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The Impact of Liberalization on the Scope of Efficiency Improvement in Electricity-Generating Portfolios for the United States and Switzerland*

Abstract

In dieser Studie werden effiziente Portfolien nach Markowitz für die USA und der Schweiz berechnet. Dabei wird die Sicht eines Investors (für den die Rendite der Veränderung der gewonnen kWh/USD entspricht) der Sicht des laufenden Benutzers (für den die Rendite den kWh/USD selbst entspricht) gegenübergestellt. Da zwischen den Schocks, die auf die Stromerzeugungskosten einwirken, Korrelationen bestehen, wird das SURE (Seemingly Unrelated Regression Estimation) Verfahren angewendet, um eine über die Zeit stabile Kovarianzmatrix zu erhalten. Das tatsächliche Technologieportfolio der USA liegt dichter an der Effizienzgrenze als dasjenige der Schweiz. Ein möglicher Grund hierfür ist die Energiemarktliberalisierung, die in den USA deutlich weiter vorangeschritten ist als in der Schweiz.

In this study, Markowitz mean-variance portfolio theory is applied to electricity-generating technologies of the United States and Switzerland. Both an investor (focused on changes in return) and a current user (focused on return in levels) view are adopted to determine efficient frontiers of electricity generation technologies in terms of expected return and risk as of 2003. Since shocks in generation costs per kWh (the inverse of returns) are correlated, Seemingly Unrelated Regression Estimation (SURE) is used to filter out the systematic components of the covariance matrix. Results suggest that risk-averse investors and risk-neutral current users in the United States are considerably closer to their efficiency frontier than their Swiss counterparts. This may be due to earlier and more thorough deregulation of electricity markets in the United States.

1 Introduction

This study applies Markowitz mean-variance portfolio theory to calculate efficient electricity- generating frontiers for the United States and Switzerland. Along the efficient electricity frontier, the expected return of a generating portfolio is maximized for a given amount of volatility or alternatively, the portfolio risk is minimized for a given expected return. The gap between the actual portfolio (AP) and the efficient frontier indicates the scope of efficiency improvement of the generating technology portfolio. Two perspectives are considered, an investor view (where expected return is defined as (the inverse of) cost *changes*, viz. percentage change of kWh/USD) and a current user view (where expected return is (inversely) defined as kWh/USD in *levels*). A comparison of the gaps between AP and efficiency frontier may show whether U.S. deregulation paid off in terms of more expected return or less risk, or both. The main benefit of deregulation is to increase competition and choice. Before the U.S. electricity markets were liberalized more than a decade ago, consumers were forced to buy electricity from local utilities while utilities had no control over pricing. By way of contrast, Switzerland has just recently started to give large users (in excess of 100,000 kWh/year) the free choice of provider. However, electricity markets will not be fully liberalized until 2014.

Mean-variance portfolio analysis has been applied to real asset portfolios in energy, among others, by Bar-Lev and Katz (1976), Adegbulugbe et al. (1989), Humphreys and McClain (1998), Awerbuch (2000), Awerbuch and Berger (2003), Awerbuch et al. (2004), Berger et al. (2003), Yu (2003), and Krey and Zweifel (2009). Yet, to the best of the authors' knowledge, the investor and the current user view were never juxtaposed and the gaps between the APs and the efficiency never related to regulation in a cross-country comparison.

This study is structured as follows, section 2 provides some background information on the electricity markets of the United States and Switzerland, section 3 presents the methodology, while section 4 presents the efficiency frontiers for the United States and Switzerland. Conclusions are offered in section 5.

* This research has been financially supported by the Swiss National Science Foundation (100012–116563). The authors would like to thank Phillipe Widmer for helpful comments. Remaining errors are our own.

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2 Background information

2.1 United States

In 2003 the United States generated approximately 4000 TWh electricity for its 290 million inhabitants by using (i) *Coal*, (ii) *Nuclear*, (iii) *Gas*, (iv) *Oil*, and (v) *Wind* technologies (due to data limitations, hydro power is not considered in this study, which contributed an estimated 9 percent to the U.S. electricity generation mix). Between the 1990s and early 2000, deregulation swept through 24 states[1] affecting more than 180 million consumers. Most states did exceptionally well after deregulation, most notably Michigan, Ohio, and Texas[2], where average retail electricity prices fell below the U.S. average of 6.7 U.S. cents per kilowatt-hour[3]. Compared to 1985 (prior to deregulation), the electricity-generating portfolio of 2003 shows an increase in the shares of *Nuclear*, *Gas*, and *Wind* technologies at the expense of *Coal* and *Oil* (see Table 1, Panel A).

