

Sunderkötter, Malte; Ziegler, Daniel

Working Paper

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EWL Working Paper, No. 03/13

Provided in Cooperation with:

University of Duisburg-Essen, Chair for Management Science and Energy Economics

Suggested Citation: Sunderkötter, Malte; Ziegler, Daniel (2013) : Perfect Competition vs. Riskaverse Agents: Technology Portfolio Choice in Electricity Markets, EWL Working Paper, No. 03/13, University of Duisburg-Essen, Chair for Management Science and Energy Economics, Essen

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Chair for Management Sciences and Energy Economics
University of Duisburg-Essen

EWL Working Paper No. [03/13]

**PERFECT COMPETITION VS. RISK-AVERSE AGENTS:
TECHNOLOGY PORTFOLIO CHOICE IN ELECTRICITY MARKETS**

by

Malte Sunderkötter,

Daniel Ziegler,

and

Christoph Weber

April 2013

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Abstract

Investments in power generation assets are risky due to high construction costs and long asset lifetimes. Technology diversification in generation portfolios represents one option to reduce long-term investment risks for risk-averse decision makers. In this article, we analyze the impact of market imperfections induced by risk-aversion on the long-term investment portfolio structure in the market. We show that risk-averse electricity market agents who receive a managerial profit share may shift the technology structure in the market significantly away from the welfare optimum. A numerical example provides estimates on the potential scale of this effect and discusses sensitivities of key parameters.

*Keywords : long-term market equilibrium, generation expansion planning,
mean-variance portfolio theory, fuel mix diversification*

JEL-Classification : G11, L94, Q43, C45

** Corresponding Author:*

DIPL.-WI.-ING. DANIEL ZIEGLER

Chair for Management Sciences and Energy Economics,
University of Duisburg-Essen (Campus Essen)

Universitätsstr. 11, 45117 Essen

++49 - (0)201 / 183-2279

www.ewl.wiwi.uni-due.de

Daniel.Ziegler@uni-due.de

*The authors are solely responsible for the contents which do not necessarily represent the opinion of
the Chair for Management Sciences and Energy Economics*

1. Introduction

More than 10 years after the liberalization of electricity markets in Europe, there is a continuing discussion among energy researchers and policy makers whether fully liberalized electricity markets provide an adequate framework in which competition leads also to welfare optimal results (e.g. [Roques et al., 2008](#); [Müsgens, 2006](#); [Bunn and Day, 2009](#)). Following neoclassical economic theory, the set of decisions by individual investors should also lead to a socially optimal capacity allocation in efficient markets.²

In fact, there are several indications for insufficiencies observable on real electricity markets that could lead to a suboptimal degree of fuel mix diversification from a welfare perspective:³ Thereby, one potential conflict of interests between individual investors and social welfare is caused by different valuation of market risks inherent to a generation portfolio with a particular fuel mix: Given that all technology portfolios realize the same level of expected costs and profits, risk averse plant investors on electricity markets will favor the plant portfolio with least variability in the net cash flow (income minus operating costs). In contrast, the welfare optimal technology mix would minimize the variability of total operating costs. This indicates that pricing mechanisms in particular market settings do not allow an adequate risk transfer from investors to consumers so that investor incentives lead to a market equilibrium which is also optimal from a social wealth point of view.

This article aims to investigate impact of risk aversion on the choice of technology portfolios on liberalized electricity markets. To our knowledge, a related study has only been published by [Meunier \(2012\)](#): The author proposes a simple equilibrium model taking into account correlation between technology costs and their implication on the firms' revenues. Yet specific operating times of the different technologies are neglected, implying an unrealistic derivation of the electricity market price. Instead, we use an equilibrium model based on the peak-load pricing concept to analyze the influence of risk aversion of the electricity market agents on the market outcome.

1.1. Market imperfections and risk-averse agents

Risk averse investor behavior represents one market imperfection which could lead to deviations from a welfare optimal investment policy. The fact that many companies commit significant resources to corporate

²However, there are several important preconditions for this to hold: In addition to perfect competition ([Pigou, 1932](#)), complete financial spot and forward markets or perfect foresight, risk neutrality (or risk-sharing opportunities), and convex production possibilities, which imply non-increasing returns to scale, are required to obtain a match of investor and wealth optimum (e.g. [Arrow and Debreu, 1954](#); [Debreu, 1959](#)).

³Imperfect competition on electricity markets has drawn great attention in academic literature. Market imperfections are usually analyzed using game theory and price equilibrium models ([Bolle, 1992](#); [Green and Newbery, 1992](#); [Hobbs et al., 2000](#); [Hobbs, 2001](#); [Kleindorfer et al., 2001](#); [Moitre, 2002](#)). Several models have been discussed in literature, including Cournot and Bertrand models ([Joskow and Tirole, 2007](#); [Ellersdorfer, 2005](#)) and supply function models ([Day et al., 2002](#)).

risk management and portfolio management indicates the existence of risk-averse behavior at the company level although this practice raises doubts in view of neoclassical microeconomic theory. Following the validity of the CAPM ([Sharpe, 1964](#); [Lintner, 1965](#); [Mossin, 1966](#)) and the APT ([Ross, 1976](#)), investors on efficient capital markets value their investment decisions solely based on the ratio of expected return and systematic risk of an investment, whereas the unsystematic (i.e. firm-specific) risk is eliminated by diversification in other financial investments. In such a world, corporate risk management has to be questioned as a whole because its impact on the firm's risk position would be irrelevant for the investors.

While the applicability of CAPM and APT with their idealistic assumptions on market perfection became increasingly questioned in view of more and more empirically observed market anomalies in the last decades, valuation of corporate risk management in view of the firm's value has attracted substantial interest in economic literature. The rationale behind different corporate risk management strategies such as corporate portfolio management including R&D project or technology portfolios optimization hedging, has been intensively investigated and is summarized e.g. in [Bartram \(2000\)](#) and [Gossy \(2008\)](#). Three main lines of argumentation can be identified that may justify corporate risk management and risk averse behavior at the company level:

Firstly, agency-theory explains risk-averse management behavior through personal interests of the management. The management's wealth including future compensation is often little diversified, so that in-company diversification is in the management's interest ([Stulz, 1984](#); [Smith and Stulz, 1985](#)). Furthermore, volatility reducing risk management activities allow an exacter corporate planning and protect from negative outliers which makes it easier for the management to deliver the promised performance and avoid situations which could be interpreted by the equity holders as managerial incompetence.

Secondly, the costs of financial distress have been intensively discussed as a reason why firms hedge their risk exposure (see e.g. [Stulz, 1996](#); [Bartram, 2000](#)): If firms cannot meet their payment obligations and enter the stage of insolvency, direct costs arise, e.g. for legal expenses, as well as indirect costs as e.g. the loss of tax shields. But even before this point, financial distress can induce high costs due to e.g. higher financing costs as a result of a lower credit rating. The thread of bankruptcy can furthermore yield a loss of reputation in view of employees and (potential) customers, resulting in higher costs for human resources and customer discounts. If shareholders see bankruptcy and financial distress as a real risk, corporate risk management can therefore increase the firm's value by reducing this risk.

Thirdly, effective capital market imperfections, such as agency costs, transaction costs (especially with not publicly listed companies such as many utilities) and taxes hinder the equity holders' from sufficient diversification in their financial portfolios. Instead, some investors may prefer adequate risk management on the company level to reduce their risk exposure. Especially equity holders in the electricity industry (to a high degree public entities) often have a strategic and long-term interest in their investments which reduces the possibilities for diversification due to limited funds.

1.2. Mean-Variance optimization of corporate portfolios

Although mean-variance optimization of corporate portfolios has been variously discussed in corporate finance literature, there is only one work transferring this approach to electricity generation portfolios of a utility company: [Roques et al. \(2008\)](#) propose an optimization framework for generation portfolios from an investor perspective.

However, the applicability of the proposed model is limited to base load generation portfolios, because the authors base their model on the assumption of a stable electricity price distribution derived from historical data. The consequence is a net present value (NPV) distribution which neglects the fact that the portfolio composition will also affect electricity prices and therewith technology-specific full load hours in the long run. If however rational investors would apply Mean-Variance Portfolio (MVP) theory market-wide, the resulting optimal technology mix will clearly influence the shape of the price duration curve and therewith specific NPVs of the considered generation technologies. By limiting the model to base load generation portfolios, [Roques et al. \(2008\)](#) circumvent the problem of modeling technology-specific adjustments of full load hours and implications on the electricity price distribution. While this limitation avoids inconsistencies in the modeling results, it however prevents to derive conclusions about the optimal generation portfolio for an electricity market as a whole and about the long-term market equilibrium which can have – even for base load portfolios – a very different electricity price distribution due to changes in the generation portfolio.⁴ Hence, a solid long-term modeling framework should therefore be based on the integrated modeling of the long-term market optimum taking into account operating and investment costs instead of unit costs.

1.3. Structure of this article

This article is structured as follows: Section 2 describes the general economic assumptions for the capital and the electricity markets as the basics for the following considerations. In section 3, we analyze the generation portfolio structure in the long-run equilibrium under perfect competition. Thereafter, we reformulate in section 4 the problem as a decentralized market model with risk-averse agents. The resulting market equilibria are compared in a numerical example in section 5.

2. General market assumptions

To study optimal investment equilibria in electricity generation portfolios, we consider a stylized economy with perfect competitive⁵ electricity and capital markets. All other parts of the economy may fairly be

⁴One central question remaining open concerns the market implications if all investors apply the proposed form of portfolio optimization.

⁵Perfect competition includes in particular atomistic and profit maximizing behavior of all market participants, perfect information and precludes personal or corporate taxes, bankruptcy penalties, fees and other types of transaction costs.

represented through the capital market. Investors decide on the amount of money they want to invest in each market and on the allocation of capital to the different available assets within each market. The capital market consists of a risk-free security with interest rate r_0 and a complete set of risky assets represented through the market portfolio with rate of return r_m . The yield of all assets and therewith the return of the market portfolio are random variables, and all investors have full information and the same perception of its distribution.

In addition to the security market, the considered economy provides opportunity to invest in generation assets on the electricity market. We assume that investment and production follows a two stage process:

At the first stage, the suppliers choose their generation capacities from a set of different technologies U without knowledge of the real production costs but in full awareness of their distribution parameters. Each technology $u \in U$ with capacity K_u is assumed to be fully flexible and completely described through its deterministic specific investment costs $c_{inv,u}$ and its normally distributed operating costs $\tilde{c}_{op,u}$ with mean $\bar{c}_{op,u}$ and standard deviation σ_u .⁶ All technologies are numbered in an increasing order of expected operating costs with $u = 1$ indicating the base load technology with the least operating costs. We assume a deterministic order of operating costs and exclude the risk of reversals in the merit order due to fuel price fluctuations, i.e. $c_{op,u} < c_{op,u+1}$ for all realizations.⁷

Different ways to model consumers' willingness-to-pay have been discussed in literature (see e.g. Weber, 2005). One simple concept to cope with the idea is the introduction of an additional backstop technology of infinite capacity which can also be interpreted as a repurchase of demand, e.g. by large industrial consumers or as a price-cap as it can be found in some electricity market designs. In the following, we assume that operating costs of this technology c_d are fix with investment cost equal to zero.⁸

At the second stage, electricity is produced and traded on the wholesale market given the realized cost levels within the period $[0; T]$ (e.g. a year). The system's energy demand is assumed to be deterministic and inelastic, given in form of the load duration curve $D : [0; T] \rightarrow \mathbb{R}_+, t \mapsto D(t)$. Then, the efficient production schedule can be determined as in the standard peak-load pricing problem: Obviously from Figure 1, the upper bound of the optimal operating time of technology 1 equals $t_0 = T$ while the lower bound of the optimal operating time of the backstop technology equals $t_d = 0$. In fact, the lower bound of the efficient operating time of technology u is given through $D(t_u) = K_u^c$, where $K_u^c = \sum_{i=1}^u K_i$ denotes the cumulative capacity (with $K_0^c := 0$).

The cumulated energy in period $[0, T]$ by technologies $1, \dots, u$ is denoted by Q_u^c , whereas the energy Q_u

⁶This idealization is justifiable for most fossil thermal plants, which represent by far the biggest share of the European generation mix.

⁷See Sunderkötter and Weber (2011) for a discussion of mean-variance efficient generation portfolios given uncertainty in the merit order.

⁸The costs of the backstop technology, c_d , can also be interpreted as the *value of lost load*.

