	0.2229
Solar_l	0.3999	-0.4484	0.2229	1

Table 3b Partial correlation coefficients of the residuals of Swiss generation cost changes; no external costs, high and low external cost scenarios (1986/1993-2003)

	Oil	Gas	Nuclear	Wind	Coal
Oil	1	-0.0995	0.5518	0.1200	-0.3031
Gas	-0.0995	1	-0.0989	0.0662	0.7057
Nucl	0.5518	-0.0989	1	0.0962	-0.4575
Wind	0.1200	0.0662	0.0962	1	-0.3340
Coal	-0.3031	0.7057	-0.4575	-0.3340	1
	Oil_h	**Gas_h**	**Nuclear_h**	**Wind_h**	**Coal_h**
Oil_h	1	-0.1913	0.4256	-0.1690	-0.3783
Gas_h	-0.1913	1	-0.0071	0.1379	0.5420
Nucl_h	0.4256	-0.0071	1	-0.2395	-0.2373
Wind_h	-0.1690	0.1379	-0.2395	1	-0.4477
Coal_h	-0.3783	0.5420	-0.2373	-0.4477	1
	Oil_l	**Gas_l**	**Nuclear_l**	**Wind_l**	**Coal_l**
Oil_l	1	-0.2499	0.4890	-0.0718	-0.3945
Gas_l	-0.2499	1	-0.0480	-0.0226	0.6098
Nucl_l	0.4890	-0.0480	1	-0.2206	-0.3465
Wind_l	-0.0718	-0.0226	-0.2206	1	-0.4792
Coal_l	-0.3945	0.6098	-0.3465	-0.4792	1

Table 4a Partial correlation coefficients of US generation cost changes; no external costs, high and low external cost scenarios (1986/1993-2003)

	Oil	Gas	Nuclear	Wind	Coal
Oil	1	-0.0241	0.4260	0.0749	-0.2693
Gas	-0.0241	1	-0.0747	0.0223	0.5446
Nucl	0.4260	-0.0747	1	0.0568	-0.3891
Wind	0.0749	0.0223	0.0568	1	-0.2865
Coal	-0.2693	0.5446	-0.3891	-0.2865	1
	Oil_h	**Gas_h**	**Nuclear_h**	**Wind_h**	**Coal_h**
Oil_h	1	-0.0712	0.3795	-0.0979	-0.3410
Gas_h	-0.0712	1	-0.0098	0.0665	0.3986
Nucl_h	0.3795	-0.0098	1	-0.2757	-0.2105
Wind_h	-0.0979	0.0665	-0.2757	1	-0.3819
Coal_h	-0.3410	0.3986	-0.2105	-0.3819	1
	Oil_l	**Gas_l**	**Nuclear_l**	**Wind_l**	**Coal_l**
Oil_l	1	-0.1060	0.4001	-0.0596	-0.3176
Gas_l	-0.1060	1	-0.0362	0.0004	0.4250
Nucl_l	0.4001	-0.0362	1	-0.2757	-0.2704
Wind_l	-0.0596	0.0004	-0.2757	1	-0.3889
Coal_l	-0.3176	0.4250	-0.2704	-0.3889	1

Table 4b Partial correlation coefficients of the residuals of Swiss generation cost changes; no external costs, high and low external cost scenarios (1986/1993-2003)

Turning therefore to the SURE results for Switzerland (Table 5), one may first note that on average, real costs of *Solar* and *Nuclear* have been decreasing much faster than the real costs of *Run of river* and *Storage hydro* (R), in the case of *Solar* even significantly so (small standard deviation, column labelled "St.D."). However, this does not translate into negative values of b_0, with the exception of *Solar*. Rather, it is the coefficient of *trend* that is large and significant for *Nuclear*, *Run of river* and *Storage hydro*, indicating a tendency for cost decreases to even accelerate. As mentioned above, four lags are significant in the case of *Nuclear*. They are all negative, indicating that a cost hike in $Nuclear_{t-4}$ is evened out in the course of four years, with the maximum adjustment occurring in the year the shock occurs (*t*-4).

