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Efficient Provision of Electricity for the United States and Switzerland

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Abstract

This study applies financial portfolio theory to determine efficient frontiers in the provision of electricity for the United States and Switzerland. Expected returns are defined by the rate of productivity increase of power generation (adjusted for external costs), volatility, by its standard deviation. Since unobserved productivity shocks are found to be correlated, Seemingly Unrelated Regression Estimation (SURE) is used to filter out the systematic component of the covariance matrix of the productivity changes. Results suggest that as of 2003, the feasible maximum expected return (MER) electricity portfolio for the United States contains more *Coal*, *Nuclear*, and *Wind* than actual but markedly less *Gas* and *Oil*. The minimum variance (MV) portfolio contains markedly more *Oil*, again more *Coal*, *Nuclear*, and *Wind* but almost no *Gas*. Regardless of the choice between MER and MV, U.S. utilities are found to lie substantially inside the efficient frontier. This is even more true of their Swiss counterparts, likely due to continuing regulation of electricity markets[1].

Keywords: efficiency frontier, energy, electricity, portfolio theory, Seemingly Unrelated Regression Estimation (SURE)

JEL: C32, G11, Q49

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December 8, 2011

1. Introduction

Like most industrial countries, the United States and Switzerland face great challenges in the provision of electricity arising from dwindling domestic resources. Both countries are expected to confront substantial 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. As for Switzerland, a study conducted by the Paul Scherrer Institute (PSI) estimates a shortfall of 20 percent by 2020 (Gantner et al., 2000).

The solutions available to the two countries are the same, viz. import more power (from Canada and France, respectively) or increase domestic supply by investing in new generating technologies. Especially with the latter strategy, there is a substantial interest in providing electricity as economically as possible. Therefore, the question of this paper is, can the United States and Switzerland improve efficiency in their provision of electricity? If so, what are the attractive technologies, taking into account external costs that sooner or later will be factored into electricity prices?

For the measurement of efficiency, Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) are the two dominant alternatives. Fundamentally, both approaches assume a uniform production technology to infer the efficient use of a technology from observed choices of input and output quantities by firms. However, these approaches only work well when productive units are homogenous with regard to technology and face stable input prices and hence little uncertainty (see e.g. Greene, 2004). In the provision of electricity, these circumstances are not satisfied for at least two reasons.

1. **Heterogenous technologies:** Each power plant has its own type of technology, depending on its primary energy source (*Coal*, *Gas*, *Hydro*, *Nuclear*, *Oil*, *Wind*). The issue therefore is not the cost-minimizing use of one common technology but determining an optimal portfolio of electricity-generating technologies.
2. **Cost uncertainty:** Exogenous shocks (e.g. the Gulf war in the case of Oil) cause unexpected changes in input prices which affect the level and development of unit cost.

Therefore, it is not sufficient to merely focus on least-cost provision of electricity; in view of a portfolio of technologies with uncertain cost characteristics, the optimal mix of technology becomes the issue.

Such a mix can be determined by applying mean-variance portfolio theory (see e.g. Kienzle and Andersson, 2008; Krey, 2008; Awerbuch, 2006; Yu, 2003; Berger et al., 2003; Humphreys and McClain, 1998; Bar-Lev and Katz, 1976). Here, a social planner (e.g. federal government) is assumed to act like a financial investor, who hedges against the ups and downs of the market by holding a diversified portfolio of securities. In contrast to a least-cost strategy, capacity planning does not only reflect productivity but also risk at a given level of productivity. Indeed, the objectives of the U.S. NEPG support the portfolio approach to electricity advocated here (see NEPG, 2004). The methodological innovation of this paper consists in recognizing that there are common shocks impinging on the production frontiers and hence the development of productivity[2] in generating technologies. Taking this correlation into account in the estimation of the covariance matrix (using 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 calculation of efficient electricity portfolios.

A comparison between the United States and Switzerland is of interest for several reasons. First, both countries heavily rely on imported fuels (*Gas* and *Nuclear*, respectively) for their power generation. While they can purchase primary energy sources at market prices, there are differences in their technology mix, giving rise to the question of whether this reflects differences in efficiency. Second, insights may be expected with regard to regulation. Contrary to the United States, the Swiss electricity market continues to be highly regulated. Swiss voters rejected liberalization efforts in a popular referendum at the end of 2002 (see EMG, 2000 and EMV, 2002). The usual presumption would be that U.S. power generation is closer to the efficient frontier than its Swiss counterpart. Finally, several countries (notably China and India) have to meet a rapidly increasing demand for electricity. For them, it is of considerable importance to invest in energy sources in a way that avoids inefficiency. This contribution should provide some help towards achieving that objective.

Results show that returns and volatilities differ greatly between technologies and between SURE and OLS estimates. While optimal choice depends on risk aversion (which is not known), the maximum expected return (MER) and the minimum variance (MV) portfolios constitute two extreme solutions. The feasible MER portfolio for the United States contains more *Coal*, *Nuclear*, and *Wind* than actual but markedly less *Gas* and *Oil*; the MV portfolio combines more *Oil*, *Coal*, *Nuclear*, and *Wind* but almost no *Gas*. Regardless of the choice between MER

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[2] From an investor perspective, rates of return associated with a particular generating technology are decisive. However, the available data do not permit to track price-cost margins. As a proxy, relative productivity changes will be used, which reflect relative unit cost changes (but have the advantage of being positively defined in the case of development.)

and MV, U.S. utilities are found to lie substantially inside the efficient frontier. This is even more true of their Swiss counterparts, likely due to continuing regulation of electricity markets.

This paper is structured as follows. Section 2 contains a short description and critique of the conventional least-cost planning approach. Sectoral optimization is shown to result in inefficiency in the presence of productivity shocks. However, the proposed mean-variance portfolio approach requires a stable variance-covariance matrix of returns. The construction of this matrix based on SURE is explained in Section 3. Section 4 is devoted to the empirical application to U.S. and Swiss data. First, the data base and the SURE and OLS specifications are described. Econometric results are presented and then used in the determination of efficient mean-variance frontiers with and without constraints imposed. Section 5 contains a summary and suggestion for future research.

2. From Least-Cost Planning to Optimal Provision of Electricity

This section expounds the relationship between least-cost planning of electricity supply and overall optimal provision of electricity. Traditionally, research has focused on identifying power plants using a particular technology (e.g. gas as fuel) that achieve maximum productivity (see e.g. Diewart and Nakamura (1999) and Kumar and Gupta, 2004). With the advent of deregulation of power generation in the United States and the European Union, this type of research has been concentrating on the distribution sector (see e.g. Resende, 2002 and Farsi et al., 2008). However, the idea continues to be to allocate output to the most productive (or least-cost, respectively) units. This sectoral approach rests on the following concepts. Let there be a production process $Y = f(X)$, mapping input quantities $X = (x_1, ..., x_m)$, $X \in \mathbb{R}_+^m$ into s output quantities $Y = (y_1, ..., y_s)$, $Y \in \mathbb{R}_+^s$. The *production set* is defined by (Koopmans, 1951 and Debreu, 1951)

$$\Gamma_j = \{(X_j, Y_j)| \ Y_j \leq f(X_j)\}, \tag{1}$$

describing all possible combinations (X_j, Y_j). For illustration purposes, Figure 1A shows the production set Γ_j for a single input (generating costs) and single output (kilowatt-hours produced) for gas-fueled power plants. The combinations of interest are those on the boundary of Γ_j which are technically efficient, meaning that for a given quantity of input $\bar{X}_j$ no more output

Y_j can be produced or inversely, no less input X_j can produce a given output $\bar{Y_j}$. According to Shephard (1970) the boundary can be expressed as an input or an output isoquant

$$\begin{aligned} Iso\; X(y) &= \{x|\; x \in X(y), \theta x \notin X(y), \forall\; 0 < \theta < 1\} \\ Iso\; Y(x) &= \{y|\; y \in Y(x), \theta^{-1} y \notin Y(x), \forall\; 0 < \theta < 1\}, \end{aligned} \tag{2}$$

with θ denoting a scalar by which all inputs can be reduced without leaving the feasibility set or becoming technically efficient, respectively. Accordingly, θ^{-1} symbolizes the scaling-up factor for the outputs.