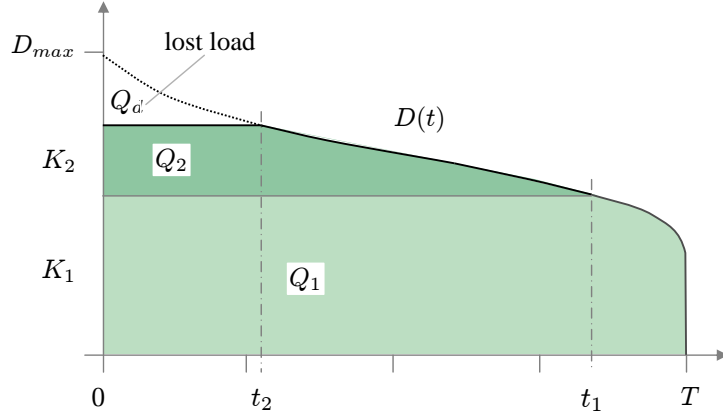


Figure 1: As in the standard peak-load pricing model, the welfare optimal generation schedule can be equivalently characterized by lower bounds of optimal operating times (t_u), optimal capacities (K_u), and produced energies (Q_u) of the generation technologies.

generated by each technology u is defined as visualized in Figure 1 by

$$Q_u^c(K_u^c) = \int_0^{K_u^c} R(\kappa) d\kappa; \quad Q_u(K_{u-1}^c, K_u^c) = Q_u^c(K_u) - Q_u - 1^c(K_{u-1}) = \int_{K_{u-1}^c}^{K_u^c} R(\kappa) d\kappa, \quad (1)$$

By setting $K_d^c = D(0)$ it is assured that the total energy produced (including demand reduction from the backstop technology) does exactly match maximal demand as a residual, i.e. $Q_d = Q_E - \sum_u Q_u$, with Q_E denoting the total energy demand in period $[0, T]$.

Since K_u, K_u^c , and Q_u, Q_u^c are invertible functions of t_u , there is a unique mapping between capacities and operating times. By defining $R(K)$ as the inverse of the monotone decreasing function $D(t)$, we may write $t_u = R(K_u)$. Consequently, t_u, K_u , and K_u^c can be used interchangeably as decision variables.

For a better traceability of the optimality conditions, we will limit our considerations in the following to the case with two generation technologies ($U \in \{1, 2\}$) and a backstop technology available for serving demand.

3. Market equilibrium under perfect competition

Among economists it is without controversy that optimal investment decisions of individual companies can as well be considered as the result of an optimal central planning if the characteristics of perfect competition are fulfilled.⁹ Thus, we consider in this section the investment problem from the perspective of

⁹This proposition, also known as the first theorem of welfare economics, is described in many economic textbooks and goes back to the Adam Smith's postulations of the "invisible hand". Among others, [Pigou \(1932\)](#), chapter II, contributed fundamentally to a precise formulation of this theorem and its prerequisites. One of the first mathematical proofs was published by [Lange \(1942\)](#).

a representative, central planning agent with limited budget $B > 0$. Two decisions have to be made: (a) The optimal capital allocation between the electricity market and other industries, and (b) the technology structure of the electricity generation portfolio.

3.1. Formulation of the optimization problem

Since the assumed inelastic electricity demand implies an infinite consumer surplus, welfare maximization in the electricity market is equivalent to minimizing total electricity generation costs including the value of lost load. Additionally, the alternative use of capital in the financial market has to be considered in the welfare function. Thus, the total welfare function W takes the form

$$W = B + r_0 X_0 + \tilde{r}_m X_m - \sum_{u \in U} (c_{inv,u} \cdot K_u + \tilde{c}_{op,u} Q_u) - c_d Q_d, \quad (2)$$

with X_0 denoting the capital invested at risk-free return r_0 in the risk-free security and X_m the capital invested at risky return \tilde{r}_m in the financial market portfolio. As a restriction, total investment in the capital market and in the electricity market must not exceed the budgeting limit B , i.e.

$$B \geq X_0 + X_m + \sum_{u \in U} c_{inv,u} K_u \quad (3)$$

From an economic perspective, it is clear that (3) will always be fulfilled with equality, since maximal profit requires that all capital is invested either in the capital market or in the electricity market.

To determine the optimal investment in the market equilibrium given the uncertainty of market return and operating costs, expected utility maximization can be applied as one of the most generic decision principles under uncertainty.¹⁰ Let societal utility be represented by an exponential utility function of the form $U(W) = -\frac{1}{A} \exp(-AW)$ with risk aversion parameter A with normally distributed profits W . It has been shown by [Schneeweiss \(1965\)](#) that in this case the exponential utility function induces a unique preference function of the form

$$\Psi = \mathbf{E}[W] - \frac{1}{2} A \text{Var}[W] \quad (4)$$

Maximization of this preference function is consistent with the decision principle of expected utility maximization. Based on these pre-considerations, the complete welfare optimization problem can be formulated as:

$$\max_{X_0, X_m, K_u} \mathbf{E}[W] - \frac{1}{2} A \text{Var}[W] \quad (5)$$

$$\text{with } W = B + r_0 X_0 + \tilde{r}_m X_m - \sum_{u \in U} (c_{inv,u} K_u + \tilde{c}_{op,u} Q_u) - c_d Q_d \quad (6)$$

$$\text{s.t. } B \geq X_0 + X_m + \sum_{u \in U} c_{inv,u} K_u, \quad (7)$$

$$X_m \geq 0, \quad X_0 \geq 0, \quad K_u \geq 0 \quad \forall u \in U. \quad (8)$$

¹⁰This decision criterion is sometimes also referred to as the *Bernoulli* principle.

3.2. Solving the optimization problem

Problem (5)-(8) can be solved under weak assumptions as shown in [Sunderkötter and Weber \(2012\)](#) for the n -technology case: Given $c_{inv,u} > c_{inv,u+1}$ the problem is strictly concave and thus has a unique solution, if and only if the covariance matrix of the market return and the technologies' operating costs is positive definite. However, an explicit formulation of the solution will in general not be possible.

In a first general solution approach, we will focus on inner solutions which include investments in both technologies and the market portfolio, i.e. $K_1, K_2, X_m > 0$.¹¹

Assuming that the total investment in the economy is sufficiently large compared to the electricity market, i.e. $X_m \gg \sum_u c_{inv,u} K_u$ and $X_m \gg \sum_u Q_u$, we can state the following approximation for the optimality conditions:

Proposition 3.1. *[Market equilibrium under perfect competition] Let be a stylized economy and as defined in Section 2 and an electricity market with two generation technologies. Furthermore, a strictly positive societal risk aversion, i.e. $A > 0$ is assumed. If an interior solution to problem (5)-(8) exists with $K_1, K_2, X_m > 0$, and under the assumption that $X_m \gg \sum_u c_{inv,u} K_u$ and $X_m \gg \sum_u Q_u$, the optimal investments into the market portfolio and the risk-free security are given by*

$$X_m = \frac{1}{A} \frac{\bar{r}_m - r_0}{\sigma_m^2}, \quad (9)$$

$$X_0 = B - X_m - \sum_{u \in U} c_{inv,u} K_u. \quad (10)$$

The optimal capacity structure within the generation portfolio is characterized by the following optimality conditions, which are only dependent on the decision variables K_1, K_2 (or equivalently on $t_1(K_1), t_2(K_1, K_2)$, and $Q_1(K_1), Q_2(K_1, K_2)$):

$$\frac{(1 + r_0)(c_{inv,1} - c_{inv,2})}{t_1} = \bar{c}_{op,2} - \bar{c}_{op,1} + \frac{\bar{r}_m - r_0}{\sigma_m^2}(\sigma_{1m} - \sigma_{2m}), \quad (11)$$

$$\frac{(1 + r_0)c_{inv,2}}{t_2} = c_d - \bar{c}_{op,2} + \frac{\bar{r}_m - r_0}{\sigma_m^2}\sigma_{2m}. \quad (12)$$

For the proof and the detailed optimality conditions without the assumptions $X_m \gg \sum_u c_{inv,u} K_u$ cf. [Appendix B.1](#). Thus risk aversion affects the welfare-optimal solution only through the correlations $\sigma_{1,m}$ and $\sigma_{2,m}$ of the fuel prices with the market returns. Positive correlations decrease the corresponding expected costs, since then the electricity generation costs in the welfare term act as a hedge to the financial market returns.

4. Market equilibrium with risk-averse agents

In the last section, we discussed the structure of the welfare optimal generation portfolio from a central planning perspective which equals the market equilibrium under perfect competition. However, risk-aversion

¹¹For the existence of corner solutions with only one technology in the efficient portfolio c.f. [Sunderkötter and Weber \(2012\)](#).

of the electricity market agents may impact the market equilibrium substantially. Therefore, we now consider a stylized economy consisting of households, an imperfect electricity market, and a perfect financial market.

Definition 4.1 (Electricity market agents). The electricity market is represented by profit maximizing agents with the following key properties:

1. **Profit share:** Each agent $j \in J$ (one could simplifyingly say, the managers) receives a certain fraction $\alpha_j \in (0, 1)$ of the profit of his firm.
2. **Risk aversion:** The agents are risk-averse. The preferences of agent $j \in J$ are represented by a mean-variance preference functional with an absolute risk aversion A_j .
3. **Diversification:** The agents diversify their investments into a set of different electricity generation technologies from the index set $U = 1, \dots, u$.
4. **Homogeneity:** All agents $j \in J$ have homogeneous risk aversion, receive identical profit fractions α_j , and thus invest in the same technologies.¹²

The optimization rationales of the market participants are characterized in the following.

4.1. Formulation of the individual optimization problems

Households can invest their capital up to a budgeting limit B in a risk-free security with interest rate r_0 or in the economy's market portfolio with uncertain return \tilde{r}_m which together may represent a complete set of assets. The amount of capital invested by the households in the risk-free and risky asset are denoted with X_0 , and X_m , respectively. In addition, households may invest an amount of capital $x_{el,j}$ in a security dedicated to electricity generation companies $j \in J$ at an uncertain return $r_{el,j}$. Thereby, the gross security return of company j is defined as the sum of profits $\Pi_{u,j}$ from all generation technologies in the portfolio per capital invested, i.e.

$$r_{el,j}(\tilde{\zeta}) := \frac{\sum_u \Pi_{u,j}}{x_{el,j}}. \quad (13)$$

Thus, companies have to fully pay out total profits in each period without any internal accumulation of funds.

Objective of the households is to optimally allocate funds into the capital and into the electricity market so that risk-adjusted expected returns minus expected electricity costs are maximized. Being $\alpha_j \in (0, 1)$ the share of profit paid to the managers (e.g. executive bonuses), then the profit share paid to the shareholders is given by $(1 - \alpha_j) \cdot r_{el,j} \cdot x_{el,j}$. The electricity costs C_{el} for the households consist of the electricity market

¹²We will first formulate the market equilibrium without the assumption of homogeneous agents and later come back to this assumption.

price $p_{el}(t, \tilde{\zeta})$ for the amount of consumed electricity plus the incurred utility losses at costs c_d through undelivered load which can be measured by the value of lost load, i.e.

$$C_{el} = \int_0^T p_{el}(t, \tilde{\zeta}) D(t) dt - \int_0^T (p_{el}(t, \tilde{\zeta}) - c_d) y_d(t) dt \quad (14)$$

Assuming again exponential utilities with constant absolute risk aversion A_h , the households' optimization problem can be written as:

$$\max_{X_0, X_m, x_{el,j,u}, y_d} \mathbf{E}[V_h] - \frac{A_h}{2} \text{Var}[V_h] \quad (15)$$

$$\text{with } V_h := r_0 X_0 + \tilde{r}_m X_m + \sum_{j \in J} (1 - \alpha_j) r_{el,j}(\tilde{\zeta}) x_{el,j} - C_{el}(\tilde{\zeta}) \quad (16)$$

$$\text{s.t. } B \geq X_m + X_0 + \sum_{j \in J} x_{el,j}, \quad (17)$$

$$X_m \geq 0, \quad X_0 \geq 0, \quad x_{el,j} \geq 0 \quad \forall j \in J. \quad (18)$$

Here, the random vector $\tilde{\zeta} := (\tilde{c}_{op,1}, \tilde{c}_{op,2}, \tilde{r}_m)$ denotes the vector of exogenous risk factors defined on the probability space $(\Omega, \mathcal{A}(\mathbb{R}), \mathbf{P})$ with $\zeta : \Omega \mapsto \mathbb{R}^3$.

