Efficient Electricity Portfolios for the United States and Switzerland

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ABSTRACT: This study applies financial portfolio theory to determine efficient electricity-generating technology mixes for the United States and Switzerland. Expected returns are given by the (negative of the) rate of increase of power generation cost, their volatility by its standard deviation. The portfolio contains *Coal*, *Nuclear*, *Gas*, *Oil*, and *Wind* in the case of the United States, and *Nuclear*, *Run of river*, *Storage hydro* and *Solar* in the case of Switzerland. Since shocks in generation costs are found to be correlated, we use seemingly unrelated regression estimation (SURE) 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 the United States contains *Coal* and *Wind* generated electricity. By way of contrast, the minimum variance (MV) portfolio combines *Coal*, *Nuclear*, *Oil* and *Wind* but not *Gas*. In Switzerland, the 2003 MER portfolio would call for a shift towards *Nuclear* and *Solar*, away from *Run of river* and *Storage hydro*, while the MV alternative mainly contains *Nuclear* power and *Storage hydro*.

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

JEL: C32, G11, Q49.

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1 Introduction

Like most industrial countries, the United States and Switzerland face great challenges in the provision of energy arising from increased demand by emerging economies and dwindling domestic resources. The experiences of California in 2001 and Italy in 2003 demonstrate the high costs of power shortages to the economy. 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, NEPG, 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 over 2000, and more than 40 percent given a surge in demand of 30 percent (Gantner, 2000).

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 technologies should also contribute to the diversification of energy supply. Investors (the government, municipalities, private and public utilities) need to know whether the current mix of power-generating technologies in the United States and Switzerland is efficient from an investor’s point of view. Can U.S. and Swiss investors do better by modifying the current electricity mix? If so, what are the attractive technologies from an investor’s point of view?

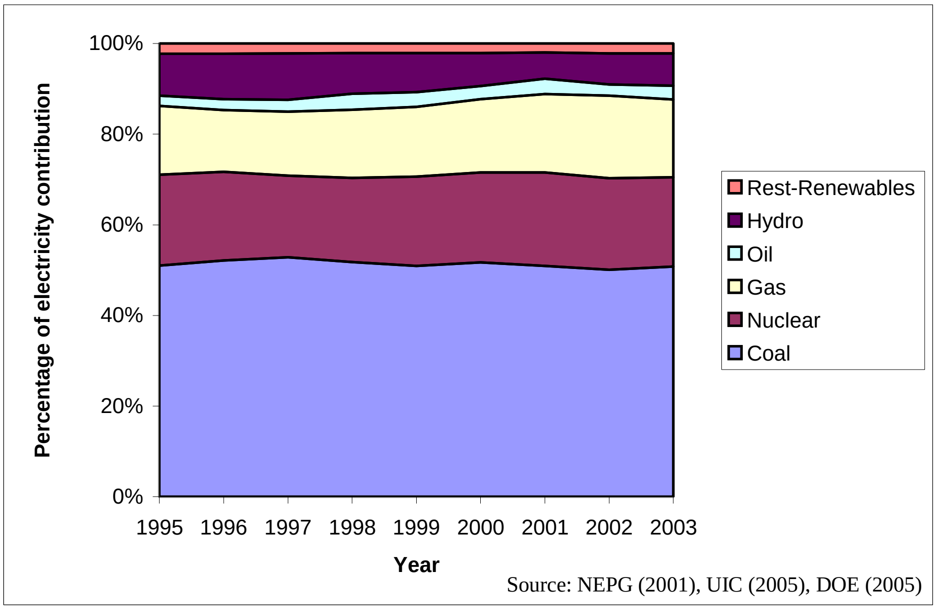
Financial investors take great interest in reducing their exposure to the ups and downs of the market by holding a diversified portfolio of securities. By taking into account the variances (standard deviations), covariances, and expected returns between assets, Markowitz (1952) constructed the set of 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 the United States and Switzerland, 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 while the definition of volatility remains the same.

Indeed, the objectives of the U.S. National Energy Policy Group (NEPG) support the asset-liability management approach to energy advocated here. They are “to promote dependable, affordable and environmentally sound production and distribution of energy for the future” (NEPG, 2001). The objectives of Swiss energy policy as laid down in section 6, art. 89 octies of the constitution are to provide energy that should be i) sufficient, ii) diversified, iii) secure, vi) economical, and v) environmentally compatible. “Dependable” energy is available in sufficient quality, diversified, and secure, “affordable” energy, if its provision is economical. Compatibility with the environment can be achieved by including external cost in price (which will be done in this study).

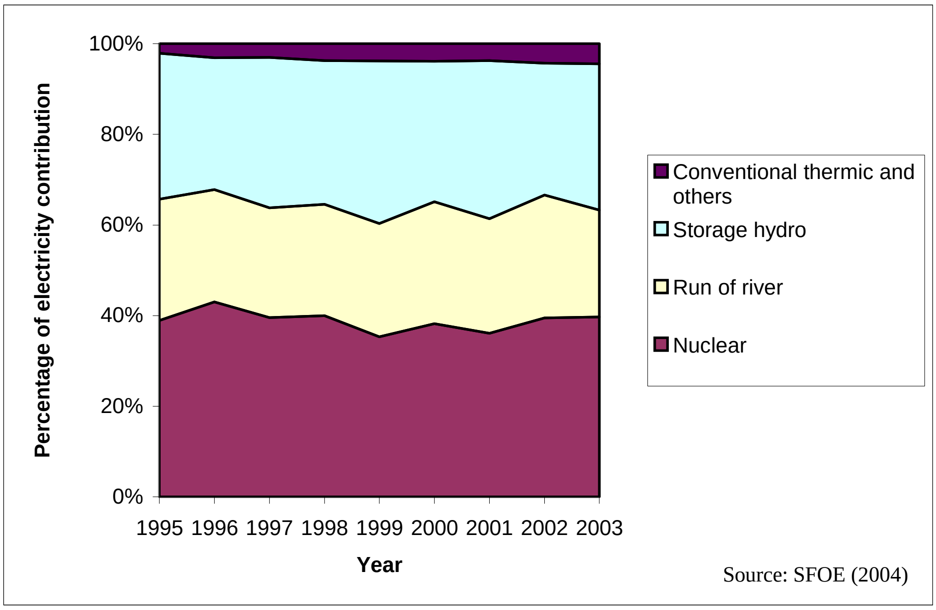
Finally, a comparison between the United States and Switzerland is of interest for several reasons. First, in spite of the difference in size (the U.S. population is almost 40 times bigger that the Swiss), both countries heavily rely on imported fuels (gas and nuclear respectively) for their power generation. Moreover, primary energy sources can be purchased at market prices in both countries. On the other hand, there are differences in their input mixes, giving rise to the question whether they reflect efficiency in investment. Specifically, about 17 percent of the total U.S. electricity mix was gas in 2003 at present Switzerland has no gas-fuelled power plants at all (see Figures 1 and 2).