Furthermore, overall productivity of domestic supply can be increased by investing in those technologies $\Psi_{least-cost}$ that are most productive, satisfying

$$\Psi_{least-cost} = \arg\,\max\{\Gamma | \Gamma_j \in \Gamma\}. \tag{3}$$

However, as already argued in the introduction, in power generation technology is not stable over time. In Figure 1A, the production set Γ_j ($j = Gas$) moves down between periods t and $t{+}1$ due to a negative productivity shock. In this case, a least-cost strategy may be inappropriate for domestic supply. Let G_t be one of the efficient gas-based power companies. If it is to maintain its contribution to electricity supply ($\bar{Y_j}$), it would have to use much more Gas (as indicated by point G'_{t+1}), imparting a cost shock to total supply. To the extent that other technologies (e.g. $Hydro$) are not affected by the shock, a reallocation in favor of these technologies is indicated. In the extreme, this would amount to holding the company to its initial input (and cost) level, causing it to move to point G''_{t+1}. The associated shortfall in power supply would have to be made up by companies using other technologies, causing them to deviate from their least-cost allocations.

A possible way to overcome the problem of inefficiency due to stochastic shocks is to account for technology risk, e.g. indicated by the variance of efficient frontier determined by the input or output isoquant. Deviations from least-cost planning now become possible if the technology considered differs from the others in terms of risk.

However, this decision rule is still sectoral, failing to benefit from the possible risk diversification effects offered by a portfolio of generation technologies. Acting like a forward-looking investor, the social planner limits his choice to the set of efficient portfolios. These are portfolios that for a given level of risk $\bar{\sigma_p^2}$ offer the highest expected return, or conversely, for a given level of expected return $\bar{R}_p$ offer the minimum risk. This is the solution of two equivalent optimization problems (Markowitz, 1952),

$$\max_{w_j} E(R_p) \quad s.t. \quad w'1 = 1,\ w'\Sigma w \leq \bar{\sigma}_p^2, \tag{4}$$

$$\min_{w_j} \sigma_p^2 \quad s.t. \quad w'1 = 1, w'E(R) \geq \bar{R}, \tag{5}$$

with w as the vector of weights and the expected return $E(R_p)$ given by

$$E(R_p) = [w_1 \cdots w_J] \begin{bmatrix} E(R_1) \\ \vdots \\ E(R_J) \end{bmatrix} = w'E(R), \quad \text{with} \quad \sum_{j=1}^{J} w_j = 1. \tag{6}$$

The volatility of the portfolio's expected return involves not only the respective variances but all the covariances as well. Therefore, one has for the variance σ_p^2,

$$\sigma_p^2 = [w_1 \cdots w_J] \begin{bmatrix} \sigma_{11} & \cdots & \sigma_{1J} \\ \vdots & \ddots & \vdots \\ \sigma_{J1} & \cdots & \sigma_{JJ} \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_J \end{bmatrix} = w'\Sigma w, \quad \text{with} \quad w'\Sigma w > 0. \tag{7}$$

In both formulations (4) and (5), the decision variables are the weights w_j assigned to the components of the portfolio, i.e. the generating technologies in the present context.

Figure 1: Sectoral Least-cost and Portfolio Efficient Frontiers (Electricity)

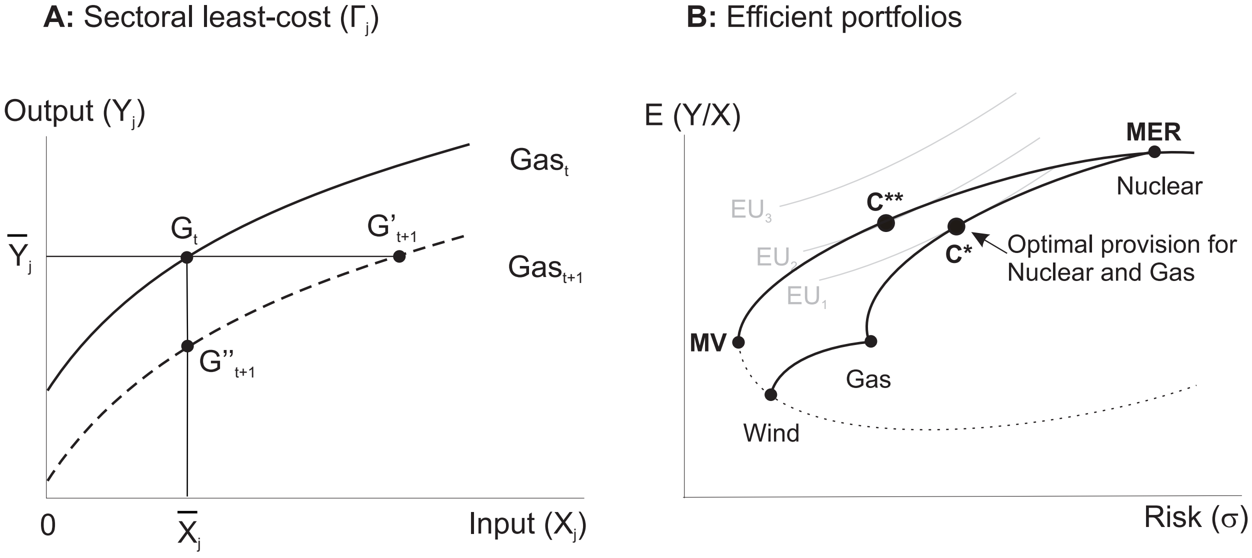

Figure 1B illustrates the case of three generating technologies *Wind*, *Gas*, and *Nuclear*. By assumption, *Wind* and *Gas* have a low risk with low expected return, while *Nuclear* has a high risk that is negatively correlated to *Wind* and *Gas*. The horizontal axis depicts risk, the vertical axis displays the expected return, respectively. For the moment, this is taken to be expected productivity $\mathrm{E}(Y/X)$; see Section 4.1 for more detail. Three possible values of Y_j/X_j can be read off Figure 1A as the slopes of rays from the origin through points G_t, G'_{t+1}, and G''_{t+1}, respectively. Note that they are defined by the least-cost productive units for a given technology.

Starting with *Gas* and *Nuclear*, the social planner can allocate domestic supply between these two risky technologies. Without incorporating risk at all, least-cost planning would call for a complete reliance on *Nuclear* because it offers the maximum expected return (MER). A sectoral approach incorporating variances but neglecting the fact that shocks can be less than perfectly correlated would result in a linear combination of *Gas* and *Nuclear*, with weights w_j inversely proportional to the respective variances (Zweifel and Eisen, 2011, ch. 4.1.2). The solution of the optimization problem (4) or (5), respectively results in the semi-elliptic efficient frontier linking *Gas* and *Nuclear*. The mix of the two technologies varies along this frontier. The lower the coefficient of correlation between shocks affecting *Gas* and *Nuclear*, the more marked is the concavity of the frontier, indicating benefits of risk diversification. However, choice of the optimal portfolio depends on the degree of risk aversion of the investor, reflected by the slope of his or her indifference curves (marked EU for constant expected utility). As long as there are only *Gas* and *Nuclear* and given moderate risk aversion, the optimum is given by point C^*, the point of tangency of the efficient frontier and the indifference curve.