Throughout, taking account of external costs does not substantially change expected (negative) returns (R), risks (St.D.), or estimation results. Values of R^2 (R-sq) are comfortably high, ranging for *Nuclear*, *Run of river* and *Solar* between 0.51 and 0.78 implying that the dependent variables are well explained. Although *Storage hydro* has lower R^2 values (ranging between 0.22 and 0.23, depending on the scenario considered), the coefficients are intuitive. The negative value of R in the high cost scenario indicates an average cost decrease of 1 percent p.a. On the whole, the SURE results are quite satisfactory.

	R	St.D.	b_0	b_1	b_2	b_3	b_4	*trend*	Obs	R-sq
Nuclear	-5.28	15.11	13.04***	-0.82***	-0.96***	-1.34***	-1.37***	-2.70***	9	0.78
Nuclear high	-4.74	12.11	4.23	-0.74***	-0.93***	-1.22***	-1.38***	-1.81***	9	0.74
Nuclear low	-5.28	15.11	13.04***	-0.82***	-0.96***	-1.34***	-1.37***	-2.70***	9	0.78
Run of river	-0.04	18.69	32.25	-0.67***	-	-	-	-1.95	9	0.51
Run of river high	-0.04	18.77	32.72	-0.70***	-	-	-	-1.98	9	0.51
Run of river low	-0.04	18.70	32.25	-0.67***	-	-	-	-1.95	9	0.51
Storage hydro	-0.69	14.93	27.95	-0.69***	-	-	-	-1.91	9	0.23
Storage hydro high	-1.00	12.65	24.71	-0.72***	-	-	-	-1.73	9	0.22
Storage hydro low	-0.69	14.93	27.95	-0.69***	-	-	-	-1.91	9	0.23
Solar	-7.01	0.77	-33.32***	-0.70***	-0.55**	-0.62*	-0.54**	0.64***	9	0.62
Solar high	-6.95	0.76	-33.00***	-0.73***	-0.56**	-0.61*	-0.55**	0.66***	9	0.63
Solar low	-7.01	0.77	-33.31***	-0.70***	-0.55**	-0.62*	-0.54**	0.64***	9	0.62

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 1 percent level

$$\mathrm{R} = \mathrm{XB} + \varepsilon, \quad \varepsilon\varepsilon' = \Omega \text{ (Covariance matrix of residuals)}$$

$$\textit{Example}: \Delta Storage\_hydro_t = b_0 const + b_1 \Delta Storage\_hydro_{t-1} + b_2 trend + u_t$$

Table 5 Results of SURE regression, Switzerland (1985/1992-2003)

The SURE results for the U.S. data set are presented in Table 6. First, note that (just as in the Swiss case) all values in Column “R” are negative, indicating that real generation costs of all technologies decreased over time. Real private cost of *Wind* exhibit the most dramatic fall (-12.28 percent p.a.), however, once social costs are taken into account, the cost reduction is comparable with those characterizing *Coal*, *Nuclear* and *Oil*, all ranging between –4.44 and -5.81 percent p.a. In contrast to the Swiss data, however, all b_0 coefficients are negative, indicating an initial drop in costs that is partially neutralized by positive coefficients of the *trend* variable. Yet *trend* is significant only in the cases of *Nuclear*, *Wind* and the high cost *Gas* scenario. In the case of *Coal*, *trend* is even excluded since SURE results significantly improved. Values of R^2 are comfortably high in most cases, with the exception of *Nuclear*.

Taking correlations of error terms across equations into account through the SURE procedure proved relevant both in the case of Switzerland and the United States.