Source: NEPG (2001), UIC (2005), DOE (2005)

Figure 1 U.S. mix of power generation, 1995 – 2003

Investment prospects seem to differ, too. Whereas about 90 percent of all new U.S. capacity for power will be fuelled by natural gas (NEPG, 2001), in Switzerland gas (much of which comes from Russia) is only slowly being considered as an alternative to nuclear power and electricity imports.



Source: SFOE (2004)

Figure 2 Swiss mix of power generation, 1995 – 2003

Indeed, Russian state-owned Gazprom raised the specter of gauching and squeezing, a behavior 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 portfolio approach, which has been applied to energy sources of the United States and the European Union. Using Markowitz theory, U.S. and Swiss efficient electricity production frontiers are specified in section 3. However, these frontiers crucially depend on estimated variances and covariances (the covariance matrix henceforth), which 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 energy portfolio optimization. In section 5

SURE-based efficient power generation frontiers are constructed for the United States and Switzerland. It will be shown that the mix of technologies importantly depends on risk aversion, i.e. whether one prefers the maximum expected return (MER) or the minimum variance (MV) portfolio. Conclusions are offered in the final section.

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 exclusively focuses 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 fluctuations. 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 in their construction of an efficient portfolio of U.S. energy sources. 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 minimum variance (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 external costs, the shift away from oil, while confirmed, now favors natural gas rather than coal. Humphreys and McClain provide 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 differing 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 easily lead to biased regression results that result in faulty predictions of future price changes. In addition, the study neglects possible correlations between shocks impinging on prices. Such correlations should be of great concern in this study since it uses data from regions in the United States, 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 Markowitz-efficient portfolios. In general, their results indicate that both existing and projected EU generating mixes are suboptimal from a risk-return perspective. The analysis further suggests that portfolios with lower cost increases and less 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, likely resulting in underestimation in the case of power generated using fossil fuels. Also, most of their 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 index, the Morgan Stanley MCSI Europe index, and treasury bills. Finally, 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 for 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 costs.

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 minimize its expected increase (or maximize its 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 $E(R_p)$ consisting of *m* risky liabilities is given by

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

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. For example, the 2003 portfolio for the United States consists of five electricity liabilities, viz. *Oil*, *Coal*, *Gas*, *Nuclear* and *Wind* (as described in section 4.2). Therefore,

$$E(R_p, US2003) = w_1E(R_1) + w_2E(R_2) + w_3E(R_3) + w_4E(R_4) + w_5E(R_5) \qquad (2)$$

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

$$\sigma_p(US2003) = \begin{pmatrix} w_1^2\sigma_1^2 + w_2^2\sigma_2^2 + w_3^2\sigma_3^2 + w_4^2\sigma_4^2 + w_5^2\sigma_5^2 + 2w_1w_2\rho_{12}\sigma_1\sigma_2 \\ + 2w_1w_3\rho_{13}\sigma_1\sigma_3 + 2w_1w_4\rho_{14}\sigma_1\sigma_4 + 2w_1w_5\rho_{15}\sigma_1\sigma_5 + 2w_2w_3\rho_{23}\sigma_2\sigma_3 \\ + 2w_2w_4\rho_{24}\sigma_2\sigma_4 + 2w_2w_5\rho_{25}\sigma_2\sigma_5 + 2w_3w_4\rho_{34}\sigma_3\sigma_4 + 2w_3w_5\rho_{35}\sigma_3\sigma_5 \\ + 2w_4w_5\rho_{45}\sigma_4\sigma_5 \end{pmatrix}^{\frac{1}{2}}, \qquad (3)$$

where $\rho_{ij} = \mathrm{cov}_{ij}/(\sigma_i\sigma_j), \quad i,j = 1,\ldots,5$, are correlation coefficients.

The 2003 portfolio for Switzerland contains four liabilities, viz. *Nuclear*, *Run of river*, *Hydro storage* and *Solar* (again as outlined in section 4.2). Equations (2) and (3) are modified accordingly. Figure 3 illustrates. In keeping with eqs. (2) and (3), $E\left(R_p\right)$ 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.

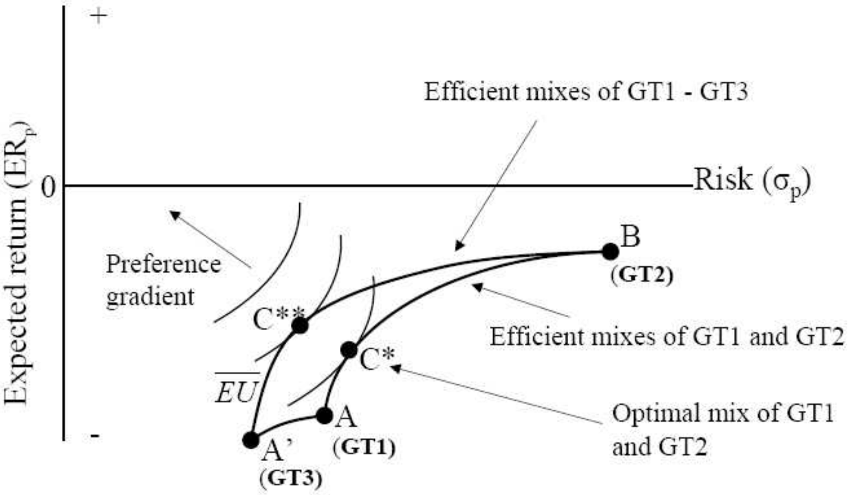


Figure 3 Efficient portfolio of generation technologies (GT)

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. 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 GT2 were to be 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 of Figure 3 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.

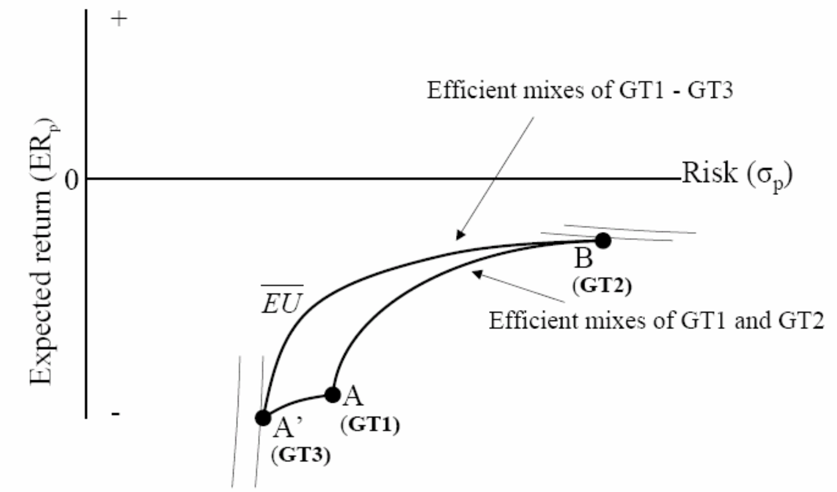


Figure 4 Optimal portfolios in two extreme cases

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 risk aversion (which is not known by policy makers nor the general population, at least 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)