Each electricity market agent seeks to maximize the expected profit $\Pi_{el,j}$ adjusted by its variance. Thereby the profit $\Pi_{el,j}$ is given by the contribution margin minus investment costs of each generation asset reduced by the interest payable to the households $(1 - \alpha_j) \cdot r_{el,j} \cdot x_{el,j}$. Therewith, the companies' optimization problem can be stated as

$$\max_{k_{u,j}, y_{u,j}(t, \tilde{\zeta})} \mathbf{E}[\Pi_{el,j}(\tilde{\zeta})] - \frac{A_j}{2} \text{Var}[\Pi_{el,j}(\zeta)] \quad (19)$$

$$\text{with } \Pi_{el,j}(\tilde{\zeta}) := \sum_u \Pi_{u,j} - (1 - \alpha_j) r_{el,j}(\tilde{\zeta}) x_{el,j}; \quad \Pi_{u,j}(\tilde{\zeta}) := \int_0^T (p_{el}(t, \tilde{\zeta}) - \tilde{c}_{op,u}) y_{u,j}(t, \tilde{\zeta}) dt - c_{inv,u} k_{u,j} \quad (20)$$

$$\text{s.t. } y_{u,j}(t, \tilde{\zeta}) \leq k_{u,j} \quad \forall j \in J, \quad \forall t, \quad \forall \zeta, \quad (21)$$

$$\sum_u c_{inv,u} k_{u,j} \leq x_{el,j} \quad \forall j \in J \quad (22)$$

Thereby, the capacity constraint (21) ensures that at every point in time the electricity produced by plant (u, j) does not exceed its capacity. The budget constraint (22) ensures that the total investment costs for the capacity installed by company j does not exceed its available funds $x_{el,j}$. Ex post, the remaining profit of each electricity generation company equals the managerial profit share from all payoffs of the generation units due to Eqn. (13), i.e.

$$\Pi_{el,j}(\tilde{\zeta}) = \alpha_j \sum_u \Pi_{u,j}. \quad (23)$$

In addition, the supply constraint (24) has to be satisfied as a market clearing condition: Total production must meet or exceed system demand less the load of the backstop technology at any point in time. It will

exactly meet demand minus the load of the backstop technology unless the electricity price is zero.

$$\sum_{u \in U} \sum_{j \in J_u} y_{u,j}(t, \tilde{\zeta}) \geq D(t) - y_d(t, \tilde{\zeta}) \quad \perp \quad p_{el}(t, \tilde{\zeta}) \geq 0 \quad \forall t \in [0, T], \quad \forall \tilde{\zeta} \quad (24)$$

To determine the market equilibrium, the intertwined optimization problems of the households and the generation companies can be split up into two stages as discussed in Section 2. Thereby, we will first determine the technology dispatching and electricity price formation at the second stage (with given generation capacities) before we turn back to the investment decision of generation companies and households at the first stage of the model. At the first stage all investment decisions are made without knowledge of the values of $\tilde{\zeta}$, i.e. the decision variables $X_0, X_m, x_{el,j,u}, u \in U_j, j \in J$ for the households and $k_{u,j}, u \in U_j, j \in J$ for the electricity market agents, respectively, are set. At the second stage these values are fix and no longer decision variables. The realization of $\tilde{\zeta}$ is now revealed and decisions are made with respect to $y_{u,j}(t, \tilde{\zeta})$, and $y_d(t, \tilde{\zeta})$.

4.2. Second stage of the market equilibrium: Technology dispatch and electricity price formation

In a perfectly competitive power market the spot price will always reflect short term marginal costs of the last producing unit as long as there is sufficient power generation capacity to meet demand. In situations when demand comes close to available capacity the end-users' willingness to pay for electricity (value of lost load) determines the price. During these periods of peak demand the resulting scarcity rent would pay off the investment cost of peak load units, and also contribute to cover the fix costs for all other plants. This intuitive result can be easily derived from the equilibrium model as formulated above (see Appendix B.2 for a formal proof).

Proposition 4.1. *Let be a stylized economy as defined in Section 2. Then, the wholesale electricity price is given by the function:*

$$p_{el}(t, \tilde{\zeta}) = \begin{cases} \tilde{c}_{op,1}, & \text{if } t > D^{-1}(K_1) \\ \tilde{c}_{op,2}, & \text{if } D^{-1}(K_1) \geq t > D^{-1}(K_2 + K_1) \\ c_d, & \text{if } D^{-1}(K_2 + K_1) \geq t \end{cases} \quad (25)$$

Note that this proposition holds both for the case of risk-neutral and risk-averse electricity market agents, as it is solely derived at the second stage of the investment problem, where uncertainty has been resolved. As a consequence, the electricity price formation can be characterized as shown in Figure 2 for the two-technology case: Given a firm order of variable costs with $c_{op,1} < c_{op,2} < c_d$ it can be concluded that the load $D(t)$ is solely served by the base load technology 1 at a market price of $p_{el}(t, \tilde{\zeta}) = c_{op,1}$ at any time when demand is smaller than its installed capacity $K_1 = \sum_j k_{1,j}$. With $D(t)$ given in a decreasing order as load duration curve, this phase can be characterized by the time segment between t_1 and T . When demand

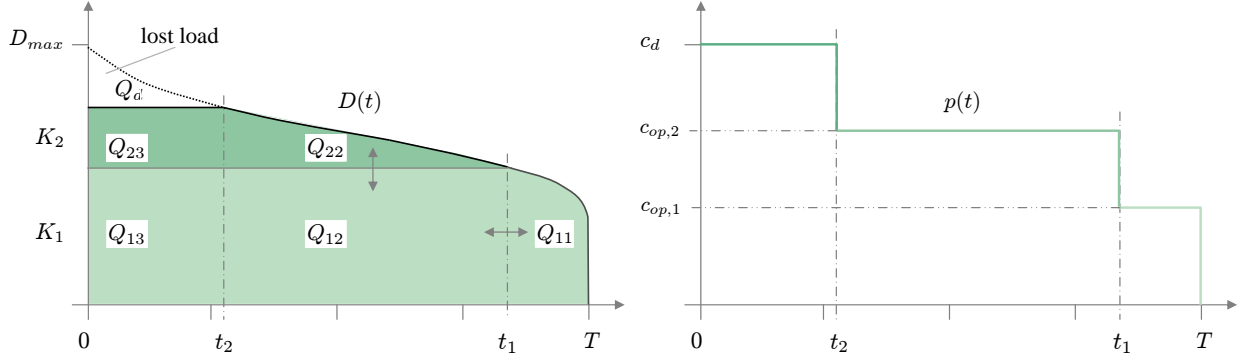


Figure 2: Load duration curve $D(t)$ (left) and the price duration curve $p(t)$ (right) in the analysis period $[0, T]$.

exceeds capacity K_1 but is still below $K_1 + K_2$, technology 2 is dispatched to serve all additional demand at price $p_{el}(t) = c_{op,2}$. In this time segment during t_2 and t_1 , the base technology earns an operational margin of $c_{op,2} - c_{op,1}$ per produced unit. Its production in this segment equals to the square $Q_{12} = \sum_j q_{12,j}$ between t_2 and t_1 and with height K_1 .¹³ Finally, when both technologies are operating at their capacity limits, demand response comes in implying lost load and resulting in an electricity price equal to the value of lost of load, i.e. $p_{el}(t) = c_d$. Both technologies, base and peak, earn contribution margins of $c_d - c_{op,1}$ and $c_d - c_{op,2}$ per produced unit respectively with the produced amounts $Q_{13} = \sum_j q_{13,j}$ and $Q_{23} = \sum_j q_{23,j}$ which are represented by the squares between 0 and t_2 with heights $K_1 = \sum_j k_{1,j}$ and $K_2 = \sum_j k_{2,j}$. As a result, it holds for the cumulated production quantities

$$q_{12,j} = (t_1 - t_2)k_{1,j}, \quad q_{13,j} = t_2 k_{1,j}, \quad q_{23,j} = t_2 k_{2,j}. \quad (26)$$

We thereby have also shown (again, under the given assumptions, in particular for a stable merit order) the simple intuitive result that production of each technology is not dependent at the realization of the stochastic parameters $\tilde{\zeta}$, i.e. the levels of t_2 and t_1 and consequently of Q_{12} , Q_{13} and Q_{23} are deterministic functions of the choice of K_1 and K_2 at the first stage while the specific contribution margins $\tilde{c}_{op,2} - \tilde{c}_{op,1}$, $c_d - \tilde{c}_{op,1}$ and $c_d - \tilde{c}_{op,2}$ are stochastic at that point in time.

Based on these considerations at the second stage of the model, we can summarize the following

Proposition 4.2. *The profits of the individual technologies $\Pi_{u,j}(\tilde{\zeta})$ as defined in (20) can be rewritten as:*

$$\Pi_{1,j}(\tilde{\zeta}) = (t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1}) + t_2(c_d - \tilde{c}_{op,2}) - c_{inv,1})k_{1,j} \quad (27)$$

$$\Pi_{2,j}(\tilde{\zeta}) = (t_2(c_d - \tilde{c}_{op,2}) - c_{inv,2})k_{2,j} \quad (28)$$

¹³The subscription is to be read as follows: the first number is the producing technology, the second is the price-setting technology.

Proposition 4.3. *The return $r_{el,j}(\tilde{\zeta})$ as defined in (13) can be specified as:*

$$r_{el,j}(\tilde{\zeta}) = \frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})k_{1,j} + t_2(c_d - \tilde{c}_{op,2})(k_{1,j} + k_{2,j})}{c_{inv,1}k_{1,j} + c_{inv,2}k_{2,j}} - 1 \quad (29)$$

4.3. First stage of the market equilibrium: Investment optimum

Under consideration of the market price formation and the efficient dispatch structure at the second stage of the optimization problem, we can derive the equilibrium conditions for the optimization problems of the households and of the electricity market agents. At first, the optimality condition of the agents can be derived from the KKT conditions as shown in [Appendix B.3](#):

Proposition 4.4. *[Electricity market agents' optimality condition] Let be a stylized economy as defined in Section 2 and Definition 4.1.*

Under the assumption of homogeneous market agents with identical risk aversion $A_j \forall j \in J$ the necessary optimality condition for an interior solution with $k_1, k_2 > 0$ for the optimization problem of the electricity agents as stated in Eqn. (19)-(22) is given by:

$$\begin{aligned} & t_2 \left(\frac{c_d - \tilde{c}_{op,2}}{c_{inv,2}} - \frac{A_j \alpha_j}{N c_{inv,2}} (t_1 K_1 (\sigma_{12} - \sigma_2^2) + t_2 (K_1 + K_2) \sigma_2^2) \right) \\ & = t_1 \left(\frac{\tilde{c}_{op,2} - \tilde{c}_{op,1}}{c_{inv,1} - c_{inv,2}} - \frac{A_j \alpha_j}{N (c_{inv,1} - c_{inv,2})} (t_1 K_1 (\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}) + t_2 (K_1 + K_2) (\sigma_{12} - \sigma_2^2)) \right) \end{aligned} \quad (30)$$

Under the assumption of homogeneity of the market agents, we can substitute the households' decision variables $x_{el,j}$ by $X_{el} = N x_{el,j}$.

The optimality condition for the households' optimization problem can then straightforwardly be derived as shown in [Appendix B.4](#). For a better traceability of the solution, we thereby assume that the relative share of the returns which is paid to the managers is very small, i.e. we consider the limiting case with $\alpha_j \rightarrow 0$, yielding:

Proposition 4.5. *[Households' optimality condition] Let be a stylized economy as defined in Section 2 and Definition 4.1. We assume a neglectable managerial profit share, i.e. $1 - \alpha_j \approx 1$, and total investments in the economy being sufficiently large compared to the electricity market, i.e. $X_m \gg X_{el}$. Then, the necessary optimality condition for an interior solution with $x_{el,j} > 0, \forall j \in J$ to the optimization problem of the households as stated in Eqn. (15)-(18), is given by:*

$$\frac{t_2(K_1 + K_2)(c_d - \tilde{c}_{op,2}) + t_1 K_1 (\tilde{c}_{op,2} - \tilde{c}_{op,1})}{c_{inv,1} K_1 + c_{inv,2} K_2} = 1 + r_0 + X_m \frac{\bar{r}_m - r_0}{\sigma_m^2} \cdot \frac{t_1 K_1 \sigma_{m,1} - ((t_1 - t_2) K_1 - t_2 K_2) \sigma_{m,2}}{c_{inv,1} K_1 + c_{inv,2} K_2} \quad (31)$$

Remark that the left side of Eqn. (31) equals the electricity portfolio return $r_{el,j}$ as derived in Proposition 4.3. Hence, the portfolio return equals the risk-free rate in case of $A_h = 0$ or $\sigma_{m,1} = \sigma_{m,2} = 0$. In all other cases the term $A_h X_m(\cdot)$ on the right side of Eqn. (31) describes the risk premium in the market.

We have now received two necessary conditions for an optimal solution of our equation system. In total, this system originally contained the decision variables K_1, K_2 (equaling $k_{1,j} \cdot N, k_{2,j} \cdot N$ under common homogeneity assumptions) and $y_{u,j}(t, \tilde{\zeta})$ for the agents and X_m, X_{el}, X_0 , and y_d for the households. We have outlined that the optimal values for the $y_{u,j}(t, \tilde{\zeta})$ and y_d are uniquely defined by the optimal values for K_1^* and K_2^* at the second stage of the model.