	R	St.D.	b_0	b_1	b_2	b_3	b_4	b_5	*trend*	Obs	R-sq
Oil	-4.44	14,60	-109,70***	-0.53*	-1,17***	-0,64*	-0,90**	-0,3	6,4***	17	0,60
Oil_high	-4.86	6,71	-94,19***	-0.88***	-1,24***	-1,03***	-1,14***	-0,5*	4,74***	17	0,67
Oil_low	-4.87	8,60	-105,23***	-0.82***	-1,29***	-0,97***	-1,13***	-0,5	5,53***	17	0,65
Gas	-3.24	10,10	-19,01	0.27	-0,80 ***	0,29	-	-	1,19	17	0,65
Gas_high	-3.58	8,21	-30,84***	0.05	-0,92 ***	-	-	-	1,81***	17	0,65
Gas_low	-3.46	8,45	-18,45	0.26	-0,83 ***	0,30	-	-	1,11	17	0,66
Nuclear	-4.52	5,40	-7,39***	0.38**	-	-	-	-	0,25	17	0,03
Nuclear_high	-4.47	5,06	-6,54**	0,32*	-	-	-	-	0,17	17	0,07
Nuclear_low	-4.47	5,14	-6,93**	0,35*	-	-	-	-	0,21	17	0,06
Wind	-12.28	3,90	-10,08**	0.50**	-	-	-	-	0,40**	17	0,60
Wind_high	-5.81	5,82	-3,40	0,78***	-	-	-	-	0,22*	17	0,48
Wind_low	-5.81	5,51	-4,02*	0,73***	-	-	-	-	0,25*	17	0,48
Coal	-6.83	3,05	-3,97***	0,38**	-	-	-	-	-	17	0,22
Coal_high	-5.00	1,42	-1,74**	0,59***	-	-	-	-	-	17	0,46
Coal_low	-5.44	1,95	-2,78***	0,32***	-	-	-	-	-	17	0,29

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 1 percent level

$\mathrm{R} = \mathrm{XB} + \varepsilon, \quad \varepsilon\varepsilon' = \Omega$ (Covarianc e matrix of residuals)

$Example: \Delta Nuclear_t = b_0 const + b_1 \Delta Nuclear_{t-1} + b_2 trend + u_t$

Table 6 Results of SURE regression, United States (1982-2003)

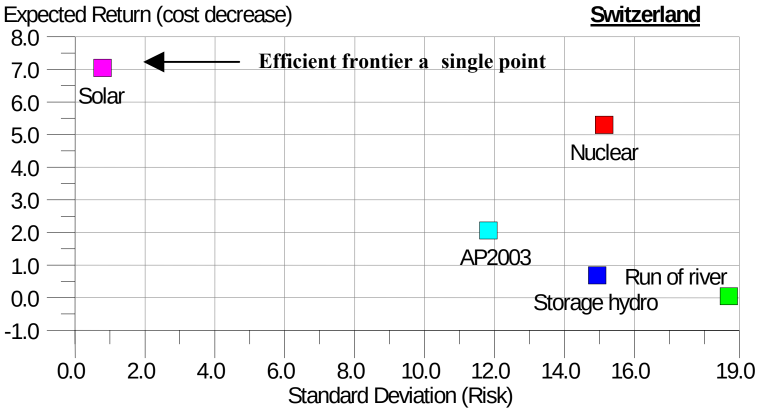
5.2 Construction of efficient electricity portfolios

In this section, theory and data are combined for the construction of efficient portfolios of electricity-generating technologies, or efficient electricity portfolios for short. The theoretical formula for this is given by eqs. (2) and (3). It calls for an estimate of expected returns ER_i for each of the technologies *i* that potentially is part of the efficient portfolio, of their standard error σ_i and their covariances σ_{ij}. Measurements of these quantities are not taken directly from the observed changes in the real cost per kWh because these estimates might be unstable due to non-stationarity.

Stationary SURE values are derived from pertinent equations, samples of which are provided at the bottom of Tables 5 and 6, respectively and which are explained in section 4. The expected rate of return of the efficient portfolio ER_p as well as the shares of the technologies entering that portfolio can be calculated for an arbitrary year *t*. In the following, only results for *t*=2003 ("current efficient portfolio") will be shown. The results are displayed as a series of frontiers.

5.2.1 Current Swiss efficient electricity portfolios (2003)

Figure 9 displays an efficiency frontier based on current (2003) Swiss data, without considering external costs. If the sole interest were to maximize expected return (thus minimizing the expected increase of electricity-generation costs), one would end up with the MER portfolio, which contains only *Solar*. If the sole interest were to minimize risk, opting for MV, then again *Solar* would be the best choice. Therefore, the efficient frontier shrinks to a single point!