In view of eq. (3), portfolio risk σ_p depends on individual standard errors σ_i and the correlations between returns 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 do not contain a systematic shift. Such residuals can be computed from the following regression,

$$R_{i,t} = \alpha_0 + \sum_{j=1}^{m} a_{i,t-j} \cdot R_{i,t-j} + u_{i,t}, \tag{4}$$

where $R_{i,t}$ is the percentage change (return) in electricity-generation cost for technology *i* in year *t*, α_0 is a constant, $\alpha_{i,t-j}$ is the coefficient of the return lagged *j* years, $R_{i,t-j}$ is the explanatory variable lagged *j* years, and $u_{i,t}$ is the error term for technology *i* in year *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 to obtain residuals $\hat{u}_{i,t}$. 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 $\alpha_{i,t-j}$, of the residuals $u_{i,t}$, and hence of the σ_i and σ_{ij} making up the covariance matrix. The pertinent econometric method is called seemingly unrelated regression estimation, or SURE for short.

The SURE model consists of *m* regression equations (*m* is the number of 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 the United States[1].

$$\begin{aligned}
R_{Oil,03} &= b_0 + x_{Oil,02}b_1 + x_{Oil,01}b_2 + x_{Oil,00}b_3 + x_{Oil,99}b_4 + x_{Oil,98}b_5 + trend_t b_6 + u_{Oil,03}\\
R_{Gas,03} &= g_0 + x_{Gas,02}g_1 + x_{Gas,01}g_2 + x_{Gas,00}g_3 + trend_t g_4 + u_{Gas,03}\\
R_{Nucl,03} &= n_0 + x_{Nucl,02}n_1 + trend_t n_2 + u_{Nucl,03}\\
R_{Wind,03} &= d_0 + x_{Wind,02}d_1 + trend_t d_2 + u_{Wind,03}\\
R_{Coal,03} &= c_0 + x_{Coal,02}c_1 + trend_t c_2 + u_{Coal,03}
\end{aligned} \tag{5}$$

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 a constant plus the cost changes of previous years and a time trend. For example, relative cost change of nuclear energy in the United States in the year 2003, $R_{Nucl,03}$, is related to a constant (n_0), the cost change in the preceding year $\mathrm{x}_{Nucl,02}$, and a time trend ($trend_t$) [see eq. (5)]. In analogy, the cost change of nuclear energy in Switzerland in the year 2003, $R_{Nucl,03}$, is related to a constant (n_0), the cost changes in the preceding years $x_{Nucl,02}$, $x_{Nucl,01}$, $x_{Nucl,00}$, $x_{Nucl,99}$, and a time trend $(trend_t)$ [cf. Table (6)].

As for $u_{i,t}$ the t_{th} element of u_i, we assume that the $(u_{1,t}, u_{2,t}, ..., u_{m,t})$ are iid, with $E(u_{i,t}) = 0$ and $E(u_{i,t}u_{j,s}) = \sigma_{ij}$ 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.

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

Written in matrix algebra, the system (5) reads,

$$\begin{bmatrix} R_{Oil,03} \\ R_{Gas,03} \\ R_{Nucl,03} \\ R_{Wind,03} \\ R_{Coal,03} \end{bmatrix} = \begin{bmatrix} X_1 & 0 & 0 & 0 & 0 \\ 0 & X_2 & 0 & 0 & 0 \\ 0 & 0 & X_3 & 0 & 0 \\ 0 & 0 & 0 & X_4 & 0 \\ 0 & 0 & 0 & 0 & X_5 \end{bmatrix} \cdot \begin{bmatrix} b_{Oil,03} \\ g_{Gas,03} \\ n_{Nucl,03} \\ d_{Wind,03} \\ c_{Coal,03} \end{bmatrix} + \begin{bmatrix} u_{Oil,03} \\ u_{Gas,03} \\ u_{Nucl,03} \\ u_{Wind,03} \\ u_{Coal,03} \end{bmatrix} \tag{6}$$

where e.g.

$X_1 = [1 \; x_{Oil,02} \;\; x_{Oil,01} \;\; x_{Oil,00} \;\; x_{Oil,99} \; x_{Oil,98} \;\; trend_t]$ and
$b_{Oil,03} = [b_0 \; b_1 \; b_2 \; b_3 \; b_4 \; b_5 \; b_5]'$,

all other variables are defined in analogy.

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 presented as a system by using **X** as the symbol of the block diagonal matrix in eq. (6),

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

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

$$\mathbf{\Omega} = E(\mathbf{uu'}) = \begin{bmatrix} \sigma_{OilOil} I & \sigma_{OilGas} I & \sigma_{OilNucl} I & \sigma_{OilWind} I & \sigma_{OilCoal} I \\ \sigma_{GasOil} I & \sigma_{GasGas} I & \sigma_{GasNucl} I & \sigma_{GasWind} I & \sigma_{GasCoal} I \\ \sigma_{NuclOil} I & \sigma_{NuclGas} I & \sigma_{NucNucl} I & \sigma_{NuclWind} I & \sigma_{NuclCoal} I \\ \sigma_{WindOil} I & \sigma_{WindGas} I & \sigma_{WindNucl} I & \sigma_{WindWind} I & \sigma_{WindCoal} I \\ \sigma_{CoalOil} I & \sigma_{CoalGas} I & \sigma_{CoalNucl} I & \sigma_{CoalWind} I & \sigma_{CoalCoal} I \end{bmatrix}. \tag{8}$$

The seemingly unrelated regression (SURE) model therefore allows to simultaneously estimate the 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 U.S. data set consists of five variables: *Oil, Gas, Nuclear*, *Coal* and *Wind* power[2], covering the years 1982 to 2003. All variables are averaged annual cost changes in U.S. cents per kWh electricity[3]. All variables are deflated by the U.S. and Swiss CPI respectively, with 2000 serving as the base year (=100). The Swiss data on *Nuclear*[4] covers the years 1986 to 2003, those on *Run of river*[5] and *Storage hydro*[6] 1993 to 2003, and *Solar*[7], 1991 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 for environmental damage caused by power generation. 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). No external cost data for the United States were available, therefore external cost data from the UK were 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. The surcharges 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. Furthermore, Swiss and UK external cost data are comparable, both being generated by the same methods.

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[2] 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 were not available for every year, values for 1983, 1985-1987, 1989-1994, 1996-1999 were generated by cubic spline interpolation.

[3] 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).