The optimal investment into the non-electricity market, X_m^* can be straightforwardly derived from the first order condition $\frac{\partial \mathcal{L}_h}{\partial X_m}$ of the household's Lagrangian (cf. [Appendix B.2](#)). The obtained investment X_m^* equals the optimal investment in the welfare optimum as stated in Eqn. (9). The relation to the value of X_0 is given by the budget restriction (17) so that the optimal investment into the risk-free security is given as in the welfare optimum in Eqn (10). Therewith, we have solved the combined optimization problem of electricity market companies and households:

Corollary 4.1. *[Market equilibrium] The long-term investment equilibrium with electricity market agents $j \in J$ with homogeneous risk aversion A_j and households with risk-aversion A_h and decision variables X_0, X_m, t_1, t_2 is given by the equation system (9), (10), (30) and (31) if an inner solution exists.*

Although an explicit solution of the equation system cannot be provided in general, it can be seen that the first order optimality conditions deviate from those of the welfare optimum discussed previously (cf. Eqs. (11)-(12)). We will further assess the deviations between welfare optimum and long-term market equilibrium in the following numerical example.

5. A numerical example

To illustrate the results, the proposed model is calibrated to the German electricity market using historical market data. The numbers thereby serve primarily as an illustration whereas it is not intended to derive a complete picture on the efficient power generation fuel mix in Germany. For the example, typical CCGT (peak) and hard coal (base) technologies are considered being available for serving demand.

5.1. Model calibration and parameter estimation

5.1.1. Market parameters

The proposed model requires assumptions on mean and standard deviation of the market portfolio and on the risk-free rate of return. [Dimson et al. \(2006\)](#) have analyzed historical equity returns and equity premiums for different countries over the period 1900–2005. The authors report a global average equity risk premium of 5.15% p.a. (relative to bonds) at a standard deviation of 14.96%. Given recent developments of German bond interest rates, we assume a risk-free rate of $r_0 = 2\%$, yielding an expected market portfolio return of $\bar{r}_m = 7.2\%$.

5.1.2. Generation technologies and value of lost load

Economic and technical key parameters of the coal and CCGT plant technologies are based on [Konstantin \(2009\)](#) as depicted in Table 1. We exogeneously assume costs of capital of the electricity firms being 7.2%. This implies an investment cost annuity of 179.9 €/kW for the coal technology, and 78.442€/kW for the CCGT technology, respectively.

Total operating costs are based on fuel, CO₂ emission, and variable operating and maintenance costs. Thereby, long-term time series of monthly coal and natural gas import prices 1970–2010 are used based on the price indices provided by the German Federal Statistical Office ([StaBu, 2010](#)) and absolute data of the German Federal Office of Economics and Export Control ([BAFA, 2010](#)) to estimate variance and covariance parameters. The price data reflect the average cross-border price converted to €/MWh_t for all contracted deliveries in the respective month. Starting with the beginning of the European Union Emission Trading System in 2005, total fuel prices are computed including the costs of CO₂ emission allowances (EUA) based on front year price data from [ECX \(2010\)](#). EUAs are modeled to be purchased at market conditions (full auctioning) as it has been put in place by the EU for ETS Phase III starting in 2013. The mean operating costs are estimated from the same data set over the short-term period 2006–2008. This combination of estimation periods is most suitable in our view since it allows appropriate long-term estimates for variance and covariance while it takes into account recent shifts in the means of operating costs. The estimated covariance of the operating cost levels of each technology with the market return are very small. Since there is also no theoretical evidence for a linear dependency between the returns and the cost levels, these parameters are set to zero.

Empirical studies on the value of lost load vary by country, by customer segment, and according the applied research methodology. Following [Gilmore et al. \(2010\)](#) for the U.S., typical values are ranging between 2\$/kWh and 16\$/kWh for the U.S. market. Reflecting these findings, we assume a value of lost load of 5000€/MWh_e.

5.1.3. Load duration curve

The estimation of a load duration function is based on 2006–2008 load data for Germany provided in an hourly resolution by [ENTSO-E \(2009\)](#). For comparability reasons, we adjust the data sets for the general increase in energy consumption by 1.02% in 2007 and 0.4% in 2008, respectively. A reference load duration curve is then fitted as a polynomial function to the hourly means of the historical data using OLS regression. The resulting maximum system load is $D(0) = 78377$ MW.

Table 1: Key parameters new conventional coal and CCGT technologies (source: [Konstantin, 2009](#); [Sunderkötter, 2011](#); [BAFA, 2010](#); [StaBu, 2010](#); [ECX, 2010](#), own analysis).

Parameter	Unit	Base	Peak
Total net investment costs	€/KW	1419	608
Technical lifetime	a	45	30
Fixed O&M, overhead	€/KW a	36.1	14.0
Annualized investment costs $c_{inv,u}$	€/KW a	179.9	78.4
Variable O&M, transport	€/KWh _e	2.9	5.5
Thermal efficiency	MWh _e /MWh _t	0.46	0.56
Carbon emission rate	tCO ₂ /MWh _t	0.34	0.20
Mean operating costs \bar{c}_u	€/KWh _e	37.3	56.8
Variance of operating costs σ_u	€/KWh _e	84.5	195.6
Covariance of operating costs σ_{12}		116.6	116.6
Covariance of operating costs σ_{mi}		0.0	0.0
Value of lost load c_d	€/KWh _e		5000.0

5.1.4. Risk aversion parameters

We first determine the societal risk aversion coefficient A_h . For given X_m , it can be seen from the Lagrangian of the households' optimization problem and the corresponding first order conditions¹⁴

$$A_h X_m = \frac{r_m - r_0}{\sigma_m^2}. \quad (32)$$

Thereby X_m can be estimated from total gross asset investments in Germany which amounted to 469B€ in 2010 ([Statistisches Bundesamt, 2012](#)). This yields a societal risk aversion in the order of magnitude of $A_h \approx 5 \cdot 10^{-12}$. Claiming a similar level of relative risk aversion for the market agents on their idiosyncratic risk factor $r_{el}(\tilde{\zeta})$ requires

$$\alpha_j A_j \frac{X_{el}}{N} = \frac{r_m - r_0}{\sigma_m^2}. \quad (33)$$

Power generation asset investments account for approximately 1% of total investments in the German economy¹⁵, i.e. approximately 5B€. Furthermore, we assume $N = 50$ power producers and an agents' profit share of $\alpha_j = 0.001$. Consequently, we obtain $A_j \approx A_h \cdot 5 \cdot 10^6$.

¹⁴Eqn. (32) can be derived after some simple transformations from the first order conditions

$$\frac{\partial \mathcal{L}_h}{\partial X_m} = r_m - A_h X_m \sigma_m^2 - \mu_h = 0, \quad \frac{\partial \mathcal{L}_h}{\partial X_0} = r_0 - \mu_h = 0.$$

¹⁵[Statistisches Bundesamt \(2012\)](#) reports gross asset investments in the German electricity industry of 13B€ in 2010, whereof estimated one third is attributable to generation assets.

5.2. Determining the optimal technology mix

First, we determine the welfare optimal technology mix straightforwardly as discussed in Proposition 3.1. The optimal values for t_1^*, t_2^* (and subsequently K_1^*, K_2^*) can be determined directly from Eqs. (11) and (12) for the case with two generation technologies.

The mix of base and peak load technology in the decentralized market equilibrium case can be determined from the optimality conditions (30) and (31) for varying firms' risk aversion A_j . Plotting these implicit functions of t_1 and t_2 allows to determine graphically the stationary points for the households' and the agents' optimization problem as shown in Fig. 3 for different values of A_j : For risk-neutral companies, the electricity market agents' optimality condition is represented by a linear function $t_1(t_2)$ (Fig. 3, left). For increasing values of A_j , the intersection point of both functions represents the market equilibrium (Fig. 3, middle). With A_j exceeding a certain threshold, there is no stationary point for an inner solution within the domain of t_1, t_2 (Fig. 3, right). In this case the market equilibrium is characterized by a corner solution.

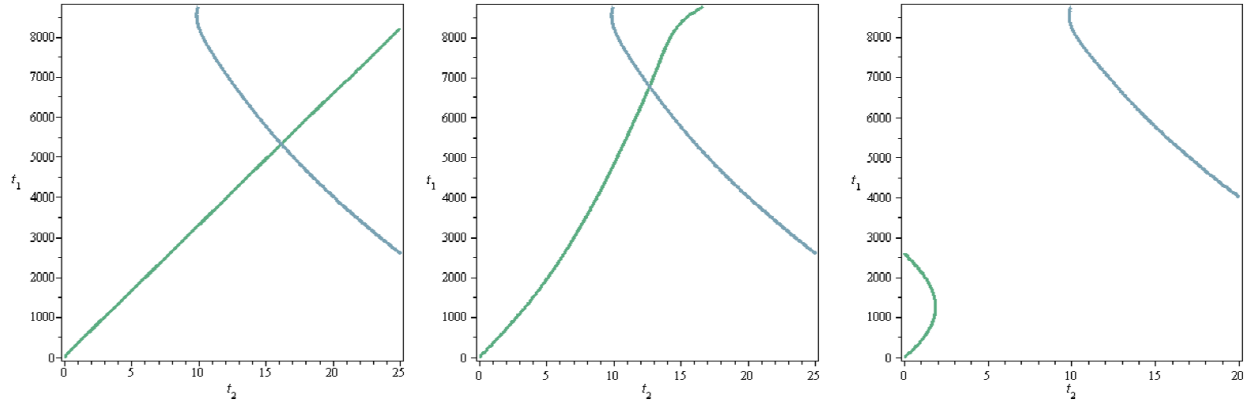


Figure 3: Optimality conditions (14) and (14) plotted as implicit functions of t_1, t_2 . The parametrization is $\alpha_j = 0.001$ for the managerial profit share, $A_h = 5 \cdot 10^{-12}$ for the societal risk aversion and firm's risk aversion $A_j = 0$ (left), $A_j = A_h \cdot 5 \cdot 10^7$ (middle), and $A_j = A_h \cdot 5 \cdot 10^8$ (right).

5.3. Results I: Impact of agents' risk aversion

Based on the analytical considerations in the previous sections, we compare the efficient portfolio structure under perfect competition with the market equilibrium under imperfect competition given risk averse electricity market agents. The efficient portfolio structures for varying agent risk aversion A_j and resulting technology returns are summarized in Fig. 4. Thereby, we first assume that the operating costs of technologies 1 and 2 and the return of the market portfolio are uncorrelated, i.e. $\sigma_{m1} = \sigma_{m2} = 0$.

In the market equilibrium under perfect competition and societal risk aversion, the equilibrium investment portfolio consists 67.7% base-load technology, 31.9% peak-load technology and 0.5% loss of load.

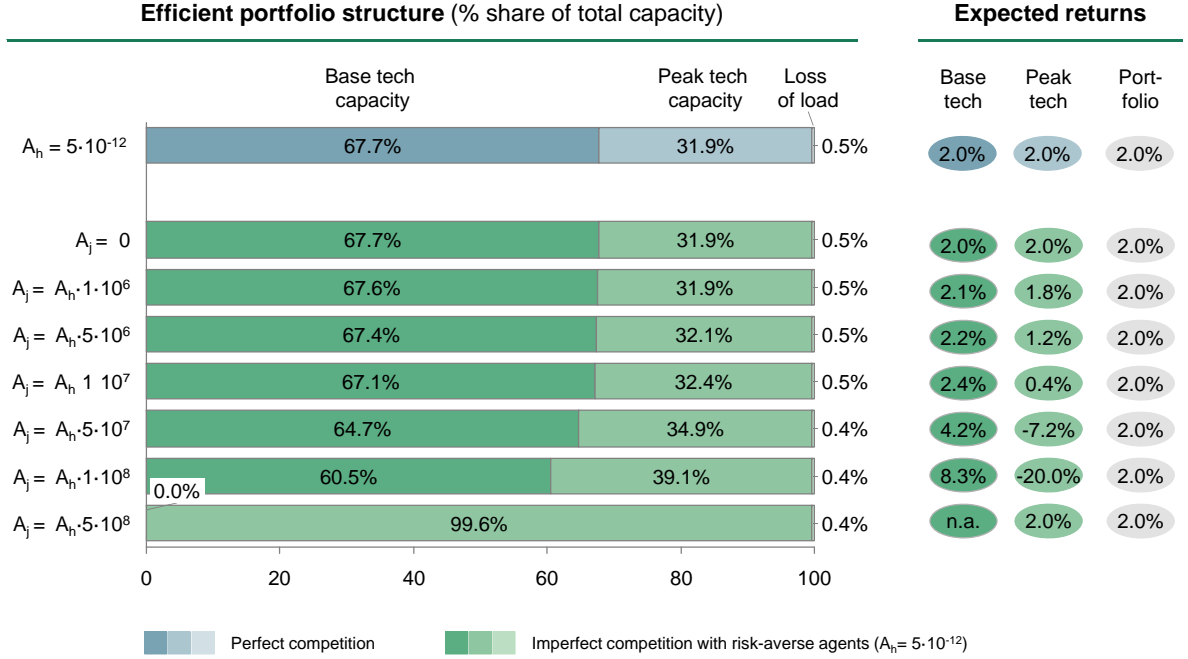


Figure 4: Efficient portfolio technology mix structures (as shares of installed capacity) in the long-term market equilibrium under perfect competition (blue) and under imperfect competition with risk-averse firms (green) for varying risk aversion of the electricity market agents A_j at a managerial profit share of $\alpha_j = 0.001$ and societal risk aversion $A_h = 5 \cdot 10^{-12}$.