Now let there be a third technology (*Wind*). This creates additional opportunities for diversification, shifting the efficient frontier upward and inward. As before, knowledge of the investor's risk preference would be necessary to predict the choice of optimal provision (C^{**}). But because this knowledge is not available (at least concerning the provision with electricity) for the United States and Switzerland, two extreme solutions are worth pointing out. As can be gleaned from Figure 1B, a very risk-averse investor is predicted to opt for the minimum variance (MV) provision. By way of contrast, an (almost) risk-neutral investor prefers the maximum expected return (MER) alternative, usually implying a very different mix of generating technologies. Comparing these two extreme solutions permits to assess the maximum influence of risk aversion on the optimal provision of electricity.

Note that the portfolio approach does not revolve around single technologies, but an efficient mix of several technologies. Even if a particular technology is dominated by others in terms of risk and expected return, it may still contribute to the optimal provision of electricity because of its diversification effect.

3. Construction of a Stable Variance-Covariance Matrix (Σ)

One important condition for calculating the optimal allocation of generating technologies is the estimation of a stable variance-covariance matrix Σ. An unstable estimate of Σ would result in highly variable optimal weights w_j^* of technologies [see Eq. (6)]. Lack of stability can be due to extreme shocks, which may cause outliers during several years.

One possibility that is widely suggested in financial literature (see e.g. Bodie et al., 2005, ch. 13) to achieve time-invariant estimates is the generalized autoregressive conditional heteroscedasticity (GARCH) of the autoregressive model of Eq. (8),

$$R_{j,t} = \beta_{j,0} + \sum_{n=1}^{N} \beta_{j,n} R_{j,t-n} + \varepsilon_{j,t}, \tag{8}$$

where $R_{j,t}$ is the return of technology j in year t, $\beta_{j,0}$ is a constant for technology j, $\beta_{j,n}$ is the coefficient pertaining to the returns lagged n years, $R_{i,t-n}$ is the dependent variable lagged n years, and $\varepsilon_{j,t}$ is the error term pertaining to technology j in year t.

However, while this formulation suffices to insulate expected conditional values $\overline{R_{j,t}}$ from extreme shocks (which would spill over into the estimated correlation matrix), Krey and Zweifel (2009) find that due to unobserved common shocks impinging on technologies at the same time, SURE (Seemingly Unrelated Regression Estimation) is the more efficient alternative. The correlation between the error terms $\varepsilon_{j,t}$ constitutes information that can be used in SURE to obtain sharper estimates of the β parameters (see Section 4.2 for empirical evidence).

In the example above, the SURE model consists of three regression equations (for *Wind*, *Gas*, and *Nuclear*), each of which satisfies the assumptions of the standard regression model,

$$\begin{aligned}
R_{1,t} &= a_0 + \sum_{n=1}^{N1} a_{1,n} R_{1,t-n} + \varepsilon_{1,t} \\
R_{2,t} &= b_0 + \sum_{n=1}^{N2} b_{1,n} R_{2,t-n} + \varepsilon_{2,t} \\
R_{3,t} &= c_0 + \sum_{n=1}^{N3} c_{1,n} R_{3,t-n} + \varepsilon_{3,t},
\end{aligned} \tag{9}$$

where $R_{1,t}$, $R_{2,t}$, $R_{3,t}$ are the returns of technologies $j = 1, 2, 3$ in year t. a_0, b_0, and c_0 are their respective constants, $a_{1,n}$, $b_{2,n}$, $c_{3,n}$ are the coefficients of returns lagged n years, $R_{1,t-n}$, $R_{2,t-n}$, $R_{3,t-n}$ are the dependent variable lagged n years, and $\varepsilon_{1,t}$, $\varepsilon_{2,t}$, $\varepsilon_{3,t}$ are the error terms with $E(\varepsilon_{j,t}) = 0$, and $E(\varepsilon_{i,t}\varepsilon_{j,s}) = \sigma_{i,j}$ if $t = s$ and $= 0$ if $t \neq s$. This is the SURE specification, admitting nonzero contemporaneous correlations between error terms. Thus, the variance-covariance matrix Σ of residuals is not diagonal,

$$\Sigma = E(\varepsilon\varepsilon') = \begin{bmatrix} \sigma_{1,1} & \sigma_{1,2} & \sigma_{1,3} \\ \sigma_{2,1} & \sigma_{2,2} & \sigma_{2,3} \\ \sigma_{3,1} & \sigma_{3,2} & \sigma_{3,3} \end{bmatrix} . \tag{10}$$

By way of contrast, OLS estimation would be superior if the variance-covariance matrix were diagonal. However, this does not hold for U.S. and Swiss power technologies (see Section 4.2)

In sum, SURE allows to simultaneously estimate the expected returns and the variances for all power generation technologies in one regression, taking into account possible correlations of error terms across equations.

4. Empirical Application to U.S. and Swiss Electricity Data

In this section, theory and data are combined for the construction of efficient frontiers for electricity-generating technologies in the United States and Switzerland. This calls for an estimate of expected returns $E(R_j)$ for each technology j that potentially is part of the optimal provision, of its variance σ_j^2, and its covariances σ_{ij}. Estimates of these quantities come from the SURE results shown in Section 4.2. Results presented in Sections 4.3 and 4.4 contrast the actual portfolio (AP) of both countries with the minimum variance (MV) and maximum expected return (MER) alternatives, which correspond to the optimum allocation in case of extremely marked and very weak degrees of risk aversion, respectively (see Section 2).

4.1. Data and Model Specifications

This article uses time-series data on annual power generation returns for several technologies. Contrary to the theoretical exposition in the preceding sections, which is in terms of productivity levels for simplicity, returns are measured as annual changes in productivity, with productivity equated to kWh electricity produced per U.S. dollar[3]. This definition is similar to that of

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

Berger et al. (2003) and Awerbuch and Berger (2003), who point out that a rational investor more likely relies on productivity changes than levels when choosing the technology mix for the future. In full analogy, a financial investor buys a stock in view of its expected future change in value rather than its current price.

The U.S. data set consists of five variables; *Coal, Nuclear, Gas, Oil*, and *Wind* power[4], covering the years 1982 to 2003. Unfortunately, no data were available for *Hydro*, which contributed an estimated 6 to 10 percent to total U.S. power supply. Nevertheless, more than 90 percent of U.S. generating capacity is covered, going beyond earlier work that was limited to three technologies (Awerbuch, 2006; Humphreys and McClain, 1998). The Swiss data on *Nuclear*[5] cover the years 1986 to 2003, those on *Run of river*[6] and *Storage hydro*[7] 1993 to 2003, and *Solar*[8], 1991 to 2003. Throughout, generation costs comprise (i) fuel costs, (ii) costs of current operations, and (iii) capital user cost[9] (depreciation of book value plus interest). In the case of *Nuclear*, decommissioning and waste disposal are also included.