Maximum Expected Return Portfolio (MER)
Max. E(Rp) = 7.01, St.D. = 0.77
100% *Solar*

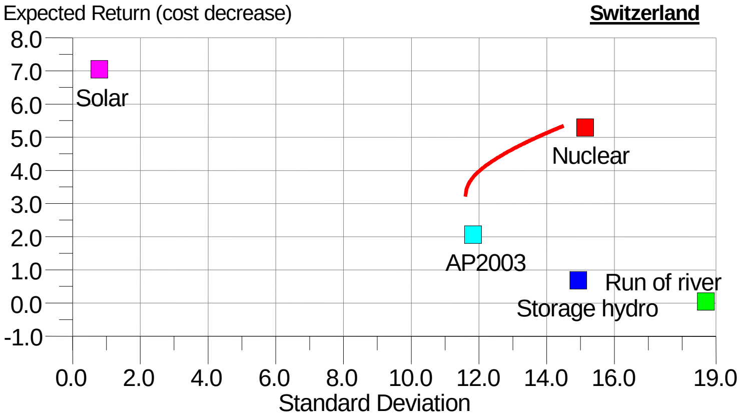
Minimum Variance Portfolio (MV)
E(Rp) = 7.01, Min St.D. = 0.77
100% *Solar*

Actual Portfolio 2003 (AP2003)
Return = 2.06, St.D. = 11.83
40% *Nuclear*
24% *Run of river*
32% *Storage hydro*
4% *Solar*

Figure 9 Swiss Efficient Electricity Portfolio
(2003, SURE-based, no constraint, without external costs)

However, a technology mix that only contains *Solar* in 2003 is unrealistic because it would not have been technologically feasible. Figure 10 offers a solution by constraining *Run of river*, *Storage hydro* and *Solar* (which for simplicity also includes all other renewables used in power generation) not to exceed their current 2003 weights in the generating portfolio, allowing only *Nuclear* to be unconstrained. This can be justified by noting that *Run of river* and *Storage hydro* are already being fully utilized while a share of *Solar* electricity of 4 percent is at the limit of what could have been achieved. In terms of MER, a shift towards *Nuclear* (96 percent) and *Solar* (4 percent) and therefore away from *Storage hydro* and *Run of river* would be efficient. If the sole interest were to minimize risk (MV), a more diversified mix would be advisable, with the largest shares for *Nuclear* (51 percent), *Storage hydro* (32 percent) and *Run of river* (13 percent) and (due to the constraints imposed) a smaller share for *Solar* (4 percent).

In all, Frontier 10 suggests that even if constraints that hold at present are respected, Swiss power generation could be made considerably more efficient by allowing the share of *Nuclear* to increase and the share of *Run of river* to decrease (from a current 24 percent in 2003 down to 13 percent).



Constraints imposed (maximum shares):
Run of river ≤ 24%, *Storage hydro* ≤ 32% & *Solar* ≤ 4%

Maximum Expected Return Portfolio (MER)
Max. E(Rp) = 5.35, St.D. = 14.51
96% *Nuclear*
4% *Solar*

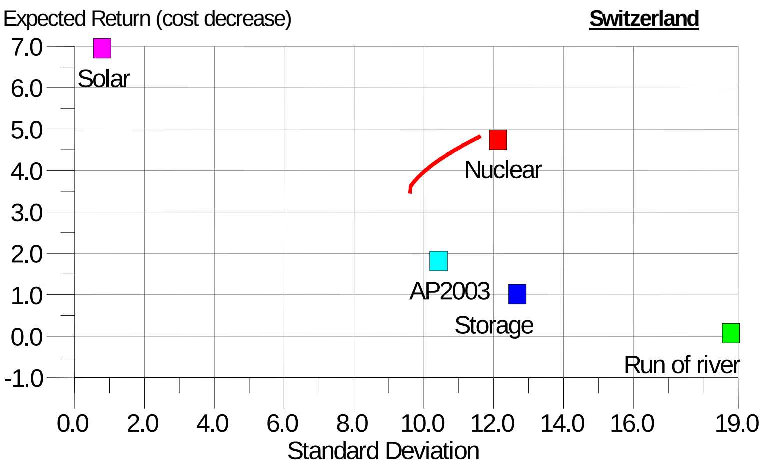
Minimum Variance Portfolio (MV)
E(Rp) = 3.21, Min St.D. = 11.60
51% *Nuclear*
32% *Storage hydro*
13% *Run of river*
4% *Solar*