Thereby, the results derived according to Proposition 3.1 match the portfolio structure derived from Corollary ?? for the case $A_j = 0$.

A risk averse investment behavior at the company level can induce structural changes in the long-term equilibrium portfolio: Given a company risk aversion of $A_j = A_h \cdot 5 \cdot 10^6$, the portfolio structure in the market equilibrium consists of 67.4% peak load and 32.1% base load technology. The share of peak load technology steadily increases with higher levels of risk aversion. At risk aversion levels of $A_j \geq A_h \cdot 5 \cdot 10^8$, the market equilibrium is characterized by a corner solution with solely peak load technology in the portfolio. The increasing investment in peak load can be explained by the fact that it sets the price most of the time and is therefore less risky from the investor's point of view.

These results are consistent with the observations of Roques et al. (2008): “High degrees of correlation between gas and electricity prices—as observed in most European markets—reduce gas plant risks and make portfolios dominated by gas plant more attractive.” Our model shows that in the long-term market equilibrium risk-averse firms would clearly invest into higher shares of peak technologies—even more if the companies receive a substantial profit share.

The change in the technology structure in the decentralized market equilibrium leads also to remarkable

changes in the expected return $\mathbf{E}[r_{i,j}]$ for each generation technology.¹⁶ The investment returns for each technology in the welfare optimum equal the risk-free return given that we have assumed so far no correlation between the fuel price risk and the market returns.

Independently from A_j , the total expected returns $\mathbf{E}[r_{el,j}]$ of the electricity generation portfolio remains constant and equal to the risk-free rate for the case $\sigma_{m1} = \sigma_{m2} = 0$. This becomes obvious from the right side of optimality condition (31). The returns deviate with increasing company risk aversion substantially between the two technologies. Since the loss of load remains almost constant in all considered portfolios, the increasing company risk aversion and therewith the increasing share of the less risky peak load technology lead to lower returns of investment for the peak load and higher returns for the base load technology. Interestingly, the return of the peak technology turns negative at risk aversion levels of $A_j = A_h \cdot 5 \cdot 10^7$. Nevertheless an increasing share of the peak technology is beneficial from a company perspective as it helps decreasing the variability of cash flow.

5.4. Results II: Impact of correlation between risk factors

In this section, we will relax the assumption $\sigma_{m1} = \sigma_{m2} = 0$ and investigate the impact of different levels of correlation between operating costs and the return of the market portfolio. Market agents' and societal risk aversion are kept constant with $A_j = A_h \cdot 5 \cdot 10^6$ and $A_h = 5 \cdot 10^{-12}$ at a managerial profit share of $\alpha_j = 0.001$. For the purpose we use definition of the correlation coefficient

$$\rho_{m,u} := \frac{\sigma_{m,u}}{\sigma_u \sigma_m}, \quad u \in \{1; 2\} \quad (34)$$

As shown in Fig. 5, the capacity share of a generation technology in the long-term equilibrium portfolio increases with increasing levels of correlation between operating costs of the respective technology and the market portfolio return. This holds both for the market equilibrium under perfect competition and under imperfect competition given risk averse market agents. However, risk-averse behavior of electricity market agents diminishes the degree of diversification compared to the case with perfect competition. The assumed degree of correlation has significant impact at the expected portfolio returns—even on the portfolio level: While the overall expected portfolio return turns negative in the equilibrium portfolios for $\rho_{m,1} = 0.7$ and $\rho_{m,2} = 0$, we obtain a clearly higher expected portfolio return for the inverse case $\rho_{m,1} = 0$ and $\rho_{m,2} = 0.7$.

¹⁶Remember that the (non risk-adjusted) return on investment is obtained by the cumulated cash flow divided by the investment costs, i.e.

$$r_{el,j} = \frac{\Pi_{el,j}}{\sum_{i \in j} c_{inv,i} K_i}; \quad r_{1,j} = \frac{(t_1(c_{op,2} - c_{op,1}) + t_2(c_d - c_{op,2}) - c_{inv,1})k_{1,j}}{c_{inv,1}k_{1,j}}; \quad r_{2,j} = \frac{(t_2(c_d - c_{op,2}) - c_{inv,2})k_{2,j}}{c_{inv,2}k_{2,j}}.$$

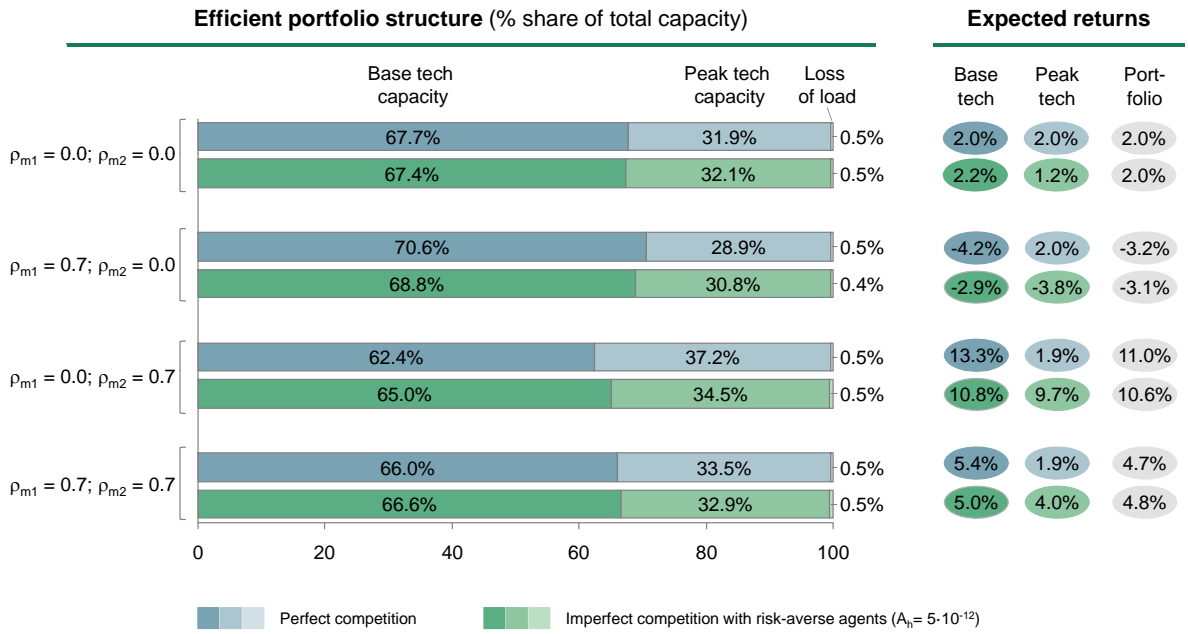


Figure 5: Efficient portfolio technology mix (as shares of installed capacity) in the long-term market equilibrium under perfect competition (blue) and under imperfect competition with risk-averse firms (green) for varying levels of correlation between generation costs and market return, $\rho_{m,1}, \rho_{m,2}$. The risk aversion of the market agents is $A_j = A_h \cdot 5 \cdot 10^6$ at a managerial profit share of $\alpha_j = 0.001$ and societal risk aversion $A_h = 5 \cdot 10^{-12}$.

6. Conclusion

This article compares optimal technology portfolio choices under market imperfections. Taking investment decisions on electricity markets as an example, we first propose a partial equilibrium model to determine the optimal portfolio consisting of two generation technologies with different cost and risk characteristics under the assumption of perfect competition. The resulting portfolio matches the welfare optimal technology mix, i.e. a generation portfolio minimizing the total risk-adjusted costs of households over consumption and investments. Efficient generation portfolios are derived from exogenous factors such as demand, risk aversions of the market participants, costs and available budget on the basis of classic mean-variance-preference calculus and peak load pricing theory. This immediately implies a distribution of prices with respective consumer and investor surpluses. In a second step, the model is extended by introducing electricity market agents (i.e. companies) and market imperfections based on agency-theoretic considerations. By considering that market agents receive a certain profit share and are risk-averse, we focus on two—in our view crucial—imperfections which may be caused by lacking transparency in investment decisions.

In case of risk averse agents receiving a profit share, the long-term investment equilibrium can substantially deviate from the welfare efficient portfolio mix. This implies that the risk-preferred technology from a societal perspective (i.e. minimizing total cost risks) deviates from the risk-preferred technology from a company perspective (i.e. minimizing total cost and revenue risks).

For a better traceability of the results, we have conceded a couple of strong simplifications in the model. While these may open the need for further research, we are convinced that they do not bias our principal findings in a substantial way. Many of these simplifications refer to the design of the underlying peak-load pricing model and have been considered before by other authors: We consider only two technologies but most arguments can easily be transferred to the n -technology case (cf. [Sunderkötter and Weber, 2012](#)). In addition, we assume a deterministic merit order and exclude the possibility of a fuel switch in our calculations. [Sunderkötter and Weber \(2011\)](#) discuss this topic in detail and show that a fuel switch risk requires generation technologies with little difference in the mean operating costs. Furthermore, one may criticize that the assumption of a constant non-stochastic backstop technology is a too simple representation. Including stochastic shocks or a description of the backstop price as an increasing function of load may be suitable for making the model more realistic at this point. However, we expect that implementing these extensions would improve the quality of the numerical estimates but not lead to structural changes of key results of this article.

Appendix A. Symbols and model notation

Indices

u	Plant technology
j	Electricity market company
t	Time step during analysis period $[0; T]$

Operators

$\text{Var}[\cdot]$	Variance operator
$\mathbf{E}[\cdot]$	Expected value operator

Parameters and variables

A_h	1/€	Households' coefficient of risk aversion
A_j	1/€	Market agents' coefficient of risk aversion
α_j		market agents' profit share
$r_{el,j}$		Rate of return of electricity company j
r_m		Rate of return of the market portfolio j
r_0		Risk-free rate of return
$D(t)$	MW	Total system demand at time t
t_u	hours	Minimal operating duration of u
$p_{el}(t)$		Electricity market price at time t
B	€	Investment budget
X_0	€	Total investment into the risk-free asset
X_m	€	Total investment into the market portfolio
X_{el}	€	Total investment into the electricity market
$x_{el,j}$	€	Investment into the electricity market company j
K_u	MW	Total installed capacity of plant technology u
$k_{u,j}$	MW	Installed capacity of plant technology u of company j
Q_E	MWh	Total energy produced (incl loss of load) in period $[0; T]$
Q_u	MWh	Total energy produced of plant technology u in period $[0; T]$
Q_d	MWh	Total loss of demand (c.f. backstop technology) in period $[0; T]$
$q_{u,j}$	MWh	Energy produced by plant technology u of company j in $[0; T]$
$y_{u,j}(t)$	MW	Output level by plant u of company j at time t
$y_d(t)$	MW	Loss of demand (load of the backstop technology) at time t
$c_{inv,u}$	€/MW _e	Annuity of specific investment costs of plant u per capacity K_u
$c_{op,u}(t)$	€/MWh _e	Specific operating costs of plant u in period t per output $y_{u,t}$
c_d	€/MWh _e	Specific value of lost load (operating costs backstop technology)
\bar{c}_u	€/MWh _e	Mean operation costs of plant u
σ_u	€/MWh _e	Standard deviation of total operation costs of plant u
σ_m	€/MWh _e	Standard deviation of the market portfolio return
σ_{uv}	€ ² /MWh _e ²	Covariance of total operation costs of plant u and v

Appendix B. Mathematical Appendix

Appendix B.1. Optimality conditions to the market equilibrium under perfect competition