For both countries, an externality surcharge for environmental damage caused by power generation is added to the costs of each technology. As in previous studies (Awerbuch, 2006; Awerbuch, 2005), these cost data are available for total production only, precluding a differentiation according to load segments. Finally, from an efficiency point of view, the price of a product should reflect external costs only to the extent that the marginal benefit of internalization effort still covers its marginal cost. However, the externality surcharge corresponds to total estimated external cost per kWh electricity, reflecting the implicit assumption that full internalization is optimal. The data on external costs were obtained from the European Commission (2003) for the United States and Hirschberg and Jakob (1999) for Switzerland[10]. While external costs related to health and global warming do enter calculations, no data are

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[4] Data for *Coal, Nuclear, Gas* and *Oil* were 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 (Knott, 2000).

[5] Data sources: KKl (2005), KKG (2005)

[6] Data source: personal correspondence

[7] Data source: personal correspondence

[8] RWE (2005); The average exchange rate of 2000 was used to convert Euro cents into U.S. cents (source: U.S. Federal Reserve). RWE data from Germany is used as a proxy for Swiss solar electricity data, since solar generation technologies in both countries are similar.

[9] Capital user cost can be defined in several ways. The variant "linear depreciation and interest" is used here exclusively due to lack of source data that would permit to calculate other variants.

[10] No external cost data for the United States were available; therefore data from the United Kingdom were used (European Commission, 2003).

available for some other categories such as external costs related to agriculture and forestry. In this paper, the upper bound of social cost estimates is adopted for both countries.

The resulting productivity levels are displayed in Table 1 together with the shares of technologies in the U.S. and Swiss power generation portfolios. As noted in panel A, the U.S. mix predominantly consists of fossil fuels (56 percent *Coal*, 18 percent *Gas*, and 3 percent *Oil*), with *Nuclear* accounting for another 21 percent of production. However, with externality surcharges included, these weights do not reflect productivity levels. While the productivity of *Coal* with its share of 56 percent is some 11 kWh per U.S. $ (busbar) in 2003, *Wind* power is far more productive but accounts for 2 percent only. By way of contrast, the Swiss portfolio in panel B seems to match productivity levels much better. It relies heavily on highly productive *Hydro* (32 percent *Storage hydro*, 24 percent *Run of river*); *Nuclear* accounts for 40 percent, *Solar* (a proxy of all renewable and conventional thermic technologies with a low productivity of 2 kWh per U.S. $), for a mere 4 percent .

Table 1: Current Portfolio Weights (Percent) and Productivity Levels (kWh/U.S. $, Prices of 2000)

Panel A: United States*					**Panel B:** Switzerland				
Technology	Weights		Productivity		Technology	Weights		Productivity	
	1995	2003	1995	2003		1995	2003	1995	2003
Nuclear	21	21	17	26	*Nuclear*	39	40	20	29
Coal	57	56	9	11	*Storage hydro*	27	32	39	52
Gas	17	18	16	13	*Run of river*	32	24	18	25
Oil	3	3	9	10	*Solar*	2	4	1	2
Wind	2	2	18	23					

* Excluding hydro

Source: Swiss Federal Office of Energy (SFOE) (2003), IAE (2005)

However, recall that productivity changes rather than levels are relevant for investors, who would have wanted to buy into Swiss *Solar* in 1995 in view of its rapid productivity increase in the course of nine years. From an investor point of view, Swiss *Solar* should therefore figure prominently in an efficient portfolio unless it has extremely unfavorable diversification properties.

Finally, the SURE models need to be specified. Equations (11) display the U.S. specifications that have the best statistical properties (see Section 4.2 below), selecting 2003 as the year of reference for the efficient portfolios,

$$\begin{aligned}
R_{Nucl,03} &= n_0 + n_1 R_{Nucl,02} + n_2 Trend_t + \varepsilon_{Nucl,03} \\
R_{Coal,03} &= c_0 + c_1 R_{Coal,02} + c_2 Trend_t + \varepsilon_{Coal,03} \\
R_{Gas,03} &= g_0 + g_1 R_{Gas,02} + g_2 R_{Gas,01} + g_3 R_{Gas,00} + g_4 Trend_t + \varepsilon_{Gas,03} \\
R_{Oil,03} &= b_0 + b_1 R_{Oil,02} + b_2 R_{Oil,01} + b_3 R_{Oil,00} + b_4 R_{Oil,99} + b_5 Trend_t + \varepsilon_{Oil,03} \\
R_{Wind,03} &= d_0 + d_1 R_{Wind,02} + d_2 Trend_t + \varepsilon_{Wind,03}. \qquad (11)
\end{aligned}$$

Generally, influences such as technological change are hypothesized to influence productivity of electricity generation and hence returns. However, estimating such a comprehensive model is beyond the scope of this study. Rather, the relative productivity change of *Nuclear* in the United States in the year 2003 e.g., $R_{Nucl,03}$, is related to a constant (n_0), the productivity changes in the preceding year $R_{Nucl,02}$, and a time trend ($Trend_t$).

In analogy, the productivity change of *Nuclear* in Switzerland in the year 2003, $R_{Nucl,03}$, is related to a constant (n'_0), the productivity changes in the preceding years $R_{Nucl,02}$, $R_{Nucl,01}$, $R_{Nucl,00}$, and $R_{Nucl,99}$, and a time trend ($Trend_t$). The remaining equations (12) refer to *Run of river (Ror)*, *Storage hydro (Sh)*, and *Solar* (*Solar* also includes other renewable energy sources such as waste),

$$\begin{aligned}
R_{Nucl,03} &= n'_0 + n'_1 R_{Nucl,02} + n'_2 R_{Nucl,01} + n'_3 R_{Nucl,00} + n'_4 R_{Nucl,99} + n'_5 Trend_t + \varepsilon'_{Nucl,03} \\
R_{Ror,03} &= r'_0 + r'_1 R_{Ror,02} + r'_2 Trend_t + \varepsilon'_{Ror,03} \\
R_{Sh,03} &= h'_0 + h'_1 R_{Sh,02} + h'_2 Trend_t + \varepsilon'_{Sh,03} \\
R_{Solar,03} &= s'_0 + s'_1 R_{Solar,02} + s'_2 R_{Solar,01} + s'_3 R_{Solar,00} + s'_4 R_{Solar,99} + s'_5 Trend_t + \varepsilon'_{Solar,03} \qquad (12)
\end{aligned}$$

4.2. Preliminary Testing and Econometric Results

The objective is to obtain a stable estimate of the covariance matrix Σ derived from Eqs. (11) and (12). In order to be able to filter out the systematic (trend stable) component of Σ, changes in productivity must form stationary time series. Given non-stationarity, the estimate of Σ would shift over time, precluding the estimation of a reasonably stable efficient frontier [Wooldridge (2003), ch. 11]. To test for stationarity, the augmented Dickey-Fuller (ADF) test was applied. Results indicate at the one percent significance level that all productivity changes 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's 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 *Oil*, three lags for *Gas*, and one lag for *Coal*. One lag was used for *Wind* and *Nuclear*, based on considerations of goodness of fit in SURE. The results for the Swiss data suggest four lags for *Nuclear*, while in the case of *Storage hydro* and *Run of river*, one lag suffices. Tests are inconclusive for *Solar*. However, Liew (2004) shows that lag selection tests may lack validity if the sample is small. Using a sample size of 25 he finds that the probability of correctly estimating the true order of an autoregressive process ranges between 58 percent (SBIC) and 60 percent (HQIC). In view of the inconclusive evidence and the fact that the coefficients on the autoregressive variables used in the SURE procedure are significant without exception, four lags were applied throughout in the case of Switzerland for *Solar*.