Actual Portfolio 2003 (AP2003)
Return = 2.06, St.D. = 11.83
40% *Nuclear*
24% *Run of river*
32% *Storage hydro*
4% *Solar*

Figure 10 Swiss Efficient Electricity Portfolios
(2003, SURE-based, with constraint, without external costs)

The cost decrease would have been accelerated accordingly, from about 2.06 p.a. to 5.35 percent (MER) and 3.21 percent (MV). At the same time volatility could have been reduced from a standard error of real cost changes amounting to 11.83 to 11.60 percent (MV portfolio) but would have increased to 14.51 percentage in the MRP portfolio.

However, it might be argued that the preponderance of *Nuclear* in the efficient frontier of 2003 is due to neglecting external costs. In order to test this hypothesis, Figure 11 displays an efficiency frontier that is calculated using externality-adjusted cost data; in terms of restrictions imposed, it is comparable to Figure 10. Results for the MER portfolio change back to 96 percent *Nuclear* and 4 percent *Solar*. However, the MV alternative is much more diversified, with 60 percent *Nuclear* (up from 51 percent) and 4 percent *Run of river* (down from 13 percent) and the remaining shares unchanged. Therefore, the high share of *Nuclear* is even enhanced when external costs are taken into account.



Constraints imposed (maximum shares):
Run of river ≤ 24%, *Storage hydro* ≤ 32% & *Solar* ≤ 4%

Maximum Expected Return Portfolio (MER)
Max. E(Rp) = 4.83, St.D. = 11.63
96% *Nuclear*
4% *Solar*

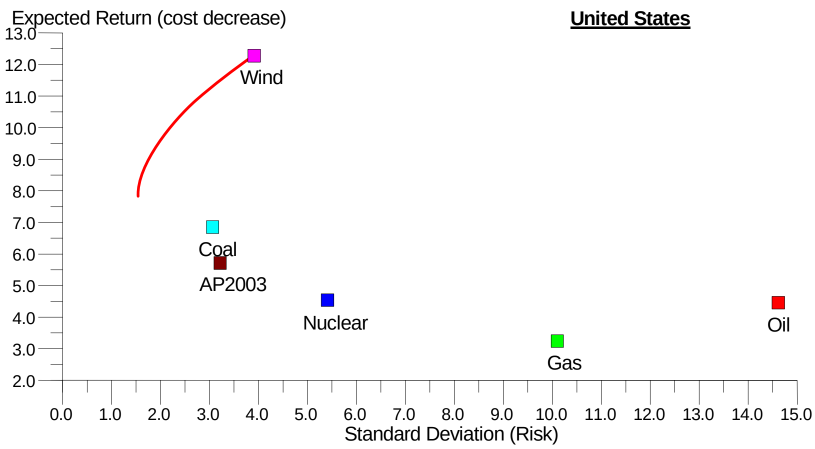
Minimum Variance Portfolio (MV)
E(Rp) = 3.45, Min St.D. = 9.60
60% *Nuclear*
32% *Storage hydro*
4% *Run of river*
4% *Solar*

Actual Portfolio 2003 (AP2003)
Return = 1.82, St.D. = 10.41
40% *Nuclear*
24% *Run of river*
32% *Storage hydro*
4% *Solar*

Figure 11 Swiss Efficient Electricity Portfolios
(2003, SURE-based, with constraint, with high external costs)