2.2 Switzerland

Switzerland is a federal state consisting of 26 cantons, inhabited by about 7.5 million citizens. In 2003, Switzerland generated 65 TWh electricity, using (i) *Nuclear*, (ii) *Run of river*, (iii) *Storage hydro*, and (iv) *Solar* (which in this study comprises all renewables plus conventional thermic power plants and other sources). Neither industry nor households had a choice of provider. Generation, transmission, and distribution were highly regulated. Since January 2008, large users (in excess of 100,000 kWh/year) have the right to choose their electricity supplier. This is the first of many steps designed to deregulate the Swiss electricity market, which is planned to be fully liberalized by 2014, subject to a public referendum however. As can be seen in Table 1 (Panel B), the technology mix has been very stable over the last few decades, comprising between 39 to 40 percent *Nuclear* and 56 to 59 percent hydro power (*Run of river* and *Storage hydro* combined).

1 These are: Arizona, Arkansas, California, Connecticut, Delaware, Illinois, Maine, Maryland, Massachusetts, Michigan, Montana, Nevada, New Hampshire, New Jersey, New Mexico, New York, Ohio, Oklahoma, Oregon, Pennsylvania, Rhode Island, Texas, Virginia, and Washington D.C.

2 California went into a crisis in 2001, when blackouts and the insolvency of PG&E, the major public utility, shocked the U.S. market. Insufficient capacity investments and bad contracting during the 1960s, 1970s and 1980s were responsible for the crisis (Borenstein/Bushnell (2000), pp. 47–48).

3 Borenstein/Bushnell (2000), p. 47

3 Methodology

3.1 Portfolio theory

Holders of a portfolio of assets seek to minimize risk given its expected return or alternatively maximize its expected return at a given level of risk. In the present context, the portfolio consists of electricity-generating technologies. Its expected return depends on the expected returns of the individual technologies, weighted by their shares. The risk of the portfolio depends on the covariance or correlation matrix of the individual returns.

The expected return of a portfolio $E(R_p)$ consisting of s risky assets is given by

$$E(R_p) = \sum_{i=1}^{s} w_i E(R_i)\ ;\ \text{with} \sum_{i}^{s} w_i = 1, \quad (1)$$

where $E(R_i)$ is the expected return of technology i and w_i is the share (weight) of technology i in the portfolio. For example, a portfolio comprising three generating technologies would have

$$E(R_p) = w_1E(R_1) + w_2E(R_2) + w_3E(R_3), \quad (2)$$

with

$$\sum_{i=1}^{3} w_i = w_1 + w_2 + w_3 = 1. \quad (3)$$

The volatility of the portfolio's expected return involves both the respective variances and covariances of the individual returns. The standard deviation (σ_p) is a common measure of risk. For a portfolio containing s technologies, it is given by

$$\sigma_p = \sqrt{\sum_{i=1}^{s} w_i^2 \sigma_i^2 + 2\sum_{i \neq 1} w_i w_j \rho_{ij} \sigma_i \sigma_j}\ , \quad (4)$$

where σ_i and σ_j are individual standard deviations of the returns of technology i and technology j, and $\rho_{ij} = \text{cov}_{ij}/(\sigma_i \sigma_j)$, $i, j = 1, \ldots, 3$, are correlation coefficients. Using the same three technology example as before, the portfolio standard deviation can be computed from

$$\sigma_p = \sqrt{w_1^2\sigma_1^2 + w_2^2\sigma_2^2 + w_3^2\sigma_3^2 + 2w_1w_2\rho_{12}\sigma_1\sigma_2 + 2w_1w_3\rho_{13}\sigma_1\sigma_3 + 2w_2w_3\rho_{23}\sigma_2\sigma_3}\ . \quad (5)$$

The set of efficient portfolios is the solution of two equivalent problems,

$$\max_{w_i} E(R_p)\ s.t. \sum_{i=1}^{s} w_i = 1, \sigma \leq \bar{\sigma}\,, \quad (6)$$

$$\max_{wi} \sigma_p\ s.t. \sum_{i=1}^{s} w_i = 1, E(R_p) \geq \bar{R}\,. \quad (7)$$

Equation (6) says that the expected return of the portfolio is to be maximized subject to the constraint that volatility must not exceed a limit value $\bar{\sigma}$. Equation (7) says that volatility shall be minimized, whereas expected return cannot fall below a limit value $\bar{R}$. In this study, the decision variables in both equations are the shares w_i that are assigned to the generation technologies of the portfolio.