Table 2: Econometric Results, United States (1982-2003)

Panel A: Results of SURE regression, dependent variable R_t: relative productivity change

	$\bar{R}$	St.D.	Const.	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	R_{t-5}	Trend	Obs	R^2
Coal	5.2	2.0	−0.09**	0.02					0.003**	17	0.67
Nuclear	5.8	1.8	−0.05*	0.38*					0.001	17	0.07
Gas	3.9	11.7	−0.32**	0.10	-0.89**	0.12			0.018**	17	0.67
Oil	2.5	10.4	−1.05**	−0.96**	-1.35**	−1.17**	-1.21**	-0.62*	0.050**	17	0.67
Wind	5.4	6.9	−0.03	0.73**					0.001	17	0.51

Panel B: Results of OLS regression, dependent variable R_t: relative productivity change

	$\bar{R}$	St.D.	Const.	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	R_{t-5}	Trend	Obs	R^2
Coal	4.8	1.5	−0.06**	0.22**					0.002*	21	0.36
Nuclear	4.8	2.3	−0.01	0.30					−0.002	21	0.21
Gas	3.6	10.5	−0.26*	0.13	-0.78**	0.23			0.015*	19	0.69
Oil	2.5	9.7	−0.91*	−0.85*	-1.21**	−0.94	-1.10*	-0.43	0.043*	17	0.62
Wind	4.1	2.6	−0.05*	0.21*					0.002	21	0.72

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

The resulting SURE and OLS regressions are displayed in Table 2 for the United States and Table 3 for Switzerland together with their estimated average returns $\bar{R}$ and standard deviations $St.D.$ Comparing the results of SURE and OLS estimates, the first thing to note is that due to its fuller use of information, SURE results in sharper coefficient estimates than OLS. In the regressions for the United States, 15 SURE but only 13 OLS coefficients out of a theoretical total of 35 are significant at the 5 percent level or better. In the regression for Switzerland, 14 SURE but only 1 OLS coefficient out of a theoretical total of 24 are significant. This difference is of importance because the objective is to filter out transitory shocks in productivity development for obtaining a stable estimate of the variance-covariance matrix Σ. Clearly, SURE estimates serve this purpose better than their OLS counterparts. Also, the contrasts between estimates are sometimes striking. Notably, the SURE results of Table 2 (col. "Const.", panel A) suggest a productivity-decreasing drift of 5 percent p.a. in American *Nuclear*, while according to the OLS estimate (panel B), the hypothesis of no drift cannot be rejected. In the case of *Wind*, it is the other way round. In the Swiss regressions, *Solar* exhibits the expected upward productivity shift in the SURE estimation (panel A of Table 3), which would have not been recognized as significant in the OLS alternative (panel B).

Table 3: Econometric Results, Switzerland (1986-2003)

Panel A: Results of SURE regression, dependent variable R_t: relative productivity change

	$\bar{R}$	St.D.	Const.	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	Trend	Obs	R^2
Nuclear	−3.6	12.9	−0.04	0.74**	0.93**	1.22**	1.37**	0.18**	9	0.74
Run of river	−4.1	18.6	−0.33	0.70**				0.20	9	0.51
Storage hydro	−1.2	12.0	−0.25	0.72**				0.02	9	0.22
Solar	6.7	1.0	0.34**	0.73**	0.56*	0.61*	0.55*	−0.01**	9	0.63

Panel B: Results of OLS regression, dependent variable R_t: relative productivity change

	$\bar{R}$	St.D.	Const.	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	Trend	Obs	R^2
Nuclear	4.3	2.2	0.10	0.03	0.29	0.14	0.38	−0.001	14	0.38
Run of river	−1.6	1.6	−0.11	0.64*				0.01	10	0.44
Storage hydro	−0.8	9.1	−0.20	0.54				0.01	10	0.35
Solar	6.7	1.0	0.32	0.69	0.60	0.58	0.40	−0.01	9	0.64

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

The presence of correlations across equations is of interest because they determine the diversification effects in the portfolio. Panel A of Table 4 does indicate some negative correlations in the SURE residuals for the United States, with that between *Wind* and *Coal* attaining a value of −0.4246. Panel B of Table 4 permits a comparison with OLS residuals. While the estimated correlation coefficient for *Wind* and *Coal* would have been similar with −0.4062, correlation coefficients between *Nuclear* and *Coal* are less marked than their SURE counterparts. A striking difference can be seen in the case of *Gas* and *Wind*. The correlation between the SURE residuals is positive, while that between OLS residuals is negative.

In the case of Switzerland (Table 5), the highest partial correlation coefficient between SURE residuals (panel A) is obtained for *Solar* and *Nuclear* (0.5933), followed by *Run of river* and *Storage hydro* (0.5054). In the latter case, the common unobserved shock clearly is weather conditions, in particular the amount of precipitation. The pertinent correlation coefficients

Table 4: Correlation Matrices for the United States

Panel A: Partial correlation coefficients for $\widehat{\varepsilon_{i,t}}$ residuals from eqs. (11), using SURE (1982-2003)

	Coal	*Nuclear*	*Gas*	*Oil*	*Wind*
Coal	1				
Nuclear	−0.1140	1			
Gas	0.7605	0.0113	1		
Oil	−0.3317	0.4461	−0.2621	1	
Wind	−0.4246	−0.2520	0.1150	−0.1492	1

Panel B: Partial correlation coefficients for $\widehat{\varepsilon_{i,t}}$ residuals from eqs. (11), using OLS (1982-2003)

	Coal	*Nuclear*	*Gas*	*Oil*	*Wind*
Coal	1				
Nuclear	−0.0329	1			
Gas	0.7050	−0.0004	1		
Oil	−0.2835	0.3670	−0.1362	1	
Wind	−0.4062	−0.1644	−0.2073	0.0998	1

between OLS residuals (panel B) are somewhat larger with 0.7201 for *Solar* and *Nuclear* and about the same for *Run of river* and *Storage hydro* with 0.5066.

Table 5: Correlation Matrices for Switzerland

Panel A: Partial correlation coefficients for $\widehat{\varepsilon_{i,t}}$ residuals from eqs. (12), using SURE (1986-2003)

	Nuclear	*Storage hydro*	*Run of river*	*Solar*
Nuclear	1			
Storage hydro	−0.4644	1		
Run of river	−0.2685	0.5054	1	
Solar	0.5933	0.0367	−0.5907	1

Panel B: Partial correlation coefficients for $\widehat{\varepsilon_{i,t}}$ residuals from eqs. (12), using OLS (1986-2003)