Proposition 3.1. [Market equilibrium under perfect competition] Let be a stylized economy and as defined in Section 2 and an electricity market with two generation technologies. Furthermore, a strictly positive societal risk aversion, i.e. $A > 0$ is assumed. If an interior solution to problem (5)-(8) exists with $K_1, K_2, X_m > 0$, and under the assumption that $X_m \gg \sum_u c_{inv,u} K_u$ and $X_m \gg \sum_u Q_u$, the optimal investments into the market portfolio and the risk-free security are given by

$$X_m = \frac{1}{A} \frac{\bar{r}_m - r_0}{\sigma_m^2}, \quad (9)$$

$$X_0 = B - X_m - \sum_{u \in U} c_{inv,u} K_u. \quad (10)$$

The optimal capacity structure within the generation portfolio is characterized by the following optimality conditions, which are only dependent on the decision variables K_1, K_2 (or equivalently on $t_1(K_1), t_2(K_1, K_2)$, and $Q_1(K_1), Q_2(K_1, K_2)$):

$$\frac{(1 + r_0)(c_{inv,1} - c_{inv,2})}{t_1} = \bar{c}_{op,2} - \bar{c}_{op,1} + \frac{\bar{r}_m - r_0}{\sigma_m^2}(\sigma_{1m} - \sigma_{2m}), \quad (11)$$

$$\frac{(1 + r_0)c_{inv,2}}{t_2} = c_d - \bar{c}_{op,2} + \frac{\bar{r}_m - r_0}{\sigma_m^2}\sigma_{2m}. \quad (12)$$

Proof of Proposition 3.1. For the welfare optimal solution discussed in Section 3, the Lagrangian can be obtained as follows:

$$\begin{aligned} \mathcal{L}_W := & \bar{r}_m X_m + r_0 X_0 - \sum_{u=1}^2 (c_{inv,u} K_u + \bar{c}_{op,u} Q_u) - c_d Q_d - \mu \left(X_m + X_0 + \sum_{u=1}^2 c_{inv,u} K_u - B \right) \\ & - \frac{1}{2} A \left(\sigma_m^2 X_m^2 + \sum_{u=1}^2 \sigma_u^2 Q_u^2 - 2\sigma_{1m} X_m Q_1 - 2\sigma_{2,m} X_m Q_2 + 2\sigma_{12} Q_1 Q_2 \right) \end{aligned} \quad (B.1)$$

Taking into account the following (partial) derivatives for the energy produced by the respective technologies

$$\begin{array}{lll} \frac{dQ_1(K_1)}{dK_1} = t_1 & \frac{\partial Q_2(K_1, K_2)}{\partial K_1} = t_2 - t_1 & \frac{dQ_d(K_1, K_2)}{dK_1} = -t_2 \\ \frac{dQ_1(K_1)}{dK_2} = 0 & \frac{\partial Q_2(K_1, K_2)}{\partial K_2} = t_2 & \frac{dQ_d(K_1, K_2)}{dK_2} = -t_2, \end{array}$$

we obtain for the derivatives of the Lagrangian:

$$\begin{aligned}
\frac{\partial \mathcal{L}_W}{\partial K_1} &= -(1+\mu)c_{inv,1} - \left(\frac{\partial Q_2}{\partial K_1} \right) \cdot \left(\bar{c}_{op,2} + \frac{1}{2}A(2\sigma_2^2 Q_2 + 2\sigma_{12} Q_1 - 2\sigma_{2,m} X_m) \right) \\
&\quad - \left(\frac{dQ_1}{dK_1} \right) \cdot \left(\bar{c}_{op,1} + \frac{1}{2}A(2\sigma_1^2 Q_1 + 2\sigma_{12} Q_2 - 2\sigma_{1m} X_m) \right) - c_d \left(\frac{dQ_d}{dK_2} \right), \\
&= (t_1 - t_2) (\bar{c}_{op,2} - \bar{c}_{op,1} - A((\sigma_{2m} - \sigma_{1m})X_m - (\sigma_2^2 - \sigma_{12})Q_2 + (\sigma_1^2 - \sigma_{12})Q_1)) + c_d t_2 - (1+\mu)c_{inv,1} \\
&= (t_1 - t_2) \left(\sum_{u=1}^2 (-1)^u (\bar{c}_{op,u} - A(\sigma_{u,m} X_m - (\sigma_u^2 - \sigma_{12})Q_u)) \right) + c_d t_2 - (1+\mu)c_{inv,1}, \tag{B.2}
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \mathcal{L}_W}{\partial K_2} &= -(1+\mu)c_{inv,2} - \left(\frac{\partial Q_2}{\partial K_2} \right) \cdot \left(\bar{c}_{op,2} + \frac{1}{2}A(-2\sigma_{2,m} X_m + 2\sigma_2^2 Q_2 + 2\sigma_{12} Q_1) \right) - c_d \left(\frac{dQ_d}{dK_2} \right) \\
&= t_2 (c_d - \bar{c}_{op,2} - A(-\sigma_{2,m} X_m + \sigma_2^2 Q_2 + \sigma_{12} Q_1)) - (1+\mu)c_{inv,2}, \tag{B.3}
\end{aligned}$$

$$\frac{\partial \mathcal{L}_W}{\partial X_m} = \bar{r}_m - \mu - A(\sigma_m^2 X_m - \sigma_{2,m} Q_2 - \sigma_{1m} Q_1) \tag{B.4}$$

$$\frac{\partial \mathcal{L}_W}{\partial X_0} = r_0 - \mu \tag{B.5}$$

$$\frac{\partial \mathcal{L}_W}{\partial \mu} = X_0 + X_m + \sum_{u=1}^2 c_{inv,u} K_u - B \tag{B.6}$$

For $K_1, K_2, X_m > 0$, it follows that $\frac{\partial \mathcal{L}_W}{\partial K_1}, \frac{\partial \mathcal{L}_W}{\partial K_2}, \frac{\partial \mathcal{L}_W}{\partial X_0}, \frac{\partial \mathcal{L}_W}{\partial X_m}, \nu_1, \nu_2$ must equal zero. Furthermore, it is $\mu = r_0$. X_m can be eliminated by solving $\frac{\partial \mathcal{L}_W}{\partial X_m} = 0$ for X_m , yielding:

$$X_m = \frac{\bar{r}_m - r_0}{A\sigma_m^2} + \frac{Q_2\sigma_{m2} + Q_1\sigma_{m1}}{\sigma_m^2}. \tag{B.7}$$

By inserting X_m into Eqs. (B.2) and (B.4), we obtain the following first order conditions:

$$(1+r_0)c_{inv,2} = t_2 \left(c_d - \bar{c}_2 + A \left(\sigma_{m2} \left(\frac{\bar{r}_m - r_0}{A\sigma_m^2} + \frac{Q_2\sigma_{m2} + Q_1\sigma_{m1}}{\sigma_m^2} \right) + \sigma_2^2 Q_2 + \sigma_{12} Q_1 \right) \right) \tag{B.8}$$

$$\begin{aligned}
(1+r_0)(c_{inv,2} - c_{inv,1}) &= \\
&- t_1 \left(\bar{c}_2 - \bar{c}_1 - A \left((\sigma_{m2} - \sigma_{m1}) \left(\frac{\bar{r}_m - r_0}{A\sigma_m^2} + \frac{Q_2\sigma_{m2} + Q_1\sigma_{m1}}{\sigma_m^2} \right) - (\sigma_2^2 - \sigma_{12})Q_2 + (\sigma_1^2 - \sigma_{12})Q_1 \right) \right) \tag{B.9}
\end{aligned}$$

Assuming that the total investment in the economy is sufficiently large compared to the electricity market, i.e. $X_m \gg \sum_u c_{inv,u} K_u$ and $X_m \gg \sum_u Q_u$, we can neglect all terms with Q_1 and Q_2 . Consequently, we obtain optimality conditions (11) and (12).

□

Appendix B.2. Proof of price formation at the second stage of the model

Proposition 4.1. *Let be a stylized economy as defined in Section 2. Then, the wholesale electricity price is given by the function:*

$$p_{el}(t, \tilde{\zeta}) = \begin{cases} \tilde{c}_{op,1}, & \text{if } t > D^{-1}(K_1) \\ \tilde{c}_{op,2}, & \text{if } D^{-1}(K_1) \geq t > D^{-1}(K_2 + K_1) \\ c_d, & \text{if } D^{-1}(K_2 + K_1) \geq t \end{cases} \quad (\text{B.25})$$

Proof of Proposition 4.1. For the proof, we derive the KKT conditions of the household's and the electricity company's optimization problem at the second stage. The Lagrangian of the household's optimization problem (15)-(18) can be stated as

$$\mathcal{L}_h(t, \tilde{\zeta}) = \mathbf{E} [V_h(\tilde{\zeta})] - \frac{A_h}{2} \text{Var} [V_h(\tilde{\zeta})] - \mu_h (X_0 + X_m + \sum_j x_{el,j} - B) \quad (\text{B.10})$$

At the second stage, the realization of all risk factors is ζ known and the Lagrangian simplifies to

$$\begin{aligned} \hat{\mathcal{L}}_h(t, \zeta) = & r_0 X_0 + \tilde{r}_m(\zeta) X_m + \sum_{j \in J} (1 - \alpha_j) \cdot r_{el,j}(\zeta) x_{el,j} - \\ & \int_0^T p_{el}(t, \zeta) D(t) dt + \int_0^T (p_{el}(t, \zeta) - c_d) \cdot y_d(t, \zeta) dt - \mu_h \cdot \left(X_m + X_0 + \sum_{j \in J} x_{el,j} - B \right) \end{aligned} \quad (\text{B.11})$$

For the electricity market agents, the Lagrangian referring to optimization problem (19)-(22) writes:

$$\mathcal{L}_{el,j}(t, \tilde{\zeta}) = \mathbf{E} [\Pi_{el,j}(\tilde{\zeta})] - \frac{A_j}{2} \text{Var} [\Pi_{el,j}(\tilde{\zeta})] - \int_0^T \lambda_{u,j}(t, \tilde{\zeta}) (y_{u,j}(t, \tilde{\zeta}) - k_{u,j}) dt d\tilde{\zeta} - \mu_j \left(\sum_u c_{inv,u} k_{u,j} - x_{el,j} \right) \quad (\text{B.12})$$

Given the deterministic realization of ζ at the second stage of the model, the Lagrangian simplifies to

$$\hat{\mathcal{L}}_{el,j}(t, \zeta) = \Pi_{el,j} - \int_0^T \lambda_{u,j}(t, \zeta) \cdot (y_{u,j}(t, \zeta) - k_{u,j}) dt - \mu_j \left(\sum_u c_{inv,u} k_{u,j} - x_{el,j} \right) \quad (\text{B.13})$$

$$\text{with } \Pi_{el,j} := \alpha_j \sum_u \left(\int_0^T (p_{el}(t, \zeta) - c_{op,u}) y_{u,j}(t, \zeta) dt - c_{inv,u} k_{u,j} \right) \quad (\text{B.14})$$

We can now straightforwardly derive the KKT conditions for the (decision) variables at the second stage of the model. The KKT conditions derived from the Lagrangian (B.13) of the suppliers' problem at the second stage have to be satisfied for each company j and each generation technology u are:

$$\frac{\partial \hat{\mathcal{L}}_{el,j}}{\partial y_{u,j}}(t, \zeta) = \alpha_j (p_{el}(t, \zeta) - c_{op,u}) - \lambda_{u,j}(t, \zeta) \leq 0 \quad \perp \quad y_{u,j}(t, \zeta) \geq 0 \quad \forall t \in [0, T], \quad \forall \zeta \quad (\text{B.15})$$

$$\frac{\partial \hat{\mathcal{L}}_{el,j}}{\partial \lambda_{u,j}}(t, \zeta) = y_{u,j}(t, \zeta) - k_{u,j} \leq 0 \quad \perp \quad \lambda_{u,j}(t, \zeta) \geq 0 \quad \forall t \in [0, T], \quad \forall \zeta \quad (\text{B.16})$$

In addition, the KKT condition for the households' optimization problem for the only decision variable at the second stage, y_d , is:

$$\frac{\partial \hat{\mathcal{L}}_h}{\partial y_d}(t, \zeta) = p_{el}(t, \zeta) - c_d \leq 0 \quad \perp \quad y_d(t, \tilde{\zeta}) \geq 0 \quad (\text{B.17})$$

Therefore it holds $p_{el}(t, \tilde{\zeta}) = c_d$ at all points in time where $y_d(t, \tilde{\zeta}) > 0$. Hence, the upper bound of the electricity price $p_{el}(t, \tilde{\zeta})$ is the value of lost load c_d and it equals this value if and only if $y_d(t, \tilde{\zeta}) > 0$.