Portfolio theory determines an efficient frontier containing a continuum of positive solutions. The optimal solution depends on whether the investor or the cur-

Table 1 | Actual portfolio technology shares of the United States and Switzerland *

Panel A: United States**			Panel B: Switzerland		
Technology	Share in percent		Technology	Share in percent	
	1985 (Before liberalization)	2003		1985	2003 (No liberalization)
Coal	64	56	*Nuclear*	39	40
Nuclear	18	21	*Storage hydro*	34	32
Gas	13.5	18	*Run of river*	25	24
Oil	4.49	3	*Solar*	2	4
Wind	< 0.01	2			

* Sources: SFOE (2004); IEA (2005) ** Excluding hydro (see section 4.3)

rent user view is adopted and on the degree of risk aversion.

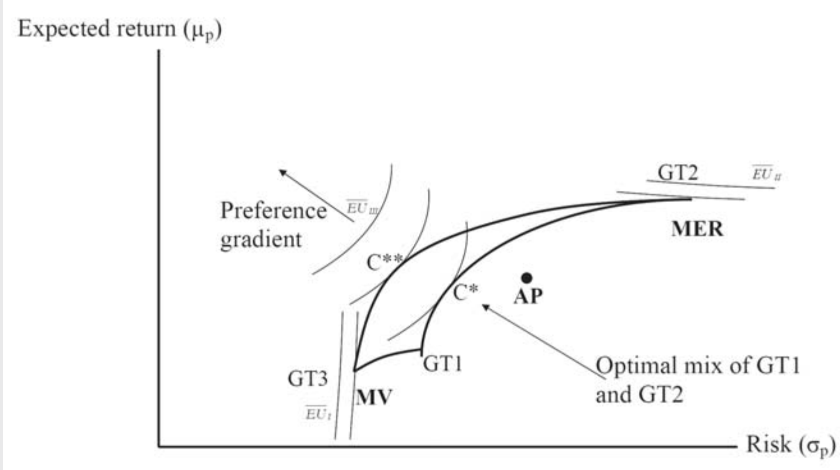
In Figure 1, the horizontal axis depicts portfolio risk as measured by the standard deviation (σ_p), while the vertical axis displays expected return (μ_p). The investor view is presented first. In that case, the vertical axis describes the percentage *change* of expected returns (measured in kWh/USD; the more positive, the larger the expected return).

To illustrate, let there be only two power electricity generation technologies, GT1 and GT2. By assumption, GT1 has little volatility in terms of change in expected returns; on the other hand, the expected change in expected return is small (e.g. *Coal* in the United States). By way of contrast, GT2 is more risky, but on expectation has higher return (e.g. *Wind* in the United States). Due to the correlation terms contained in eqs. (4) and (5), the efficient frontier linking GT1 and GT2 (i.e. combining the two technologies) is not linear but a segment of an ellipse. Thus, if the correlation between two electricity generation technologies is less than perfect ($-1 \leq \rho_{12} \leq 1$), the efficient frontier between GT1 and GT2 runs concave from below. The lower the correlation coefficient, the stronger this portfolio effect[4]. This means that by adding GT2 with its high volatility but increasing expected return to the portfolio, the investor will profit from a diversification effect.

If returns of GT1 and GT2 move in a perfectly opposite way (i.e. $\rho_{12} = -1$), then a portfolio with no volatility at all can be constructed[5]. Such a portfolio always yields the same expected return, since whenever returns of GT2 are higher than expected, returns of GT1 are below expectation by an equal amount.

If a third technology (GT3) enters the portfolio, additional opportunities for diversification arise. However, to predict the optimal portfolio (to be selected among the efficient ones), knowledge of the investor's preferences would be necessary. This will not be the topic of this study per se; nevertheless, Figure 1 is complemented by the graphic representation of preferences using indifference curves, along which expected utility (EU) rather than utility is held constant since the presence of risk

Figure 1 | Efficient portfolios of electricity generation technologies (GT)



makes it impossible to attain a fixed level of utility.

Risk-averse investors like a higher expected return but dislike volatility. This means that the peak of an imagined hill of subjective valuation is way out on the vertical axis (implying a positive rate of return, but no volatility). Accordingly, the arrow symbolizing the direction of the peak (the so-called preference gradient) points northwest. Evidently, the optimum allocation of assets is given by the highest-valued indifference curve that is still compatible (i.e. tangent) with the efficient frontier. For the frontier composed of GT1 and GT2, this optimum is depicted by the tangency point C*. If GT3 is indeed available, C** becomes the new optimum, with a higher increase of the value of the portfolio and at the same time less volatility. Clearly, C** lies on a higher-valued indifference curve than C*, demonstrating the contribution to welfare that can be expected from the availability of additional energy technologies thanks to improved diversification.