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

[5] Data source: personal correspondence

[6] Data source: personal correspondence

[7] RWE Schott Solar (2005); The average exchange rate of 2000 was used to convert Euro cents into US cents (source: U.S. Federal Reserve). 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.

While external costs related to health and global warming enter calculations, 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, estimates prepared by Hirschberg and the European Commission are used to generate a lower bound and an upper bound of social cost estimates for both countries (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 constitutes the input to the portfolio allocation model.

All U.S. generation technologies have comparable unit costs, ranging between 3 and 10 U.S. cents (busbar) in 2003. Table 1 shows *Wind* power to be amongst the cheapest sources as of 2003.

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

Three of the four generation technologies considered in the Swiss data set are comparable to the United States in terms of unit cost, being in the 1 to 4 U.S. cents/kWh (busbar) range in 2003 (see Table 2). By way of contrast, *Solar* was markedly more expensive in 1995 but experienced large cost decreases, since then.

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

However, note that 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 full analogy, an investor would want to buy into Swiss *Solar* in 1995 regardless of its initial unit cost. From an investor's point of view, Swiss *Solar* should therefore figure prominently in an efficient portfolio unless it has extremely unfavorable diversification properties.

Admittedly, utilities adopt a current user's rather than an investor's point of view, seeking to meet their current primary energy needs at minimum cost. 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 wants to answer the question, How should policy makers have started restructuring the electricity generating portfolio in the 1980s (assuming they knew the cost changes occurring until 2003) in order to arrive at the MER or the MV portfolio by 2003, depending on their risk preferences?

In keeping with the definition of returns in section 3, the historical development of percentage changes in U.S. power generation costs, are shown in Figure 5. This is the scenario with high external costs. The data cover 1982 to 2003 for *Oil*, *Coal*, *Gas*, *Wind* and *Nuclear* power. *Oil* shows large cost fluctuations throughout the observation period, due to the revolution in Iran (early 1980s) and the aftermath of 9/11. Similar cost fluctuations can be found in *Gas* pointing to its strong correlation with *Oil*. The time series for *Wind* hovers around zero, indicating fairly constant unit cost over time.

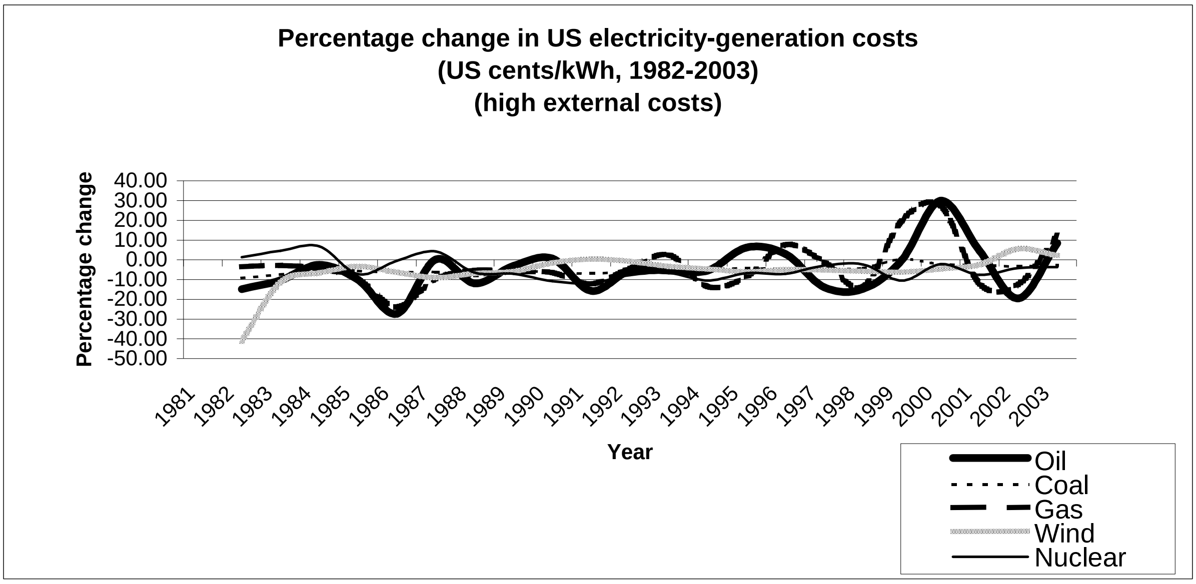

Figure 5 Percentage changes in U.S. electricity-generation costs (US cents/kWh), 1982-2003

The Swiss data cover 1986 to 2003 (*Nuclear*), 1993 to 2003 (*Run of river* and *Storage hydro*), and 1991 to 2003 (*Solar*). As can be seen from Figure 6, *Run of river* exhibits the strongest fluctuations, particularly in 1999 and 2000. The likely reason is changes in financial transactions between key *Run of river* electricity suppliers (Axpo, 2002). In contrast, changes in the generation cost of *Nuclear* deviate little from zero, pointing to stability of real cost over time.

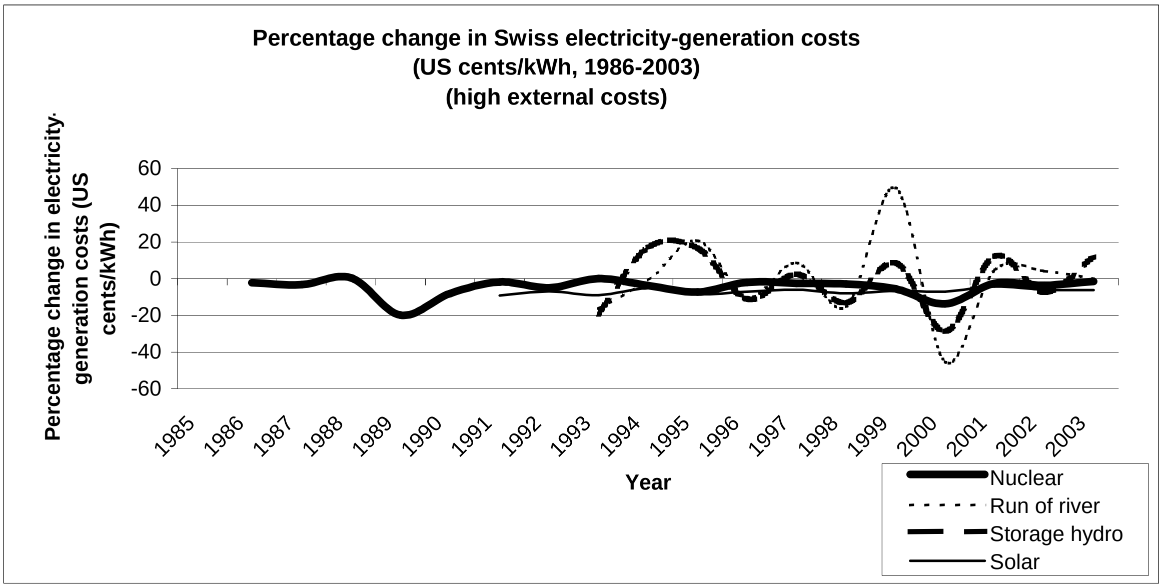

Figure 6 Percentage changes in Swiss electricity-generation costs (U.S. cents/kWh), 1986/1993-2003

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

Figure 7 displays the 2003 mix of U.S. power generation which will be used as the reference in this study, which is *Coal* 56%, *Nuclear* 21%, *Gas* 18%, and *Wind* and *Oil* with 2% and 3%, respectively.