5.2.2 Current U.S. efficient electricity portfolios (2003)

Figure 12 displays the U.S. predicted efficient electricity portfolios for 2003 without external costs. Here, it is *Wind* rather than *Nuclear* (as in Switzerland) that is dominant (with 100 percent) in the MER portfolio. The transition to MER would have afforded a substantial cost reduction of 12.28 percent p.a. (up from 5.73 percent), while the MV alternative would have achieved a reduction of 7.83 percent p.a. Volatility is low throughout. While the MER portfolio would have increased to 3.90 percent p.a., the MV alternative (with 27 percent share of *Wind*, up from 2 percent in the actual portfolio) would have reduced it to a mere 1.54 percent. At this point, it already becomes clear that in both countries, renewables (*Solar* in Switzerland and *Wind* in the United States) play a very dominant role in the unconstrained MER portfolio.



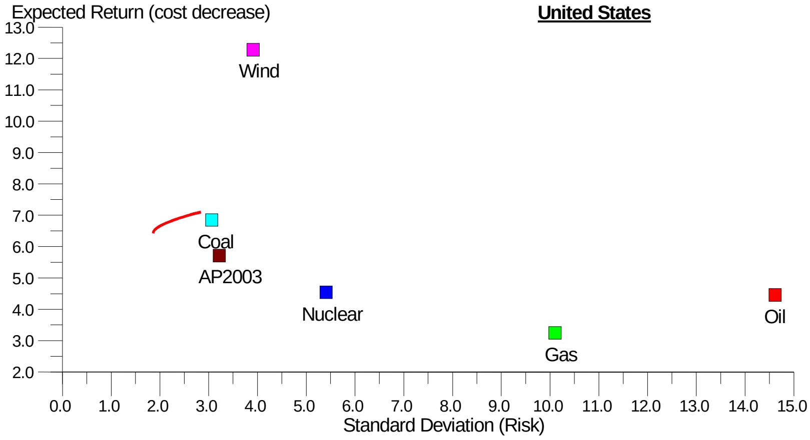
Maximum Expected Return Portfolio (MER)
Max. E(Rp) = 12.28, St.D. = 3.90
100% *Wind*

Minimum Variance Portfolio (MV)
E(Rp) = 7.83, Min St.D. = 1.54
53% *Coal*
27% *Wind*
20% *Nuclear*

Actual Portfolio 2003 (AP2003)
Return = 5.73, St.D. = 3.20
56% *Coal*
21% *Nuclear*
18% *Gas*
3% *Oil*
2% *Wind*

Figure 12 U.S. Efficient Electricity Portfolio
(2003, SURE-based, no constraint, without external costs)

However, a share of *Wind* amounting to 27 percent must be deemed unrealistic for the United States. Accordingly, a maximum admissible share of 5 percent of *Wind* power is imposed in Figure 13. In the MER portfolio, the generation mix reminds one of the constrained Swiss case in that one technology becomes entirely dominant, with 95 percent *Coal* (96 percent *Nuclear* in Switzerland, see Figure 10). This would permit accelerating the cost decrease from 5.73 percent to 7.10 percent p.a., while volatility would have been reduced from 3.20 percent to 2.84 percent. In the MV alternative, the highest share is allocated to *Coal* (66 percent, up from 56 percent in the actual portfolio), followed by *Nuclear* (29 percent, up from 21 percent) and *Wind* (5 percent). This would serve to increase the cost reduction from 5.73 percent to 6.42 percent p.a., and volatility would be reduced from 3.20 percent to a low 1.86 percent p.a. Therefore U.S. power generation could be made more efficient by allowing the share of *Coal* and *Nuclear* to increase. Both the MER and MV portfolios would have been more attractive to investors than the actual portfolio.