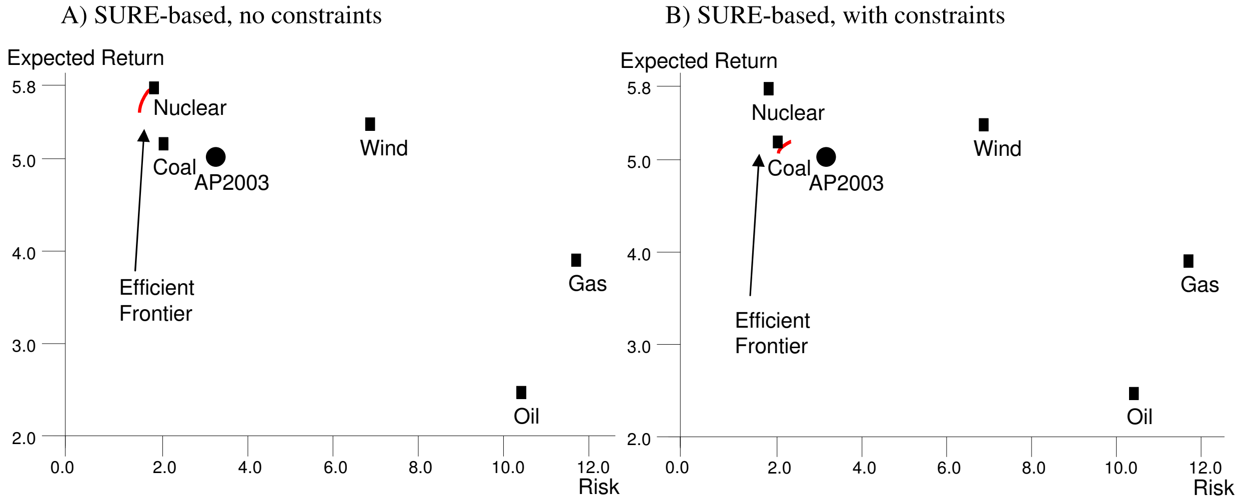
	Nuclear	*Storage hydro*	*Run of river*	*Solar*
Nuclear	1			
Storage hydro	0.3111	1		
Run of river	−0.0550	0.5066	1	
Solar	0.7201	0.2056	−0.3824	1

In sum, in contradistinction to previous studies which solely relied on OLS estimates, SURE is found to benefit from substantial correlations between unobserved shocks impinging on generating technologies. Therefore, the pertinent estimate of the variance-covariance matrix of returns Σ can be expected to be more stable than its OLS-based counterpart.

4.3. Efficient Provision of U.S. Electricity

Figure 2A displays the efficient frontier for the provision of electricity in the United States, along with the actual portfolio (AP) of 2003. No constraints are imposed on the optimization problem [see Eqs. (4) and (5)] at this time. If the country's sole interest were to maximize expected return (thus maximizing the expected decrease of power generation costs), it would choose the MER (maximum expected return) portfolio, which contains *Nuclear* exclusively. If it wished to minimize risk, opting for the MV (minimum variance) portfolio, then a mix of 56 percent *Nuclear* and 44 percent *Coal* would be optimal. Therefore, the degree of risk aversion characterizing the United States clearly matters. However, risk aversion has its price because opting for MV rather than MER would entail a productivity increase of 5.50 rather than 5.76 percent p.a. Still, the MV portfolio with its annual volatility of 1.46 percent beats the actual one whose productivity advance is 5.00 percent only, associated with an annual volatility of 3.10 percent. Yet a share of *Nuclear* amounting to 100 rather than 21 percent in the MER portfolio (56 rather than 21 percent in the MV portfolio, respectively) must be deemed unrealistic for the United States of 2003. Therefore, Figure 2B shows an efficient frontier that takes into account that the current portfolio could be adjusted at considerable cost only. Since adjustment costs are unknown, upper limits for *Coal* $\leq 60\%$, *Nuclear* $\leq 25\%$, *Oil* $\leq 10\%$, and *Wind* $\leq 5\%$ are imposed on the individual shares for simplicity to reflect technical feasibility.

Figure 2: Efficient Electricity Portfolios for the United States (2003, SURE-based)


A) SURE-based, no constraints

B) SURE-based, with constraints

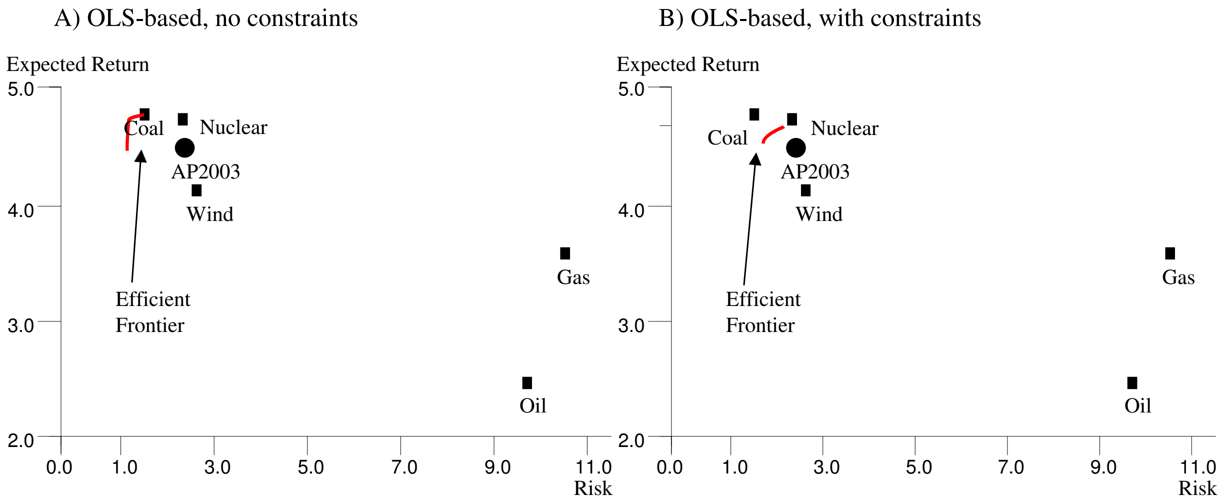
	ER	Risk		Coal	Nuclear	Gas	Oil	Wind
AP2003	5.00	3.10		56	21	18	3	2
MER	5.76	1.80			100			
MV	5.50	1.46		44	56			

	ER	Risk		Coal	Nuclear	Gas	Oil	Wind
AP2003	5.00	3.10		56	21	18	3	2
MER_C	5.20	2.32		60	25	10		5
MV_C	5.07	2.03		60	25	1	9	5

In the MER_C (with "C" for constrained) portfolio, the generation mix now contains 60 percent *Coal*, 25 percent *Nuclear*, 10 percent *Gas*, and 5 percent *Wind*, indicating that constraints are binding. Compared to the actual portfolio, productivity development would still speed up (from 5.00 percent p.a. to 5.20 percent p.a.), while volatility would be reduced from 3.10 to 2.32 percent p.a. In the MV_C alternative, the highest share is again allocated to

Coal (60 percent, binding[11], up from 56 percent in the actual portfolio), followed by *Nuclear* (25 percent, binding, up from 21 percent), *Oil* (9 percent, up from 3 percent), and *Wind* (5 percent, again binding, up from 2 percent). The only technology to lose market share is *Gas* (a mere 1 percent, down from 18 percent). The rate of productivity increase would still attain 5.07 percent p.a. rather than 5.00 as in the actual portfolio, while risk declines to 2.03 from 3.10. One explanation of why *Gas* is almost phased out is its weak diversification effect, the correlation coefficient of its SURE residuals with *Coal* attaining 0.7605, the maximum value of panel A of Table 4. In the whole, current U.S. power generation is inefficient. It could be made more efficient by substituting *Gas* by *Coal*, *Nuclear*, *Oil* (not in the MER_C portfolio), and *Wind*.