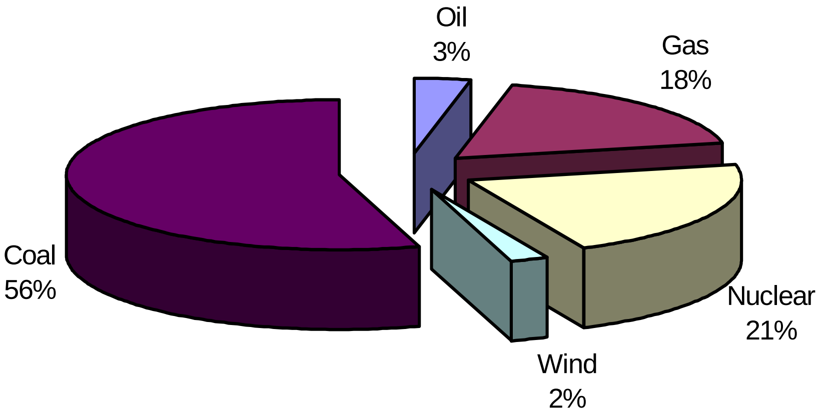

Figure 7 U.S. mix of power generation in 2003

No yearly data was available for *Hydro* generated electricity, which usually makes up around 7 percent of total electricity production (see Figure 1 in section 1). *Wind* is used as a proxy for renewables and remaining sources.

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 the total (see Figure 8). 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.

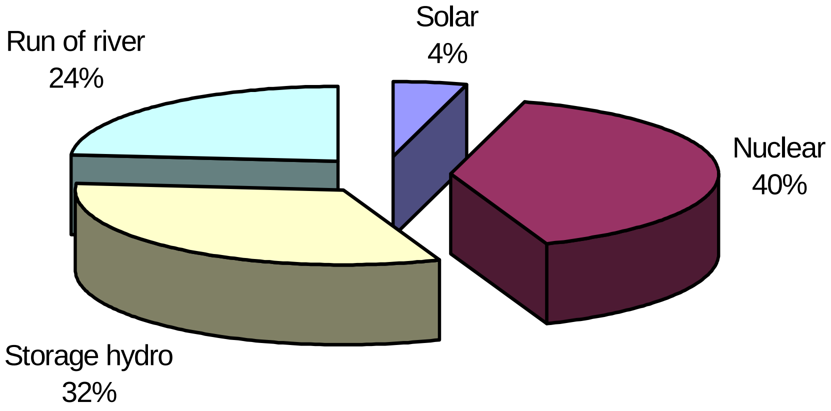

Figure 8 Swiss mix of power generation in 2003

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

5.1 Time series analysis

5.1.1 Preliminary testing

The objective is to obtain a stable estimate of the covariance matrix Ω of equation (7). In order to be able to filter out the systematic (and *trend* stable) component of the Ω, changes in generation cost must be stationary time series. Given nonstationarity, the estimate of Ω 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 U.S. and Swiss 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 U.S. data suggest five lags for all *Oil* variables[9], three lags for *Gas*[10] and one lag for *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 5).

The results for the Swiss data suggest that in the case of *Nuclear*, four lags should be applied, for *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* has even a mere 13 observations), 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). Therefore, four lags were applied here throughout since the coefficients on the autoregressive variables used in the SURE procedure are significant in most cases (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. Panel A of Table 3 does indicate some strong positive correlations in the U.S. data as expected. For instance, the cost changes of *Coal* and *Gas* exhibit a positive correlation coefficient of 0.71 in the private cost case and 0.54 to 0.61 depending on external costs considered (suffix “_h” indicates the high cost scenario; “_l” stands for the low cost scenario). Negative and strong correlations are evident for *Nuclear* and *Coal*. Here again, correlations among private cost

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[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*^2 results with two lags are higher than three lags in SURE

changes are more marked (-0.46) than for total cost changes (-0.24 and –0.35, respectively). Panel B of Table 3 shows how the $\hat{u}_t$ residuals from eq. (7) which represent unobserved shocks, are correlated. There is clear evidence of correlations across equations. For instance, the correlation coefficient between *Coal* and *Gas* is 0.5446, which (albeit not as high as the 0.7057 between the cost changes themselves) is still substantial.

In the case of Switzerland, the highest correlation coefficients are obtained for *Storage hydro* and *Run of river*. Clearly, the common unobserved shock is weather conditions, in particular the amount of precipitation. As in the case of the United States, it makes no difference whether changes of private or full social costs are considered. Generally however, correlation coefficients of this magnitude should be accounted for by SURE.

The results of SURE regression are displayed in Tables 5 and 6.

	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

Panel A: Generation cost changes

	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

Panel B: $\hat{u}_t$ residuals from eq. (7)

Table 3: Partial correlation coefficients for the U.S., no external cost, high (_h) and low (_l) external cost scenarios (1982-2003)

	Nuclear	Run of river	Storage hydro	Solar
Nuclear	1			
Run of river	0.2532	1		
Stor. 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		
Stor. 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		
Stor. Hydro_l	0.2703	0.7220	1	
Solar_l	0.0794	0.1726	0.4689	1

Panel A: Generation cost changes

	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
Stor. 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
Stor. 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
Stor. Hydro_l	-0.1990	0.4622	1	0.2229
Solar_l	0.3999	-0.4484	0.2229	1

Panel B: $\hat{u}_t$ residuals from eq. (7)

Table 4: Partial correlation coefficients for Switzerland, no external cost, high (_h) and low (_l) external cost scenarios (1986/1992-2003)

For the United States (Table 5), one may note from the column denoted $\overline{\mathbf{R}}$ that the real private cost of *Wind* exhibit a most dramatic fall (-12.28 percent p.a.); however, once social costs are taken into account, the reduction is comparable with those characterizing *Coal*, *Nuclear* and *Oil*, ranging between –4.47 and –6.83 percent p.a. The *trend* is significant only in the cases of *Oil*, *Wind* and the high cost *Gas* scenarios. Values of R^2 are comfortably high in most cases, with the exception of *Nuclear*.