Now the current user view is adopted, which characterizes decision-makers with a short-term planning horizon, arguably regulators and regulated utilities. In this case, the vertical axis describes expected returns in *levels* of kWh/USD (the higher the value, the larger the expected return). By assumption, GT1 (e.g. *Solar* generated power in Switzerland) has a low expected return but also a low volatility of expected return. By way of contrast, GT2 has much higher expected return but is more risky (e.g. *Run of river* in Switzerland). As before, a correlation between the two generation technologies that is less than perfect makes the efficient frontier run concave, resulting in a diversification effect[6]. In a study assessing the efficient electricity portfolio for Scotland, Awerbuch[7] showed that by adding *Wind* generation to the existing technology mix, a much lower standard deviation of the portfolio (with returns defined in kWh/USD) can be attained. This is because Scottish *Wind* generation costs (the inverse of returns) do not correlate with fossil fuel-intensive technologies, causing it to have a diversification effect[8].

In the following, focus will be on two extreme solutions, the minimum variance (MV) portfolio and the maximum expected return (MER) portfolio. The MV portfolio, which coincides with GT3 in Figure 1, is preferred by strongly risk-averse decision makers. The MER alternative, which coincides with GT2 in the example, is the option for (almost) risk neutral types. These two portfolios permit to narrow down the efficient choices of both investors and current users. The gap between the actual portfolio AP and these two efficient portfolios indicates the scope of efficiency improvement. It also reflects foregone efficiency gains, which are to be related to the state of liberalization. Specifically, a liberalized electricity market is predicted to be closer to the efficiency

4 Awerbuch (2006) argues that portfolio effects become more pronounced once correlation coefficients are below 0.6.
5 Ingersoll (1987), chp. 4
6 Awerbuch/Berger (2003)
7 Awerbuch (2006)
8 Awerbuch (2006) also refers to Brealey/Myers (1994), who illustrate that by adding riskless government bonds yielding as little as 3 percent to a stock portfolio yielding 8 percent serves to raise the expected return at any level of risk.

frontier (smaller gap) than a regulated one, since regulation tend to consider a single generation technology at a time, rather than an efficient portfolio mix.

3.2 Seemingly Unrelated Regression Estimation (SURE)

To derive time-invariant estimates of the covariance matrix (i.e. of σ_i and σ_{ij}) predicted values of each time series of electricity-generating returns without a systematic shift are estimated by

$$\hat{R}_{i,t} = R_{i,t} - \hat{u}_{i,t}\,. \tag{8}$$

As has been shown in detail by Krey and Zweifel[9] shocks in the error term $u_{i,t}$ causing volatility in the dependent variable $R_{i,t}$ are correlated across technologies for both investors and current users. Therefore, the SURE (Seemingly Unrelated Regression Estimation) method is used to improve the efficiency of estimation, resulting in sharper estimates of the parameters and residuals, and hence of the σ_i and σ_{ij} making up the covariance matrix of returns.

The set of equations making up SURE in the three technology example read

$$\begin{aligned} R_{1,t} &= a_0 + \sum_{j=1}^{m} a_{1,j} \cdot R_{1,t-j} + u_{1,t} \\ R_{2,t} &= b_0 + \sum_{j=1}^{m} b_{2,j} \cdot R_{2,t-j} + u_{2,t} \\ R_{3,t} &= c_0 + \sum_{j=1}^{m} c_{3,j} \cdot R_{3,t-j} + u_{3,t} \end{aligned} \tag{9}$$

where $R_{1,t}$, $R_{2,t}$, $R_{3,t}$ are the returns for technologies i = 1,2,3 in year t. a_0, b_0, c_0 are their respective constants, $a_{1,j}$, $b_{2,j}$, $c_{3,j}$ are the coefficients of returns lagged j years, $R_{1,t-j}$, $R_{2,t-j}$, $R_{3,t-j}$ are the dependent explanatory variables lagged j years, and $u_{1,t}$, $u_{2,t}$, $u_{3,t}$ are the error terms.

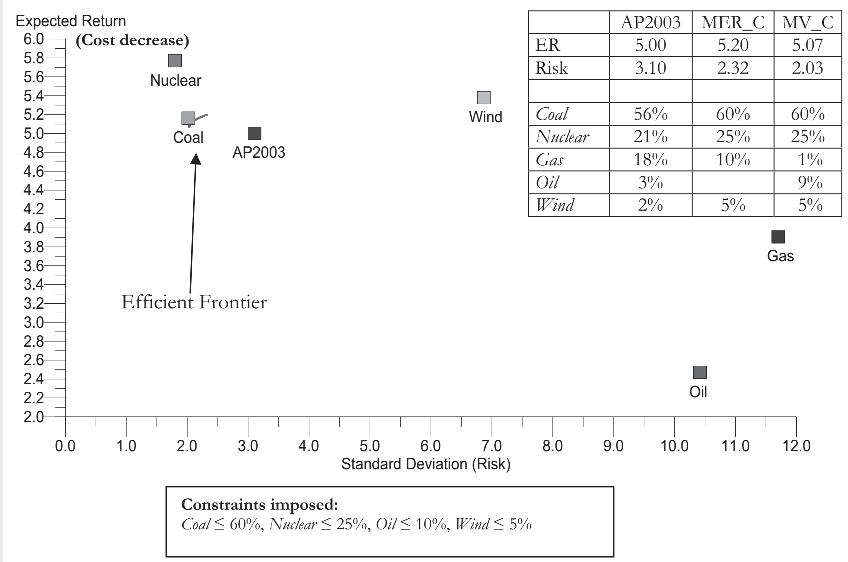
The crucial assumption of SURE is that the covariance matrix of residuals Ω is not diagonal,