Figure 3: Efficient Electricity Portfolios for the United States (2003, OLS-based)


A) OLS-based, no constraints

B) OLS-based, with constraints

	ER	Risk		Coal	Nuclear	Gas	Oil	Wind
AP2003	4.50	2.40		56	21	18	3	2
MER	4.80	1.50		100				
MV	4.72	1.35		63	27			10

	ER	Risk		Coal	Nuclear	Gas	Oil	Wind
AP2003	5.00	3.10		56	21	18	3	2
MER_C	4.63	1.91		60	25	10		5
MV_C	4.55	1.70		60	25	2	8	5

If correlated shocks affecting generation costs would not have been taken into account (as in past studies), the results would have been very different, quite possibly misguiding the choice of an optimal technology mix. Figure 3 displays the OLS-based efficient frontiers and allocations. Without constraints (Figure 3A), the MER portfolio would have contained 100 percent *Coal*[12] (rather than 100 percent *Nuclear* as in the SURE-based case, see Figure 2A).

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[11] Using portfolio theory for three U.S. generating technologies, Berger et al. (2003) also concluded that *Coal* dominates the MV portfolio with a share of 77 percent.

[12] Berger et al. (2003), who do not control for correlation between unobserved shocks, also arrive at 100 percent *Coal*.

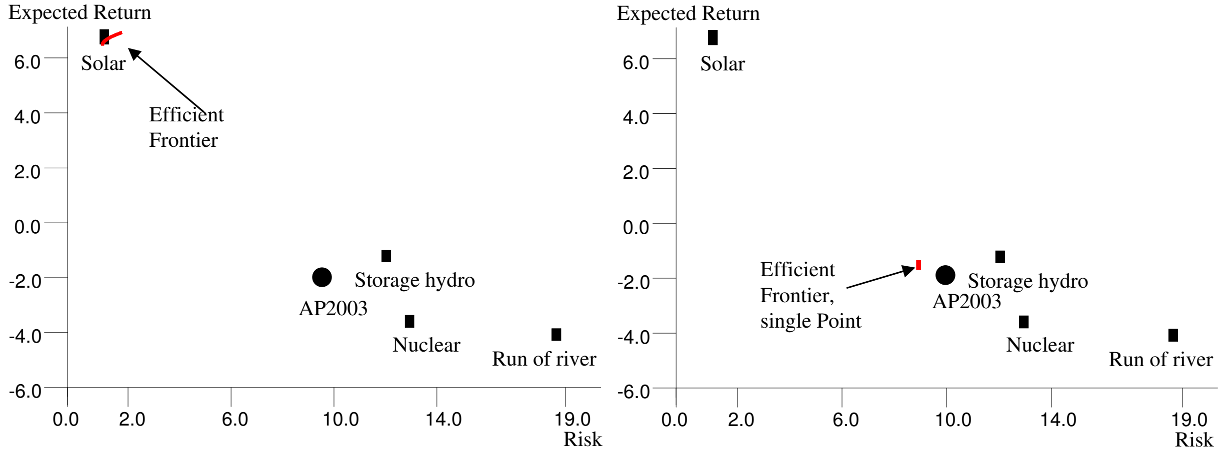
The MV alternative, on the other hand, would have called for a portfolio with 63 percent *Coal*, 27 percent *Nuclear*, and 10 percent *Wind*, quite different from the SURE-based solution that excludes *Wind* while allocating 56 percent (rather than 27 percent) to *Nuclear*. Moreover, the United States would have little incentive to adjust its technology mix because OLS-based expected returns are only slightly higher and volatilities slightly lower than estimated actual ones. With constraints imposed, however, OLS-based estimates would have resulted in efficient portfolios that practically coincide with the SURE-based ones (compare weights below Figures 2B and 3B). This was to be expected since most constraints are binding in both alternatives.

4.4. Efficient Provision of Swiss Electricity

Figure 4 displays the efficient electricity portfolios (as of 2003) for Switzerland. In Figure 4A (no constraints imposed), it is *Solar* rather than *Nuclear* (contrary to the United States) that dominates the MER portfolio with a 100 percent share. Opting for the MER portfolio, the country would achieve a productivity increase of 6.67 percent p.a. (rather than the 2 percent decrease with the actual portfolio), with volatility down from 10 to 1.05 percent p.a.. The MV portfolio consists of 98 percent *Solar* and 2 percent *Nuclear*, expected return being 6.43 percent p.a. and risk, a mere 1 percent. Clearly, in both countries non-CO2 emitting technologies (*Nuclear* in the United States and *Solar* in Switzerland) play a dominant role in the unconstrained efficient portfolios. However, shares of *Solar* close to 100 percent must be deemed unrealistic for Switzerland. Therefore, *Storage hydro*, *Run of river*, and *Solar* are constrained to their actual shares in 2003 (32, 24 and 4 percent p.a., respectively), leaving only *Nuclear* unconstrained. This can be justified by noting that *Storage hydro* and *Run of river* are already being utilized to full capacity (Laufer et al., 2004), while a share of *Solar* electricity of 4 percent constitutes the limit of what could have been achieved. The corresponding efficient frontier is shown in Figure 4B.

The MER_C portfolio calls for a complete substitution of *Run of river* (actual share 24 percent) by *Nuclear* (64 percent), *Storage hydro* (32 percent, binding), and *Solar* (4 percent, binding). This surprising result is due to the fact that *Run of river* is highly correlated with *Storage hydro*, indicating that it has no diversification potential (see the correlation coefficient of 0.5054 in Table 5A). At the same time, this technology has been subject to productivity decrease (see panel A of Table 3. In all, Figure 4B suggests that if ”realistic” constraints are respected, Swiss power generation could be made more efficient by allowing the share of *Nuclear* to substantially increase and abandoning *Run of river*. Expected return would slightly increase,

Figure 4: Efficient Electricity Portfolios for Switzerland (2003, SURE-based)



A) SURE-based, no constraints

B) SURE-based, with constraints

	ER	Risk		Nuclear	Storage hydro	Run of river	Solar
AP2003	-2.00	10.00		40	32	24	4
MER	6.67	1.05					100
MV	6.43	1.00		2			98

	ER	Risk		Nuclear	Storage hydro	Run of river	Solar
AP2003	-2.00	10.00		40	32	24	4
MER_C	-1.82	8.89		64	32		4
MV_C	-1.82	8.89		64	32		4

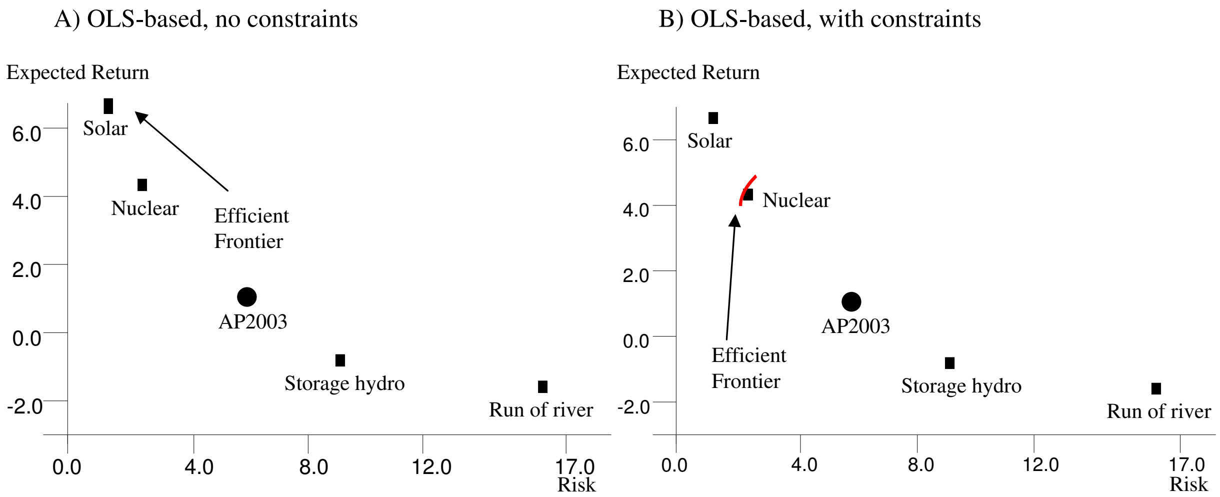
from -2.00 (actual) to -1.82 percent, regardless of choice between MER and MV portfolios, and volatility would drop from 10 (actual) to 8.89.