It becomes visible in condition (B.16) that the shadow price of capacity is zero whenever production is beneath the corresponding capacity, i.e. $\lambda_{u,j}(t, \zeta) = 0 \forall \{t \in [0, T] | y_{u,j}(t, \zeta) < k_{u,j}\}$. Equation (B.15) implies that the shadow price of capacity $\lambda_{u,j}(t, \zeta)$ must equal company's share of the operational margin $\alpha_j(p_{el}(t, \zeta) - c_{op,u})$. Hence, the electricity price equals the marginal production costs whenever production of the respective technology is beneath its installed capacity, i.e. $p_{el}(t, \zeta) = c_{op,u} \forall \{t \in [0, T] | 0 < y_{u,j}(t, \zeta) < k_{u,j}\}, \forall \zeta$. It can also be concluded that at time of operation of technology u with costs $c_{op,u} > 0$, the electricity price must always be positive. If $y_d(t, \zeta) > 0$, it is known from (B.17) that $p_{el}(t, \zeta) = c_d$. When $y_d(t, \zeta) = 0$, the market clearing condition (24) requires that at least one technology is operating since $D(t) > 0 \forall t \in [0, T]$. For this technology, equation (B.15) requires that $p_{el}(t, \tilde{\zeta}) = c_{op,u} + 1/\alpha_j \lambda_{u,j}(t, \tilde{\zeta}) \forall t \in [0, T]$ implying $p_{el}(t, \tilde{\zeta}) > 0$ due to the non-negativity of the Lagrange multiplier $\lambda_{u,j}(t, \tilde{\zeta}) \geq 0$. Furthermore, the market clearing condition (24) holds with equality, i.e. $\sum_{u \in U} \sum_{j \in J_u} y_{u,j}(t, \tilde{\zeta}) = D(t) - y_d(t, \tilde{\zeta}) \forall t \in [0, T]$ (but only if $c_{op,u} > 0, u \in U$).

□

Proposition 4.2. *The profits of the individual technologies $\Pi_{u,j}(\tilde{\zeta})$ as defined in (20) can be rewritten as:*

$$\Pi_{1,j}(\tilde{\zeta}) = (t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1}) + t_2(c_d - \tilde{c}_{op,2}) - c_{inv,1})k_{1,j} \quad (27)$$

$$\Pi_{2,j}(\tilde{\zeta}) = (t_2(c_d - \tilde{c}_{op,2}) - c_{inv,2})k_{2,j} \quad (28)$$

Proof of Proposition (4.2). Starting with the definition of $\Pi_{u,j}$, $\Pi_{u,j}(\tilde{\zeta}) = \int_0^T (p_{el}(t, \tilde{\zeta}) - \tilde{c}_{op,u})y_{u,j}(t, \tilde{\zeta})dt - c_{inv,u}k_{u,j}$, and with prices as derived in Equation (25) we can argue:

For $t > t_1$, it holds $p_{el}(t, \tilde{\zeta}) = c_1$ and consequently

$$(p_{el}(t, \tilde{\zeta}) - \tilde{c}_{op,1})y_{1,j}(t, \tilde{\zeta}) = (\tilde{c}_{op,1} - \tilde{c}_{op,1})y_{u,j}(t, \tilde{\zeta}) = 0$$

for technology 1 and

$$(p_{el}(t, \tilde{\zeta}) - \tilde{c}_{op,2})y_{2,j}(t, \tilde{\zeta}) = (p_{el}(t, \tilde{\zeta}) - \tilde{c}_{op,1}) \cdot 0 = 0$$

for technology 2, i.e. neither technology earns any contribution margin for all $t \in (t_1, T]$. Analogously, one can conclude that technology 2 does not earn any margin for all $t \in (t_2, t_1]$.

Hence, it follows that one can write t_u as the upper bound of the integral describing the total operational margin, $\int_0^T (p_{el}(t, \tilde{\zeta}) - \tilde{c}_{op,u}) y_{u,j}(t, \tilde{\zeta}) dt = \int_0^{t_u} (p_{el}(t, \tilde{\zeta}) - \tilde{c}_{op,u}) y_{u,j}(t, \tilde{\zeta}) dt$. For the points in time t with $t < t_u$, we have shown that the prices are constant within the intervals $[0, t_1]$ and $(t_2, T]$ as given in Eqn.(25). With the given definitions of $q_{12,j}$, $q_{13,j}$ and $q_{23,j}$ we can then rewrite the operational margins $\Pi_{1,j}$ and $\Pi_{2,j}$ as:

$$\Pi_{1,j}(\tilde{\zeta}) = q_{12,j} \cdot (\tilde{c}_{op,2} - \tilde{c}_{op,1}) + q_{13,j} \cdot (\tilde{c}_d - \tilde{c}_{op,1}) \quad (\text{B.18})$$

$$\Pi_{2,j}(\tilde{\zeta}) = q_{23,j} \cdot (\tilde{c}_d - \tilde{c}_{op,2}) \quad (\text{B.19})$$

Replacing $q_{12,j}$, $q_{13,j}$ and $q_{23,j}$ as in Eqn.(26) immediately delivers the proof of Proposition (4.2). \square

Proposition 4.3. *The return $r_{el,j}(\tilde{\zeta})$ as defined in (13) can be specified as:*

$$r_{el,j}(\tilde{\zeta}) = \frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})k_{1,j} + t_2(c_d - \tilde{c}_{op,2})(k_{1,j} + k_{2,j})}{c_{inv,1}k_{1,j} + c_{inv,2}k_{2,j}} - 1 \quad (29)$$

Proof of Proposition (4.3). $r_{el,j}(\tilde{\zeta})$ is defined by: $r_{el,j}(\tilde{\zeta}) := \frac{\sum_u \Pi_{u,j}}{x_{el,j}}$ (cp. Eqn.13). Putting the expressions for $\Pi_{1,j}$ and $\Pi_{2,j}$ from Proposition (4.2) into this definition yields the new term for $r_{el,j}$ as given in Eqn.(29). \square

Appendix B.3. Proof of Market Agent Optimality Condition

Proposition 4.4. *[Electricity market agents' optimality condition] Let be a stylized economy as defined in Section 2 and Definition 4.1.*

Under the assumption of homogeneous market agents with identical risk aversion $A_j \forall j \in J$ the necessary optimality condition for an interior solution with $k_1, k_2 > 0$ for the optimization problem of the electricity agents as stated in Eqn. (19)-(22) is given by:

$$\begin{aligned} & t_2 \left(\frac{c_d - \tilde{c}_{op,2}}{c_{inv,2}} - \frac{A_j \alpha_j}{N c_{inv,2}} (t_1 K_1 (\sigma_{12} - \sigma_2^2) + t_2 (K_1 + K_2) \sigma_2^2) \right) \\ & = t_1 \left(\frac{\tilde{c}_{op,2} - \tilde{c}_{op,1}}{c_{inv,1} - c_{inv,2}} - \frac{A_j \alpha_j}{N (c_{inv,1} - c_{inv,2})} (t_1 K_1 (\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}) + t_2 (K_1 + K_2) (\sigma_{12} - \sigma_2^2)) \right) \end{aligned} \quad (30)$$

Proof of Proposition 4.4. Starting from the Lagrangian of the market agents' optimization problem,

$$\mathcal{L}_{el,j}(t, \tilde{\zeta}) = \mathbf{E} [\Pi_{el,j}(\tilde{\zeta})] - \frac{A_j}{2} \text{Var} [\Pi_{el,j}(\tilde{\zeta})] - \int \int_0^T \lambda_{u,j}(t, \tilde{\zeta}) (y_{u,j}(t, \tilde{\zeta}) - k_{u,j}) dt d\tilde{\zeta} - \mu_j \left(\sum_u c_{inv,u} k_{u,j} - x_{el,j} \right) \quad (B.20)$$

The first order condition with respect to $x_{el,j}$ yields

$$\frac{\partial \mathcal{L}_{el,j}}{\partial x_{el,j}} = -(1 - \alpha_j) \frac{\mathbf{E} [\sum_u \Pi_{u,j}]}{x_{el,j}} + A_j (1 - \alpha_j) \alpha_j \frac{1}{x_{el,j}} \text{Var} \left[\sum_u \Pi_{u,j} \right] + \mu_j = 0. \quad (B.21)$$

After substituting $\sum_u \Pi_{u,j}/x_{el,j}$ with $r_{el,j}$, a defining equation for the shadow price of the investment capital from the market agent's perspective is given by

$$\Leftrightarrow \mu_j = (1 - \alpha_j) (\mathbf{E} [r_{el,j}(\tilde{\zeta})] - A_j \alpha_j x_{el,j}(\tilde{\zeta}) \text{Var} [r_{el,j}(\tilde{\zeta})]) \quad (B.22)$$

From Proposition 4.2, we know that $r_{el,j}(\tilde{\zeta})$ can be written directly in terms of t_i and $k_{i,j}$, i.e. instead of Eqn. (B.22), we can write:

$$\begin{aligned} \mu_j = & (1 - \alpha_j) \left(\frac{t_1 k_{1,j} \mathbf{E} [\tilde{c}_{op,2} - \tilde{c}_{op,1}] + t_2 (k_{1,j} + k_{2,j}) \mathbf{E} [c_d - \tilde{c}_{op,2}]}{c_{inv,1} k_{1,j} + c_{inv,2} k_{2,j}} - 1 - A_j \alpha_j \left(\frac{t_1^2 k_{1,j}^2 \text{Var} [\tilde{c}_{op,2} - \tilde{c}_{op,1}]}{c_{inv,1} k_{1,j}} \right. \right. \\ & \left. \left. + \frac{t_2^2 (k_{1,j} + k_{2,j})^2 \text{Var} [c_d - \tilde{c}_{op,2}]}{c_{inv,1} k_{1,j}} + \frac{2 t_1 t_2 k_{1,j} (k_{1,j} + k_{2,j}) \text{Cov} [\tilde{c}_{op,2} - \tilde{c}_{op,1}, c_d - \tilde{c}_{op,2}]}{c_{inv,1} k_{1,j} + c_{inv,2} k_{2,j}} \right) \right) \end{aligned} \quad (B.23)$$

Additionally, equations (27) and (28) enable us to express the condition for the shadow price of investment also as a function of t_i and $k_{i,j}$:

$$(1 + \mu_j) c_{inv,2} = t_2 \mathbf{E} [c_d - \tilde{c}_{op,2}] - A_j \alpha_j (t_2 t_1 k_{1,j} \text{Cov} [(c_d - \tilde{c}_{op,2}), (\tilde{c}_{op,2} - \tilde{c}_{op,1})] + t_2^2 (k_{1,j} + k_{2,j}) \text{Var} [c_d - \tilde{c}_{op,2}]) \quad (B.24)$$

$$\begin{aligned} (1 + \mu_j) c_{inv,1} = & t_2 \mathbf{E} [c_d - \tilde{c}_{op,2}] + t_1 \mathbf{E} [\tilde{c}_{op,2} - \tilde{c}_{op,1}] - A_j \alpha_j \left(t_2 t_1 k_{1,j} \text{Cov} [(c_d - \tilde{c}_{op,2}), (\tilde{c}_{op,2} - \tilde{c}_{op,1})] \right. \\ & + t_2^2 (k_{1,j} + k_{2,j}) \text{Var} [c_d - \tilde{c}_{op,2}] + t_1^2 k_{1,j} \text{Var} [\tilde{c}_{op,2} - \tilde{c}_{op,1}] \\ & \left. + t_2 t_1 (k_{1,j} + k_{2,j}) \text{Cov} [(\tilde{c}_{op,2} - \tilde{c}_{op,1}), (c_d - \tilde{c}_{op,2})] \right) \end{aligned} \quad (B.25)$$

We can equate these two by dividing them by $c_{inv,1}$ and $c_{inv,2}$, respectively. At the same time, we can replace the individual capacities $k_{i,j}$ by K_i/N and use simplified expressions to write the variances and covariances, $\sigma_i^2 := \text{Var}[\tilde{c}_{op,i}]$ und $\sigma_{i,j} := \text{Cov}[\tilde{c}_{op,i}, \tilde{c}_{op,j}]$ and under consideration of $\text{Cov}[(c_d - \tilde{c}_{op,2}), \tilde{c}_{op,2} - \tilde{c}_{op,1}] = (\sigma_{12} - \sigma_2^2)$, $\text{Var}[\tilde{c}_{op,2} - \tilde{c}_{op,1}] = (\sigma_1^2 + \sigma_2^2 - 2\sigma_{12})$, we obtain:

$$\begin{aligned} & \frac{1}{c_{inv,1}} \left(t_2 \mathbf{E}[c_d - \tilde{c}_{op,2}] + t_1 \mathbf{E}[\tilde{c}_{op,2} - \tilde{c}_{op,1}] \right. \\ & - \left(A_j \alpha_j \left(t_2 t_1 \frac{K_1}{N} (\sigma_{12} - \sigma_2^2) + t_2^2 \frac{K_1 + K_2}{N} \sigma_2^2 + t_1^2 \frac{K_1}{N} (\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}) + t_2 t_1 \frac{K_1 + K_2}{N} (\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}) \right) \right) \\ & = \frac{1}{c_{inv,2}} \left(t_2 \mathbf{E}[c_d - \tilde{c}_{op,2}] - \left(A_j \alpha_j \left(t_2 t_1 \frac{K_1}{N} (\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}) + t_2^2 \frac{K_1 + K_2}{N} \sigma_2^2 \right) \right) \right) \end{aligned} \quad (\text{B.26})$$