$$\mathbf{\Omega} = E(\mathbf{uu'}) = \begin{bmatrix} \sigma_{1,1}I & \sigma_{1,2}I & \sigma_{1,3}I \\ \sigma_{2,1}I & \sigma_{2,2}I & \sigma_{2,3}I \\ \sigma_{3,1}I & \sigma_{3,2}I & \sigma_{3,3}I \end{bmatrix}. \tag{10}$$

Taking into account the possible correlation of error terms across equations, SURE simultaneously estimates the expected returns of all electricity-generating technologies in one set of regressions.

9 Krey/Zweifel (2008)

Figure 2 | Efficiency frontier for the United States (2003, SURE-based, with constraints, investor view)



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

Constraints imposed:
Coal ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

3.3 Data

U.S. and Swiss data on generating technology costs (the inverse of expected returns) comprise fuel costs, costs of current operations, capital user costs and an externality surcharge for environmental damage[10]. The U.S. data set covers five technologies, *Coal*, *Nuclear*, *Gas*, *Oil* and *Wind* power for the years 1981 to 2003. The Swiss data set consists of four variables, *Nuclear* for the years 1985 to 2003, *Run of river* and *Storage hydro* for 1993 to 2003, and *Solar*, covering the years 1991 to 2003. All variables are annual costs in changes (levels, respectively) in U.S. cents[11] per kWh electricity (inverse of expected returns), deflated by the CPI, with 2000 serving as the base year. Only annual aggregated data are available, representing more than 50 percent of capacity in both countries. Actual portfolios relate to the observed technology shares as of 2003 (see section 2), obtained from the International Energy Agency (IEA)[12] and the Swiss Federal Office of Energy (SFOE)[13]. Figures 2 and 4 show the AP2003 for the United States, Figures 3 and 5, that for Switzerland. For example, in 2003 *Coal* was the most prominent U.S. technology, with a share of 56 percent; in Switzerland, it was *Nuclear* with 40 percent.

10 External cost data for the United States were approximated by data from the United Kingdom, which has a similar generation mix and structure (European Commission, (2003)).

11 A conversion factor of USD 1 = CHF 1.65 was used (2003)

12 IEA (2005); IEA (2006)

13 SFOE (2004)

4 Efficient U.S. and Swiss electricity-generating frontiers

4.1 Efficiency frontier for the United States: Investor view

Figure 2 displays the feasible efficiency frontier for the United States adopting an investor view. To reflect technical feasibility[14], upper limits are imposed on technology shares. For example, the share of *Coal* cannot exceed 60 percent by assumption (see insert below Figure 2).

The MER_C (with "C" for constrained) portfolio contains *Coal* (60 percent, binding, up from 56 percent in the actual portfolio), *Nuclear* (25 percent, binding, up from 21 percent), *Gas* (10 percent, down from 18 percent), and *Wind* (5 percent, binding, up from 2 percent). Compared to the actual portfolio (AP 2003), the cost decrease would speed up (from 5.00 percent p.a. to 5.20 percent p.a.), while volatility would decline from 3.10 to 2.32 percent p.a.

14 Over the course of two decades and less, radical changes in the share of any single technology must be deemed unrealistic in view of the costs of adjustment implied.

In the MV_C alternative, the highest share is allocated to *Coal*[15] (60 percent, binding), followed by *Nuclear* (25 percent, binding), *Oil* (9 percent, up from 3 percent), and *Wind* (5 percent, again binding). The only technology to lose market share is *Gas* (to a mere 1 percent, down from 18 percent). The rate of cost reduction 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. Therefore, two important conclusions can be drawn. First, current U.S. power generation is inefficient from an investor point of view. Second, it could be made more efficient by substituting *Gas* by *Coal*, *Nuclear*, *Oil* (not in the MER_C portfolio), and *Wind*.