The SURE results for Switzerland are presented in Table 6. On average, the real cost of *Solar* and *Nuclear* has been decreasing much faster than that of *Run of river* and *Storage hydro* (see $\overline{\mathbf{R}}$ column).

	$\overline{\mathbf{R}}$	St.D.	b_0	b_1	b_2	b_3	b_4	b_5	*trend*	Obs	R^2
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

Element of system : $\Delta Nuclear_t = n_0 const + n_1 \Delta Nuclear_{t-1} + n_2 trend_t + u_t$

$\mathrm{R} = \mathrm{XB} + u,\ \ uu' = \Omega$ (Covariance matrix of residuals)

Table 5 Results of SURE regression, United States (1982-2003)

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*, indicating a tendency for cost decreases to even accelerate. This stands in contrast to the U.S. data, where all b_0 coefficients are negative, indicating a regular drop in cost that is partially neutralized by positive coefficients of the *trend* variable.

Throughout, taking account of external costs does not substantially change expected (negative) returns ($\overline{\mathbf{R}}$), their volatility (St.D.), or estimation results. Estimated coefficients are intuitive; for example, the fact that four lags are identified in the U.S. *Oil* regression reflects the fact that price increases (which tend to magnify as suggested by the positive coefficient of the trend variable) take several years to even out (as shown by the negative estimates of b_1 through b_4). On the whole, the SURE results are quite satisfactory.

	$\bar{R}$	St.D.	b_0	b_1	b_2	b_3	b_4	*trend*	Obs	R^2
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

Element of system $: \Delta Storage\_hydro_t = b_0 + b_1 \Delta Storage\_hydro_{t-1} + b_2 trend + u_t$
$\mathrm{R} = \mathrm{XB} + u,\ uu' = \Omega$ (Covariance matrix of residuals)

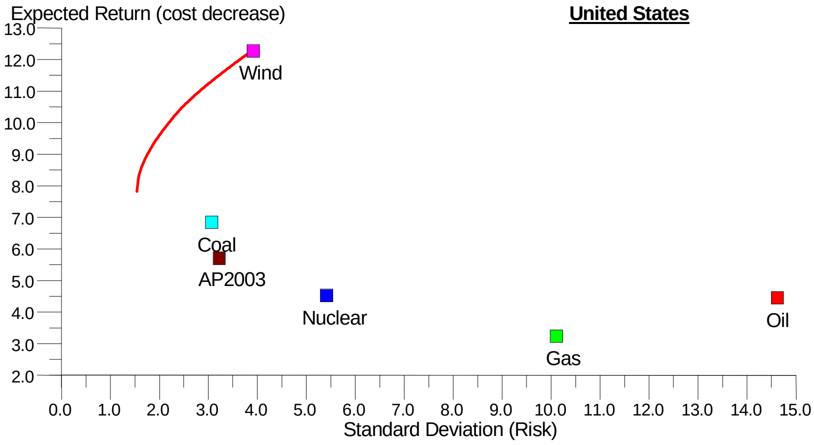
Table 6 Results of SURE regression, Switzerland (1986/1992-2003)

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 theory 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, which might be unstable due to non-stationarity but rather from the SURE results shown in Tables 5 and 6. They are the predicted values of the pertinent equations, samples of which are provided at the bottom of Tables 5 and 6, respectively and which are explained in section 4. Therefore, 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 (2003) efficient electricity portfolios for the United States

Figure 9 displays an efficiency frontier without considering external costs. If the sole interest were to maximize expected return (thus minimizing the expected increase of the generation costs of electricity), one would end up with the MER portfolio, which contains only *Wind*. If the sole interest were to minimize risk, opting for the MV portfolio, then a mix of 53 percent *Coal*, 27 percent *Wind* and 20 percent *Nuclear* would be efficient. Opting for MER would entail a substantial cost reduction of 12.28 percent p.a. (up from 5.73 percent p.a. in the actual portfolio), but accompanied by an increase in volatility from 3.20 to 3.90 percent p.a.



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*

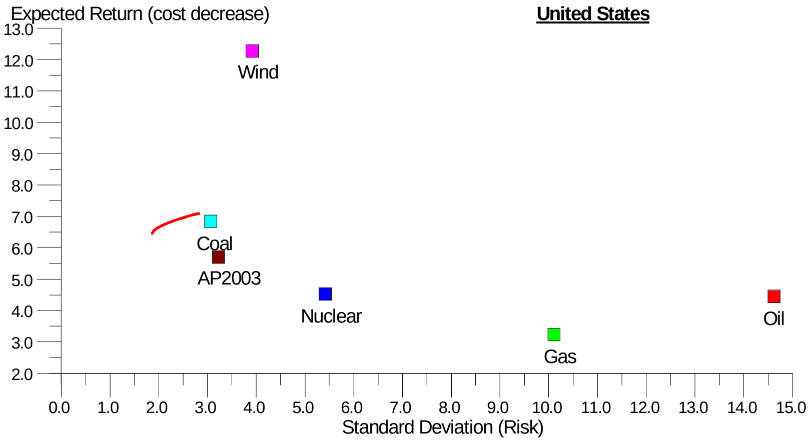
Actual Portfolio 2003 (AP2003)
Return = 5.73, St.D. = 3.20

56%	*Coal*
21%	*Nuclear*
18%	*Gas*
3%	*Oil*
2%	*Wind*

Figure 9 Efficient Electricity Portfolios for the United States
(2003, SURE-based, no constraint, without external costs)

However, a share of *Wind* amounting to 27 percent in the MV portfolio (or even 100 percent in the MER portfolio) must be deemed unrealistic for the United States; therefore, a maximum admissible share of 5 percent of *Wind* power is imposed in Figure 10 (its current share being 2 percent).

In the MER portfolio, the generation mix now contains 95 percent *Coal* and 5 percent *Wind*. This would slow the cost decrease (from 12.28 percent to 7.10 percent p.a.) while reducing volatility from 3.90 percent to 2.84 percent p.a. 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, up from 2 percent). However, the rate of cost reduction would be reduced from 5.73 percent p.a. to 6.42 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.