Results based on OLS-estimated efficient frontier are displayed in Figure 5. Acting on OLS-based estimates, Switzerland would have expected marked productivity increases rather than the decreases implied by SURE, at the same time severely underestimating volatility. Finally, the country would have wrongly slashed the share of *Storage hydro* from 32 percent to 0 percent (MER_C) or 8 percent (MV_C), respectively. Therefore, the choice of statistical specification may again well matter for decision-making.

4.5. United States and Switzerland Compared

This section is devoted to a comparison of results obtained for the two countries as of the year 2003, using SURE-based estimates. Starting with no constraints imposed (Figures 2A and 4A), the United States could have achieved an average productivity increase of 5.76 p.a. by adopting the MER portfolio, Switzerland even 6.67 percent p.a. However, both countries would have had to completely change the composition of their technology portfolio, to 100 percent *Nuclear* (United States) and 100 percent *Solar* (Switzerland), respectively. Turning to the MV alternative, the volatility reduction achieved amounts to 1.54 percentage points (3.10 - 1.46) for the United States, much less than for Switzerland with its 9.00 percentage points (10.00 - 1.00). The implications in terms of portfolio composition are quite different for

Figure 5: Efficient Electricity Portfolios for Switzerland (2003, OLS-based)


A) OLS-based, no constraints

B) OLS-based, with constraints

	ER	Risk		Nuclear	Storage hydro	Run of river	Solar
AP2003	1.00	6.00		40	32	24	4
MER	6.67	1.00					100
MV	6.67	1.00					100

	ER	Risk		Nuclear	Storage hydro	Run of river	Solar
AP2003	1.00	6.00		40	32	24	4
MER_C	4.41	2.12		96			4
MV_C	3.98	1.95		88	8		4

the two countries as well. Whereas opting for the MV alternative calls for 56 percent (rather than 100 percent) *Nuclear* in the case of the United States, it would leave *Solar* at almost 100 percent in the case of Switzerland. Since shares close to 100 percent are far from reality in either country, constraints on admissible shares of technologies were imposed in Figures 2B and 4B. This causes the existing amount of diversification to diminish in both countries, with *Coal* (United States) and *Nuclear* (Switzerland) becoming the principal energy sources. However, only the Swiss expected rate of return drops (from a 6.43 percent productivity increase to a 1.82 percent decrease for the MV_C portfolio), associated with a marked surge in volatility.

On the whole, it appears that the U.S. electricity industry, while respecting feasibility constraints, would have gained by substituting *Gas* by *Coal*, *Nuclear*, and *Wind* technologies by 2003, regardless of the choice between the MER_C and the MV_ C portfolio. Swiss utilities would have stood to gain as well by adopting more *Nuclear* to the detriment of *Run of river*, an important source of primary energy until recently. Divergences of U.S. and Swiss actual choices and efficient choices likely arose in the past since generating technologies have been selected solely on an individual, case-per-case basis, failing to consider their contribution to overall portfolio performance. Both industries at present fall short of their respective efficiency frontiers. In the United States, the gap amounts to a foregone 0.07 to 0.20 percentage points productivity increase p.a. and 0.78 to 1.07 points reduction of volatility (see Figure 2B). In Switzerland, the estimates amount to a foregone 0.18 percentage points of productivity growth and 1.11 points reduction of risk (see Figure 4B). Therefore, there is some evidence suggesting that the more heavily regulated Swiss industry is characterized by a higher degree of inefficiency in the allocation of generating technologies than its largely deregulated U.S. counterpart.

5. Conclusion

The objective of this contribution is to determine the efficient provision of electricity in the United States (traditionally fossil-based) and Switzerland (traditionally hydro- and nuclear-based), applying portfolio theory. The observation period covers 1982 to 2003 (United States) and 1986 to 2003 (Switzerland), respectively. Because the error terms proved to be correlated across equations explaining technology-specific productivity changes, Seemingly Unrelated Regression Estimation (SURE) was adopted for estimating the covariance matrix used in determining the efficient frontier. Interestingly, the maximum expected return (MER) portfolios of both countries boil down to one non-CO2 energy source (*Nuclear* in the United States and *Solar* in Switzerland). When constraints limiting changes from the status quo are imposed to reflect the high cost associated with adjusting the technology mix, the MER_C portfolio for the United States contains 60 percent *Coal* (up from 56 percent) and for Switzerland, 64 percent *Nuclear* (up from 40 percent).

However, one could argue that for populations as risk-averse as the American and the Swiss (Szpiro, 1986), the minimum variance portfolio (MV) is appropriate. Adopting the MV criterion and imposing the same constraints, U.S. utilities would still want to assign 60 percent of their portfolio to *Coal*, almost entirely replacing *Gas*. The productivity changes and hence returns of *Gas* are not only highly volatile but also strongly correlated with those of other technologies, depriving it of a possible 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 point of view. In the Swiss MV_C portfolio (subject to constraints), *Nuclear* accounts for even 64 percent while *Run of river* drops out (down from 24 percent). One is therefore led to conclude that as of 2003, both the U.S. and Swiss technology mix are inefficient even if ”realistic” constraints are respected. While U.S. utilities are currently closer to their efficiency frontier than their more heavily regulated Swiss counterparts, they still may reap efficiency gains by investing more in *Coal* and moving away from *Gas*.

The choice of econometric methodology proves important for decision-making. Efficiency frontiers estimated by OLS would tend to underestimate both expected returns and risk reduction potential in the case of the United States but overestimate achievable expected returns and underestimating risk reduction in the case of Switzerland. These discrepancies largely vanish, however, when feasibility constraints are imposed. Still, failure to account for correlation between unobserved shocks impinging on the different generation technologies using SURE does create the risk of opting for an inefficient solution. This finding contrasts with Berger et al. (2003), who concluded that the outcome of portfolio analysis is insensitive to econometric estimation techniques. However, the present study agrees with earlier ones in suggesting that utilities and policy makers, by adopting a single-technology approach typical of conventional least-cost planning, fail to take account of correlations between risky generating technologies. The consequence is a portfolio of generating technologies that is inefficient, achieving a too low expected rate of return and/or suffering from excessive volatility.

These statements are based on an investor view. One could also adopt a current user view, which emphasizes productivity levels rather than productivity changes over time. Future contributions therefore may compare the two views. They could also focus on prediction rather than postdiction, examining whether emergent new technologies are part of future efficient frontiers. Finally, the strong assumption of a once-and-for-all decision regarding the choice of technology needs to be relaxed. A real options approach could be used to account for the irreversibility often inherent in the decision to adopt a technology. Deferring adoption may become the preferred choice in the face of stochastic productivity changes caused e.g. by a liberalization of electricity markets – or its failure to materialize as expected. Still, the present study provides first indications of where to go in the future in an attempt to reach the efficient mix of power-generating technologies in countries that are as diverse as e.g. the United States and Switzerland.

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