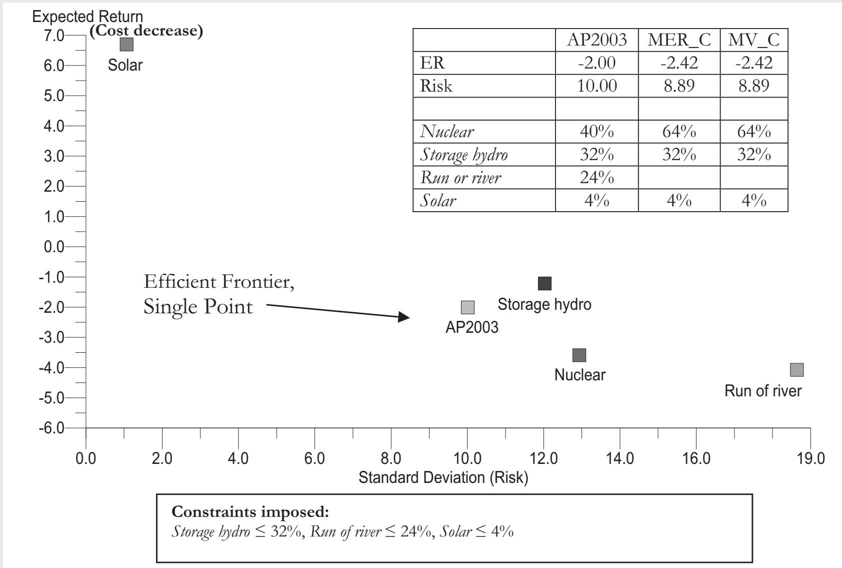
4.2 Efficiency frontier for Switzerland: Investor view

Figure 3 shows the efficient MER_C and MV_C electricity portfolios adopting an investor view for Switzerland. This time, *Storage hydro*, *Run of river*, and *Solar* are constrained to their actual shares in 2003 (32, 24, and 4 percent p.a., respectively, see insert below Figure 3), leaving only *Nuclear* unconstrained. This can be justified because *Storage hydro* and *Run of river* are already utilized to full capacity[16], while a share of *Solar* electricity (a proxy for all renewables plus conventional thermic power plants and other sources) of 4 percent constitutes the limit of what could have been achieved.

Because the feasible efficient frontier shrinks to a single point, both MER_C and MV_C portfolios call for a complete substitution of *Run of river* (actual share 24 percent) by *Nuclear* (64 percent, up from 40 percent), *Storage hydro* (32 percent, binding), and *Solar* (4 percent, binding). *Run of river* has been subject to cost increases, which, combined with its poor diversification effect due to high correlations with other technologies, makes it an unattractive choice for an investor.

In all, Figure 3 suggests that even if "realistic" constraints are respected, Swiss electricity generation could be made more efficient (thus the 2003 mix is inefficient) by allowing the share of *Nuclear* to substantially increase while abandoning *Run of river*. Returns would fall at a slightly

Figure 3 | Efficiency frontier for Switzerland (2003, SURE-based, with constraints, investor view)



higher rate, from –2.00 (actual) to –2.42 percent p.a., regardless of choice between MER_C and MV_C portfolios, but volatility would drop from 10.00 (actual) to 8.89.

4.3 United States and Switzerland compared: Investor view

According to the feasible efficient portfolios, *Coal* in the United States and *Nuclear* in Switzerland are the principal sources for electricity generation. 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.

Therefore, 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 p.a. of cost and 0.78 to 1.07 points volatility reduction (see Figure 2). In Switzerland, the estimates amount to a foregone 1.11 points reduction of risk (see Figure 3), which is larger than in the United States (between 0.78 and 1.07). However, the reduction in risk comes at the cost of a loss in expected return of 0.42 percentage points (in the United States, unit cost USD/kWh is falling and hence kWh/USD increasing). Therefore, a risk-averse U.S. investor would have gained by adopting the MV_C portfolio, a Swiss investor, possibly so. Interestingly, the evidence suggests that the scope of reducing risk in the more heavily regulated Swiss industry is bigger than in its largely deregulated U.S. counterpart.

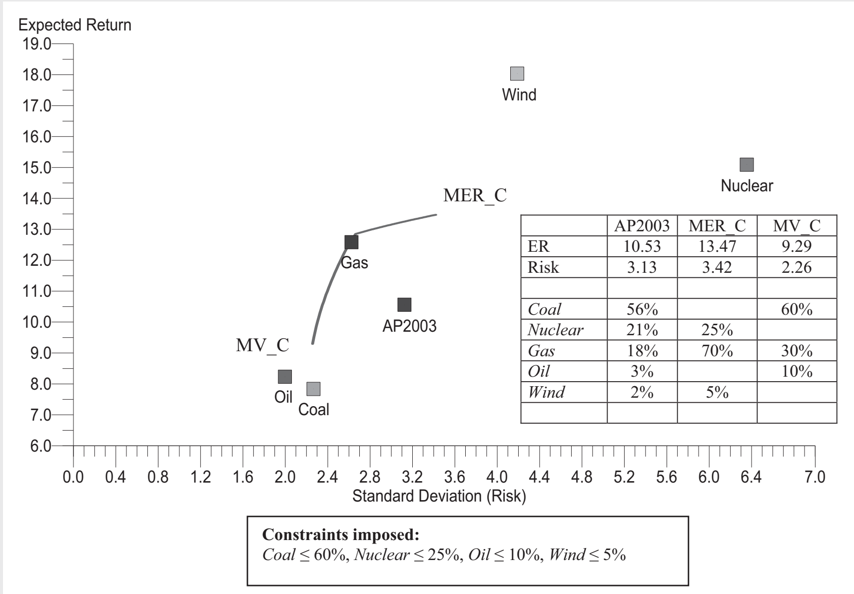
4.4 Efficiency frontier for the United States: Current user view