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

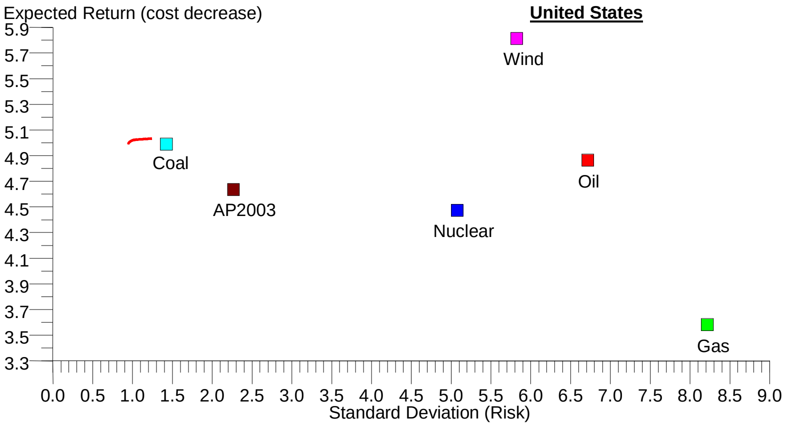
Minimum Variance Portfolio (MV)
E(Rp) = 6.42, Min St.D. = 1.86
66% *Coal*
29% *Nuclear*
5% *Wind*

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

Constraints imposed (maximum shares):
Wind ≤ 5%

Figure 10 Efficient Electricity Portfolios for the United States
(2003, SURE-based, with constraint, without external costs)

However, it might be argued that the preponderance of *Coal* in the efficient frontier of 2003 is due to neglecting external costs. In order to test this conjecture the efficiency frontier is calculated using externality-adjusted cost data (see Figure 11), with the same restriction imposed as in Figure 10. The MER portfolio continues to be 95 percent *Coal* and 5 percent *Wind*. However, the MV alternative becomes more diversified, with 81 percent *Coal* (up from 66 percent), 7 percent *Oil* (up from 0 percent), 7 percent *Nuclear* (down from 29 percent), and 5 percent *Wind* (same as before). Therefore, the high share of *Coal* is even enhanced when external costs are taken into account. 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 serve to even improve the diversification properties of *Coal*.



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

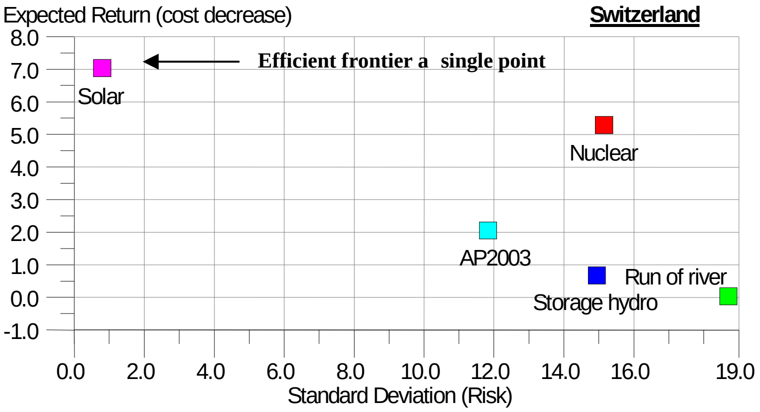
56%	*Coal*
21%	*Nuclear*
18%	*Gas*
3%	*Oil*
2%	*Wind*

Figure 11 Efficient Electricity Portfolios for the United States
(2003, SURE-based, with constraint, with high external costs)

To summarize briefly: 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 over by *Coal*, with a share of 95 percent regardless of whether (high) external costs are taken into account or not. The MV portfolio is more diversified; with no constraints imposed, the largest share goes to *Coal* (53 percent). With a constraint imposed on *Wind*, *Coal* dominates the MV portfolio with 66 to 81 percent, depending on whether the private or social cost scenario is considered. *Gas* does not play any role regardless of the portfolio and scenario chosen.

5.2.2 Current (2003) efficient electricity portfolios for Switzerland

Figure 12 displays the predicted efficient electricity portfolios (as of 2003) for Switzerland, neglecting external costs. Here, it is *Solar* rather than *Wind* (as in the United States) that dominates (with a 100 percent share) in the MER portfolio. The transition from the actual to the MER portfolio would have afforded a cost reduction of 7.01 percent p.a. (rather than 2.06 percent p.a.). Volatility would have gone down to 0.77 percent p.a. (from 11.83). Since the efficient frontier happens to shrink to a single point, the MV alternative would have used exclusively *Solar* to achieve the same reductions. At this point, it already becomes clear that in both countries renewables (*Wind* in the United States and *Solar* in Switzerland) play a very dominant role in the unconstrained MER portfolio.



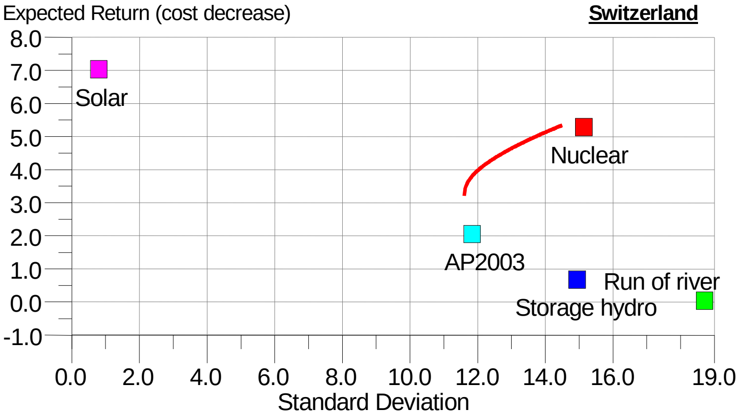
Maximum Expected Return Portfolio (MER)
Max. E(Rp) = 7.01, St.D. = 0.77
100% *Solar*

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*
32% *Storage hydro*
24% *Run of river*
4% *Solar*

Figure 12 Efficient Electricity Portfolios for Switzerland
(2003, SURE-based, no constraint, without external costs)

However, a share of *Solar* amounting to 100 percent must be deemed unrealistic for Switzerland. Therefore, the sum of *Run of river*, *Storage hydro* and *Solar* is constrained to its share in 2003, leaving *Nuclear* 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. The corresponding efficient frontier is shown in Figure 13. The MER portfolio calls for a shift towards *Nuclear* (96 percent) and *Solar* (4 percent) and therefore away from *Storage hydro* and *Run of river*.



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*
32% *Storage hydro*
24% *Run of river*
4% *Solar*

Figure 13 Efficient Electricity Portfolios for Switzerland
(2003, SURE-based, with constraints without external costs)

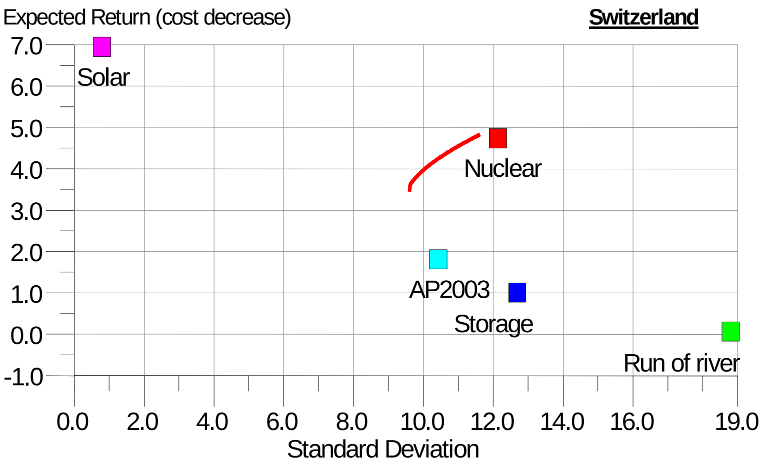
If the sole interest were to minimize risk (MV), a more diversified mix becomes optimal with the largest shares for *Nuclear* (51 percent), *Storage hydro* (32 percent) and *Run of river* (13 percent) and (due to the constraints imposed) a 4 percent share for *Solar*.