Constraints imposed (maximum shares):
Wind ≤ 5%

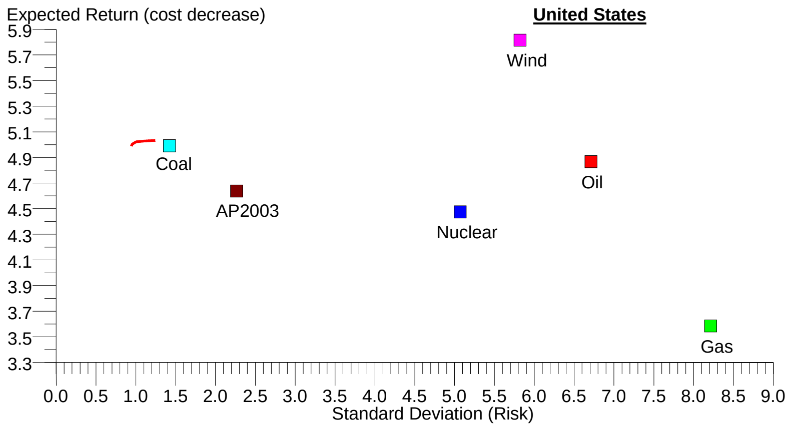
Maximum Expected Return Portfolio (MER)
Max. E(Rp) = 7.10, St.D. = 2.84
95% *Coal*
5% *Wind*

Minimum Variance Portfolio (MV)
E(Rp) = 6.42, Min St.D. = 1.86
66% *Coal*
29% *Nuclear*
5% *Wind*

Actual Portfolio 2003 (AP2003)
Return = 5.73, St.D. = 3.20
56% *Coal*
21% *Nuclear*
18% *Gas*
3% *Oil*
2% *Wind*

Figure 13 U.S. Efficient Electricity Portfolios
(2003, SURE-based, with constraint, without external costs)

In analogy to the Swiss case, (high) external costs are taken into account, in the construction of the efficient frontier shown in Figure 14.



Constraints imposed (maximum shares):
Wind ≤ 5%

Maximum Expected Return Portfolio (MER)
Max. E(Rp) = 5.03, St.D. = 1.24
95% *Coal*
5% *Wind*

Minimum Variance Portfolio (MV)
E(Rp) = 4.99, Min St.D. = 0.94
81% *Coal*
7% *Oil*
7% *Nuclear*
5% *Wind*

Actual Portfolio 2003 (AP2003)
Return = 4.64, St.D. = 2.26
56% *Coal*
21% *Nuclear*
18% *Gas*
3% *Oil*
2% *Wind*

Figure 14 U.S. Efficient Electricity Portfolios
(2003, SURE-based, with constraint, with high external costs)

The MER portfolio has an average real cost reduction of 5.03 percent p.a., down from 7.10 percent without external costs (see Figure 13), suggesting that external costs are increasing at a higher pace in the United States than in Switzerland (where accounting for them lowers the cost reduction from 5.35 to 4.83 percent p.a. only, see figure 10 and 11). On the other hand, externalities are not volatile; the standard deviation of returns falling from 2.84 percent in Figure 13 to 1.24 percent here. Opting for the MV rather than the MER portfolio would not have made much of a difference, with the mean cost decrease still 4.99 percent p.a. and only 24% less volatility. However, adjustment for external cost leaves the MER unchanged, the MV portfolio shifts back *Coal* (81 rather than 66 percent in Figure 13) and *Oil* (7 rather than 0 percent). This seems puzzling at first sight but can be explained by recalling that changes rather than levels of cost matter from an investor's point of view. If external costs of fossil fuels are high but increase slowly, they even serve to enhance the diversification properties of especially *Coal* (which has a share of 53 percent in the MV portfolio without external costs, see Figure 12 again).

With no constraints imposed, *Wind* continues to dominate with 100 percent in the MER alternative; with *Wind* constrained to 5 percent, that role is taken by *Coal* with 95 percent regardless of whether high external costs are taken into account or not.

To summarize briefly, in the unconstrained portfolio without external costs the MER portfolio is 100 percent *Wind*. The MV portfolio is more diversified, with the largest share going to *Coal* (53 percent). *Gas* does not play any role regardless of what portfolio and scenario is considered.