For a current user of a technology, it is the return of a portfolio defined in kWh/USD that matters, and not its relative change (see section 3). Therefore, Figure 4 below displays the efficiency frontier for the United States in terms of levels. As before, constraints reflecting technical feasibility are imposed (see insert below Figure 4).

The estimated MER_C mix contains *Gas* (70 percent, up from 18 percent), *Nuclear* (25 percent, binding, up from 21 percent), and *Wind* (5 percent, binding, up from 2 percent), leading to a large increase in expected return to 13.47 kWh/USD (rather than 10.53 in the AP2003) but also to higher risk (3.42 vs 3.13 kWh/USD). The MV_C portfolio on the other hand calls for *Coal* (60 percent, binding, up from 56 percent), *Gas* (30 percent) and *Oil* (10 percent, binding, up from 3 percent). This time, return falls from the AP2003 (10.53 kWh/USD) to 9.29. Risk is also reduced, from 3.42 to 2.26 kWh/USD. As can also be gleaned from Figure 4, the re-

15 Using portfolio theory for three U.S. generating technologies, Berger et al. (2003) also concluded that *Coal* dominates the MV portfolio taking a share of 77 percent.
16 Laufer/Grötzinger/Peter/Schmutz (2004)

Figure 4 | Efficiency frontier for the United States (2003, SURE-based, with constraints, current user view)



	AP2003	MER_C	MV_C
ER	10.53	13.47	9.29
Risk	3.13	3.42	2.26
Coal	56%		60%
Nuclear	21%	25%	
Gas	18%	70%	30%
Oil	3%		10%
Wind	2%	5%	

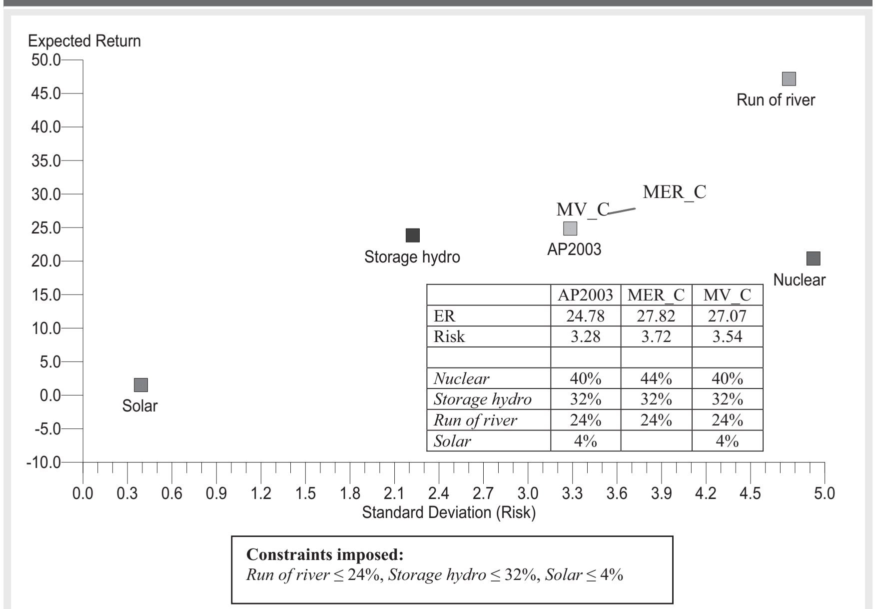
duction in risk comes at the expense of a lower expected return.

4.5 Efficiency frontier for Switzerland: Current user view

Figure 5 displays the set of efficient power-generation portfolios for Switzerland defined in terms of kWh/USD. The same feasibility restrictions are imposed on the technology shares as in section 4.2 above.