Finally, some simple rearrangements (in particular, separating the parts related to the investment costs of the peak technology $c_{inv,2}$ and to the extra investment costs $c_{inv,1} - c_{inv,2}$ for the baseload technology) lead us to the condition of Proposition 4.4:

$$\begin{aligned} & t_2 \left(\frac{c_d - \tilde{c}_{op,2}}{c_{inv,2}} - \frac{A_j \alpha_j}{N c_{inv,2}} (t_1 K_1 (\sigma_{12} - \sigma_2^2) + t_2 (K_1 + K_2) \sigma_2^2) \right) = \\ & t_1 \left(\frac{\tilde{c}_{op,2} - \tilde{c}_{op,1}}{c_{inv,1} - c_{inv,2}} - \frac{A_j \alpha_j}{N (c_{inv,1} - c_{inv,2})} (t_1 K_1 (\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}) + t_2 (K_1 + K_2) (\sigma_{12} - \sigma_2^2)) \right) \end{aligned} \quad (\text{B.27})$$

□

Appendix B.4. Proof of Households' Optimality Condition

Proposition 4.5. *[Households' optimality condition] Let be a stylized economy as defined in Section 2 and Definition 4.1. We assume a neglectable managerial profit share, i.e. $1 - \alpha_j \approx 1$, and total investments in the economy being sufficiently large compared to the electricity market, i.e. $X_m \gg X_{el}$. Then, the necessary optimality condition for an interior solution with $x_{el,j} > 0, \forall j \in J$ to the optimization problem of the households as stated in Eqn. (15)-(18), is given by:*

$$\frac{t_2(K_1 + K_2)(c_d - \tilde{c}_{op,2}) + t_1 K_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})}{c_{inv,1}K_1 + c_{inv,2}K_2} = 1 + r_0 + X_m \frac{\bar{r}_m - r_0}{\sigma_m^2} \cdot \frac{t_1 K_1 \sigma_{m,1} - ((t_1 - t_2)K_1 - t_2 K_2) \sigma_{m,2}}{c_{inv,1}K_1 + c_{inv,2}K_2} \quad (31)$$

Proof of Proposition 4.5. Starting point is the Lagrangian \mathcal{L}_h of the households' optimization problem:

$$\mathcal{L}_h(t, \tilde{\zeta}) = \mathbf{E} [V_h(\tilde{\zeta})] - \frac{A_h}{2} \text{Var} [V_h(\tilde{\zeta})] - \mu_h (X_0 + X_m + \sum_j x_{el,j} - B) \quad (\text{B.28})$$

Before deriving the first order conditions, we first compute the derivatives of $\text{Var}[V_h]$ with respect to $x_{el,j}$. Thereby we use

$$\begin{aligned} \text{Var}[V_h(\tilde{\zeta})] &= \text{Var} \left[r_0 X_0 + r_m(\tilde{\zeta}) X_m + \sum_j (1 - \alpha_j) r_{el,j} - C_{el}(\tilde{\zeta}) \right] \\ &= \int (r_0 X_0 + r_m(\tilde{\zeta}) X_m + \sum_j (1 - \alpha_j) r_{el,j} - C_{el}(\tilde{\zeta}) - \mathbf{E}[V_h(\tilde{\zeta})])^2 d\tilde{\zeta} \\ &= \int ((r_m(\tilde{\zeta}) - \mathbf{E}[r_m]) X_m + \sum_j (1 - \alpha_j) (r_{el,j}(\tilde{\zeta}) - \mathbf{E}[r_{el,j}]) x_{el,j} - (C_{el}(\tilde{\zeta}) - \mathbf{E}[C_{el}]))^2 d\tilde{\zeta} \\ &= X_m^2 \int (r_m(\tilde{\zeta}) - \mathbf{E}[r_m])^2 d\tilde{\zeta} + \int \left(\sum_j (1 - \alpha_j) (r_{el,j}(\tilde{\zeta}) - \mathbf{E}[r_{el,j}]) x_{el,j} \right)^2 d\tilde{\zeta} \\ &\quad + \int (C_{el}(\tilde{\zeta}) - \mathbf{E}[C_{el}])^2 d\tilde{\zeta} + 2 X_m \int (r_m(\tilde{\zeta}) - \mathbf{E}[r_m]) \left(\sum_j (1 - \alpha_j) (r_{el,j}(\tilde{\zeta}) - \mathbf{E}[r_{el,j}]) x_{el,j} \right) d\tilde{\zeta} \\ &\quad - 2 X_m \int (r_m(\tilde{\zeta}) - \mathbf{E}[r_m]) (C_{el}(\tilde{\zeta}) - \mathbf{E}[C_{el}]) d\tilde{\zeta} \\ &\quad - 2 \int \left(\sum_j (1 - \alpha_j) (r_{el,j}(\tilde{\zeta}) - \mathbf{E}[r_{el,j}]) x_{el,j} \right) (C_{el}(\tilde{\zeta}) - \mathbf{E}[C_{el}]) d\tilde{\zeta} \end{aligned} \quad (\text{B.29})$$

Thus, we get for the derivative

$$\begin{aligned} \frac{\partial \text{Var}[V_h(\tilde{\zeta})]}{\partial x_{el,j}} &= 2(1 - \alpha_j)^2 \int (r_{el,j}(\tilde{\zeta}) - \mathbf{E}[r_{el,j}]) \left(\sum_{j'} (r_{el,j'}(\tilde{\zeta}) - \mathbf{E}[r_{el,j'}]) x_{el,j'} \right) d\tilde{\zeta} \\ &\quad + 2 X_m (1 - \alpha_j) \int (r_m(\tilde{\zeta}) - \mathbf{E}[r_m]) (r_{el,j}(\tilde{\zeta}) - \mathbf{E}[r_{el,j}]) d\tilde{\zeta} \\ &\quad - 2(1 - \alpha_j) \int (r_{el,j}(\tilde{\zeta}) - \mathbf{E}[r_{el,j}]) (C_{el}(\tilde{\zeta}) - \mathbf{E}[C_{el}]) d\tilde{\zeta} \end{aligned} \quad (\text{B.30})$$

Under the premise of symmetric market agents it follows

$$\frac{\partial \text{Var}[V_h(\tilde{\zeta})]}{\partial x_{el,j}} = 2(1 - \alpha_j)((1 - \alpha_j)X_{el}\text{Var}[r_{el,j}(\tilde{\zeta})] + X_m\text{Cov}[r_{el,j}(\tilde{\zeta}), r_m(\tilde{\zeta})] - \text{Cov}[r_{el,j}(\tilde{\zeta}), C_{el}(\tilde{\zeta})]) \quad (\text{B.31})$$

Based on these pre-considerations, the first order conditions with respect to $x_{el,j}$, X_0 , X_m can be derived as:

$$\frac{\partial \mathcal{L}_h}{\partial x_{el,j}} = \mathbf{E}[r_{el,j}] - A_h((1 - \alpha_j)X_{el}\text{Var}[r_{el,j}] + X_m\text{Cov}[r_{el,j}, r_m] - \text{Cov}[r_{el,j}, C_{el}]) - \frac{1}{(1 - \alpha_j)}\mu_h = 0 \quad (\text{B.32})$$

$$\frac{\partial \mathcal{L}_h}{\partial X_0} = r_0 - \mu_h = 0 \quad (\text{B.33})$$

$$\frac{\partial \mathcal{L}_h}{\partial X_m} = r_0 - A_h X_m \text{Var}[\tilde{r}_m] - \mu_h \quad (\text{B.34})$$

From (B.32), the expected portfolio return of company j is given by:

$$\mathbf{E}[r_{el,j}] = \frac{1}{(1 - \alpha_j)}r_0 + A_h((1 - \alpha_j)X_{el}\text{Var}[r_{el,j}] + X_m\text{Cov}[r_{el,j}, r_m] - \text{Cov}[r_{el,j}, C_{el}]). \quad (\text{B.35})$$

Likewise, the expected portfolio return of company j as defined in (13) can be specified with the price formation at the second stage according to Proposition 4.1

$$r_{el,j}(\tilde{\zeta}) = \frac{(t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1}) + t_2(c_d - \tilde{c}_{op,2}) - c_{inv,1})k_{1,j} + (t_2(c_d - \tilde{c}_{op,2}) - c_{inv,2})k_{2,j}}{c_{inv,1}k_{1,j} + c_{inv,2}k_{2,j}} \quad (\text{B.36})$$

$$= \frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})k_{1,j} + t_2(c_d - \tilde{c}_{op,2})(k_{1,j} + k_{2,j})}{c_{inv,1}k_{1,j} + c_{inv,2}k_{2,j}} - 1 \quad (\text{B.37})$$

Equating (B.35) and (B.37) and with $C_{el} = c_d \int_0^{t_2} y_d(t)dt + \tilde{c}_{op,2} \int_{t_2}^{t_1} y_d(t)dt + \tilde{c}_{op,1} \int_{t_1}^T y_d(t)dt = c_d Q_d(t_2) + \tilde{c}_{op,2} Q_2 + \tilde{c}_{op,1} Q_1(t_1)$ we obtain:

$$\begin{aligned} & \mathbf{E} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2} - 1 \right] = \frac{1}{1 - \alpha_j}r_0 + \\ & A_h \left((1 - \alpha_j)(c_{inv,1}K_1 + c_{inv,2}K_2) \text{Var} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2} - 1 \right] + \right. \\ & \quad X_m \text{Cov} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2} - 1, r_m \right] - \\ & \quad \left. \text{Cov} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2} - 1, c_d Q_d + \tilde{c}_{op,2} Q_2 + \tilde{c}_{op,1} Q_1(t_1) \right] \right) \end{aligned} \quad (\text{B.38})$$

With $1 - \alpha_j \approx 1$ and some transformations we obtain:

$$\begin{aligned} & \mathbf{E} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2} - 1 - r_0 \right] = \\ & A_h \left((c_{inv,1}K_1 + c_{inv,2}K_2) \text{Var} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2} \right] + \right. \\ & \quad X_m \text{Cov} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2}, r_m \right] - \\ & \quad \left. \text{Cov} \left[\frac{t_1(\tilde{c}_{op,2} - \tilde{c}_{op,1})K_1 + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2)}{c_{inv,1}K_1 + c_{inv,2}K_2}, c_d Q_d + \tilde{c}_{op,2} Q_2 + \tilde{c}_{op,1} Q_1(t_1) \right] \right) \end{aligned} \quad (\text{B.39})$$

In knowledge of the propoerties for variance of sums this equation can be written as

$$\begin{aligned}
& \frac{t_2(K_1 + K_2)c_d + ((t_1 - t_2)K_1 - t_2K_2)\mathbf{E}[\tilde{c}_{op,2}] - t_1K_1\mathbf{E}[\tilde{c}_{op,1}]}{c_{inv,1}K_1 + c_{inv,2}K_2} - 1 - r_0 = \\
& \frac{A_h}{c_{inv,1}K_{1,j} + c_{inv,2}K_{2,j}} \left((((t_1 - t_2)K_1 - t_2K_2)^2 \text{Var}[\tilde{c}_{op,2}] - 2((t_1 - t_2)K_1 - t_2K_2)t_1K_1 \text{Cov}[\tilde{c}_{op,1}, \tilde{c}_{op,2}] \right. \\
& \quad \left. + (t_1K_1)^2 \text{Var}[\tilde{c}_{op,1}]) + X_m (((t_1 - t_2)K_1 - t_2K_2) \text{Cov}[\tilde{c}_{op,2}, r_m] - t_1K_1 \text{Cov}[\tilde{c}_{op,1}, r_m]) - \right. \\
& \quad \left. \text{Cov}[t_1K_1(\tilde{c}_{op,2} - \tilde{c}_{op,1}) + t_2(c_d - \tilde{c}_{op,2})(K_1 + K_2), c_dQ_d(t_2) + \tilde{c}_{op,2}Q_2(t_2, t_1) + \tilde{c}_{op,1}Q_1(t_1)] \right) \\
& \hspace{25em} \text{(B.40)}
\end{aligned}$$

For $X_m \gg X_{el}$, all summands without X_m on the right side of the equation can be neglected and the optimality condition can be simplified to:

$$\frac{t_2(K_1 + K_2)c_d + ((t_1 - t_2)K_1 - t_2K_2)(\mathbf{E}[\tilde{c}_{op,2}] - A_hX_m\sigma_{m,2} - t_1K_1(\mathbf{E}[\tilde{c}_{op,1}] - A_hX_m\sigma_{m,1}))}{c_{inv,1}K_1 + c_{inv,2}K_2} - 1 - r_0 = 0
\tag{B.41}$$

After some transformations we obtain Equation (31). □

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