In all, Figure 13 suggests that even if constraints that likely characterize the status quo are respected, Swiss power generation could be made considerably more efficient by allowing the share of *Nuclear* to increase (from 40 percent to at least 51 percent, possibly even 96 percent) and the share of *Run of river* to decrease (from 24 percent in 2003 to 13 percent).

The cost decrease would have been accelerated accordingly, from about 2.06 percent p.a. to 5.35 percent (MER) and 3.21 percent (MV), respectively. Volatility could have been reduced a little from 11.83 to 11.60 percent (MV portfolio), or would have increased to 14.51 percent p.a. (MER portfolio).

In analogy to the U.S. case, (high) external costs are taken into account in the construction of the efficient frontier shown in Figure 14. The MER portfolio has an average real cost reduction of 4.83 percent p.a., down from 5.35 percent without external costs (see Figure 13). Apparently external costs are increasing at a lower pace in Switzerland than in the United States (where accounting for them serves to lower the cost reduction in the MER portfolio from 7.10 to 5.03 percent p.a., see Figures 10 and 11). On the other hand, external costs are not volatile; their inclusion causes the standard deviation of Swiss returns to fall from 14.51 percent p.a. in Figure 13 to 11.63 percent here (Figure 14). Opting for the MV rather than the MER portfolio would not have made much of a difference, with the mean cost decrease still 3.45 percent p.a. and only slightly less volatility. Accounting for external cost leaves the structure of the MER portfolio unchanged. With no constraints imposed, *Solar* continues to dominate with 100 percent. The MV portfolio favors *Nuclear* (60 rather than 51 percent as in Figure 13) while pushing back *Run of river* (4 rather than 13 percent). With *Solar* constrained to 4 percent (and *Run of river* to 24 percent and *Storage hydro* to 32 percent), *Nuclear* becomes prominent again, with a share of 96 percent regardless of whether high external costs are assumed or not.

To summarize briefly, in the unconstrained portfolio without external costs, the Swiss MER and MV portfolios contain 100 percent *Solar*. After accounting for external costs and imposing feasibility constraints, both the MER and MV portfolios are dominated by *Nuclear* power.



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*
32%	*Storage hydro*
24%	*Run of river*
4%	*Solar*

Figure 14 Efficient Electricity Portfolios for Switzerland
(2003, SURE-based, with constraints, with high external costs)

5.2.3 United States and Switzerland compared

This section is devoted to a comparison of results obtained from the two countries. Starting with private costs only and no constraints imposed (Figures 9 and 12), the volatility reduction achieved by moving away from the current power generation mix would have been much less for the United States, 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. In its turn, 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. However, both countries would have had to completely change the composition of their portfolios to activise 100 percent *Wind* (United States) and 100 percent *Solar* (Switzerland), respectively,

Since such a revolutionary change is far from reality, constraints (5 percent *Wind* in the United States, 4 percent *Solar* in Switzerland) are imposed in Figures 10 and 13. This causes the diversification benefits of MER and especially MV portfolios to completely disappear in both countries. However, a drop in the rate of return occurs only in Switzerland (4 percentage points). Finally, accounting for (high) external costs (Figures 11 and 14) does slow the achievable cost decrease of U.S. power production by about 2 percentage points p.a. (volatility being little affected), while it does not affect Swiss performance much. On the whole, it appears that the United States would 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.). Switzerland would also have stood to gain a lot in terms of risk reduction by adopting an investor's viewpoint early, allowing the country to come closer to the all-*Solar* production technology suggested both by the MER and MV portfolios for 2003.

6 Conclusions

The objective of this study was to determine current (2003) efficient frontiers for power generation in the United States and Switzerland, using portfolio optimization methods. The observation period covers 1982 to 2003 (United States) and 1986 to 2003 (Switzerland), respectively. For estimating variances and covariances of returns, the cost changes related to the different primary energy sources were tested for stationarity first. Because the error terms proved to be correlated across equations, seemingly unrelated regression estimation (SURE) was adopted for estimating the covariance matrix.

With cost changes purged from idiosyncratic shocks that could result in an unstable covariance matrix, the efficient portfolio frontiers could be constructed using quadratic optimization. Interestingly, the maximum expected return (MER) portfolios of both countries contain one renewable energy source exclusively (*Wind* in the United States and *Solar* in Switzerland). However, as soon as feasibility constraints limiting changes from the status quo are imposed, the MER portfolio for the United States contains 95 percent *Coal* and for Switzerland, 96 percent *Nuclear*.

One could argue that for populations as risk-averse as the American and the Swiss, the minimum variance portfolio (MV) is appropriate. Adopting the MV criterion and imposing a "realistic" 5 percent limit on the share of *Wind* power in the United States, one would assign *Coal* 66 percent of the portfolio (neglecting external costs) or 81 percent, respectively (high external costs). Interestingly, *Gas* does not show up in any efficient portfolio of the United States because its cost is not only highly volatile but also largely moves parallel to those of other fuels, depriving them from any diversification effect. At the same time, *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 the case of Switzerland, the MV portfolio subject to a "realistic" constraint limiting *Solar* technology to a 4 percent share, has *Nuclear* still account for 51 percent (neglecting external costs) and 60 percent, respectively (high external costs) of the 2003 efficient portfolio. Comparing these figures with their actual 2003 counterparts, 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. In contrast to Switzerland, *Nuclear* should have played only a minor role in the U.S. generation portfolio by 2003. There, *Nuclear* optimally never exceeds much its actual 21 percent share, even when external costs are taken into account. Currently (2003), the United States are more efficient in generating electricity than Switzerland but may still reap efficiency gains by investing in more *Coal* and moving away from *Gas*. Future contributions to the field of this study may relax the strong assumption of an once-and-for-all decision regarding the energy mix. A real options approach could be used to account for the irreversibility inherent in the decision to adopt a technology. Deferring adoption may become the preferred choice in the face of stochastic cost changes caused e.g. by a liberalization of energy markets - or its failure to materialize as expected. Also, the investor's point of view (with exclusive emphasis on future cost changes) might be contrasted with and modified to include the current user's point of view (where the level of cost determines the efficient technology mix in ongoing production). Still, the present study provides first indications of where to go in the future, for reaching the efficient mix of power-generating technologies in two very diverse countries.

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