Finally, the two countries may be compared as well. Starting with no constraints imposed on private costs only (Figure 9 and 12), Switzerland could have substantially lowered volatility by adopting either the MER or the MV portfolio by 2003 since the standard deviation of cost changes would have been 0.77 percent rather than 11.83 percent. For the United States, the volatility reduction would have been much less, viz. no more than 1.54 percentage points. On the other hand, by adopting the MER portfolio, it could have achieved an average cost reduction of 12.28 rather than 5.73 percent p.a. However, both countries would have had to completely change the composition of their portfolios, 100 percent *Solar* (Switzerland) and 100 percent *Wind* (United States), respectively,

Since such a revolutionary outcome is deemed unrealistic, constraints (4 percent *Solar*, 5 percent *Wind*) are imposed in Figure 10 and 13. This causes the diversification advantage of MER and especially MV portfolios to disappear completely in both countries. However, the drop in the rate of return occurs in Switzerland only (4 percentage points). Finally, according for (high) external costs (Figures 11 and 14) does not affect Swiss performance much while it does slow the cost decrease of U.S. power production by about 2 percentage points p.a. (volatility is little changed). On the whole, it appears that Switzerland would have stood to gain a lot in terms of risk reduction by adopting an investor's viewpoint early, which would have permitted to come closer to the all-*Solar* production technology suggested both by the MER and MV portfolios for 2003. The United States would also have gained by moving towards an all-*Wind* technology by 2003, which would have permitted the average cost decrease of power to be almost doubled (from roughly 6 to 12 percent p.a.).

6 Conclusions

The objective of this study was to determine current (2003) efficient frontiers for Swiss and U.S. power generation, using portfolio optimization methods. The observation period covers 1986 to 2003 (Switzerland) and 1982 to 2003 (United States), respectively. For estimating the covariance matrix of returns, the cost change data were tested for stationarity first. Because the error terms were correlated across equations, seemingly unrelated regression estimation (SURE) was adopted for estimating the covariance matrix.

With variances and covariances of cost changes purged from idiosyncratic shocks that would result in instability, the efficient portfolio frontiers could be constructed. Interestingly, both the Swiss and U.S. maximum expected return portfolios contain one renewable energy source exclusively (*Solar* in Switzerland and *Wind* in the United States). However, as soon as feasibility constraints limiting changes from the status quo are imposed, the maximum expected return portfolio for Switzerland should contain 96 percent *Nuclear* and for the United States, 95 percent *Coal*.

One could argue that for a population as risk-averse as the Swiss, the minimum variance portfolio is appropriate. Under this standard and with a "realistic" maximum share of *Solar* amounting to 4 percent, *Nuclear* still accounts for 51 percent (neglecting external costs) and 60 percent, respectively (high external costs) of the 2003 efficient portfolio. If one compares these efficient portfolios with the actual 2003 counterpart, one is led to conclude that the current Swiss mix of technologies is clearly inefficient. A move towards *Nuclear* and away from *Run of river* electricity seems to be advisable in terms of reducing risk and maximizing expected returns. For the United States, a similar discrepancy emerges in terms of *Coal* and *Gas* generated electricity. With a "realistic" 5 percent limit on the share of *Wind* power, *Coal* accounts for 66 percent in the minimum variance portfolio (neglecting external costs) or 81 percent (high external costs). Interestingly, *Gas* does not show up in any efficient portfolio. The reason is that gas prices not only are highly volatile but also largely move parallel to those of other fuel, depriving them from any diversification effect. In turn *Coal*-generated electricity became cleaner, causing (initially high) external costs to fall, and making *Coal* very attractive from an investor's point of view.

In contrast to Switzerland, *Nuclear* should have played only a minor role in the U.S. generation portfolio by 2003. *Nuclear* optimally never exceeds its actual 21 percent share, even when external costs are taken into account, with the only exception of the constrained private cost scenario where *Nuclear* exceeded its current share (29 percent). Currently (2003), the United States are more efficient in generating electricity than Switzerland, which could do a lot better by relying more on *Nuclear*. The United States thus may reap an efficiency gain by investing in more *Coal* and staying away from *Gas*. While these results need to be subjected to a sensitivity analysis at a later stage, they do offer new insights concerning the efficient mix of power-generating technologies in two very diverse countries.

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