Absent risk aversion, the MER_C portfolio would be preferred, containing *Nuclear* (44 percent, up from 40 percent), *Storage hydro* (32 percent, binding), and *Run of river* (24 percent, binding). Expected return is 27.82, compared to 24.78 kWh/USD in AP2003, while risk increases slightly from 3.28 to 3.72. The MV_C portfolio coincides with AP2003, with 40 percent *Nuclear*, 32 percent *Storage hydro*, 24 percent *Run of river*, and 4 percent *Solar*. Interestingly, it exhibits slightly more risk than AP2003 (3.54 as compared to 3.28 kWh/USD), which is due to the use of stabilized correlations in this particular instance. However, it has 2.3 percentage points more expected return (27.07 vs. 24.78), making it an attractive choice.

Figure 5 | Efficiency frontier for Switzerland (2003, SURE-based, with constraints, current user view)



	AP2003	MER_C	MV_C
ER	24.78	27.82	27.07
Risk	3.28	3.72	3.54
Nuclear	40%	44%	40%
Storage hydro	32%	32%	32%
Run of river	24%	24%	24%
Solar	4%		4%

4.6 United States and Switzerland compared: Current user view

As before (investor view, see section 4.3) *Coal* takes the largest share in the U.S. MV_C portfolio. The big change is in the current user MER_C portfolio where now *Gas* dominates, while *Coal* is phased out. By way of contrast, *Nuclear* remains the principal source for Swiss electricity generation in both MER_C and MV_C portfolios. Once more, both countries fall short of their respective efficiency frontier. The United States faces a gap amounting to a foregone expected return increase of 2.94 kWh/USD in the MER_C portfolio and a foregone risk reduction of –0.87 in the MV_C mix (see Figure 4). In Switzerland, the estimates amount to a foregone expected return increase of 3.04 kWh/USD in the MER_C portfolio (0.10 kWh/USD more than in the United States). However, the larger increase in expected return comes at the price of an increase in risk in both MER_C and MV_C portfolios (see Figure 5). Risk-neutral current users would gain by adopting the MER_C portfolio in the United States. In Switzerland, they again stand to gain even more. This differential confirms the hypothesis that liberalization serves to enhance efficiency since Swiss electricity markets continue to be heavily regulated. However, this confirmation is incomplete because it is in the United States rather than Switzerland that risk-averse current users would benefit from adopting a feasible MV_C portfolio.

5 Conclusions

This paper employed Markowitz mean-variance portfolio theory to determine efficiency frontiers for electricity-generating technologies in the United States and Switzerland. Two perspectives were adopted. According to the investor view, expected returns are defined as *changes* in kWh/USD, while according to the current user view, they are defined as kWh/USD in *levels*. The observation period covers the years 1981 to 2003 (United States) and 1985 to 2003 (Switzerland).

The Seemingly Unrelated Regression Estimation (SURE) method was used to estimate a reasonably time-invariant covariance matrix. Since shocks in generation costs per kWh (the inverse of returns) are correlated, SURE serves to filter out the systematic components of the covariance matrix. Results suggest that the actual portfolios of generating technologies of the United States and Switzerland are off their respective efficiency frontiers. Both countries (but in particular Switzerland) could do better by rearranging their current portfolios.

Adopting the investor view, the United States are best advised to use more *Coal* and *Nuclear*. However, changes since 1985 have been in the right direction, likely fostered by early liberalization of electricity markets. As can be gleaned from Table 1 (Panel A), the share of *Nuclear* increased from 18 percent in 1985 to 21 percent in 2003, whereas the efficient value for risk-averse investors is 25 percent (see MV_C portfolio in Figure 2). In addition, the share of *Wind* increased from less than 0.01 percent in 1985 to about 2 percent in 2003 (the efficient value is 5 percent). However, the share of *Gas* did grow from 13.5 to 18 percent by 2003 while a mere 1 percent would be regarded efficient in this study. The observed value is much more in line with the current user view, which would prescribe 30 or even 70 percent (see Figure 4).

This should be contrasted with the Swiss experience. The share of *Nuclear* remained very stable between 39 to 40 percent between 1985 and 2003 (see Table 1, Panel B), whereas from an investor point of view (regardless of risk aversion, see Figure 3) it should be 64 percent. Like- wise, the share of *Run of river* stayed between 24 and 25 percent whereas efficiency would have called for a phase-out. This continuity looks only efficient if the static current user view combined with tight feasibility constraints is adopted (see Figure 5). Of course, it is precisely this view that is typically compatible with regulation. The evidence therefore tends to support the hypothesis that U.S. producers and consumers of electricity benefited from liberalization, while their Swiss counterparts have to wait for a few more years to reap its benefits.

Future research may try to analyze more generating technologies, also taking into account imports of electricity, which can be considered as an additional component of the efficient technology portfolio. It would also be interesting to include more countries, among them a fully liberalized one, such as the United Kingdom.

6 References

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