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TRusT: A Two-stage Robustness Trade-off approach for the design of decentralized energy supply systems

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ABSTRACT

The design of decentralized energy supply systems is a complex task and thus best addressed by mathematical optimization. However, design problems typically rely on uncertain input data, such as future energy demands or prices. Still, conventional optimization models are usually deterministic and thus neglect uncertainties. For this reason, the deterministic optimal solution is in general suboptimal or even infeasible. Robust design methods are available to guarantee security of energy supply, however, they usually lead to significant additional costs. In this work, we show that energy supply systems with guaranteed secure energy supply are not expensive per se. For this purpose, we propose the ***T**wo-stage **Robu**stness **T**rade-off (TRusT)* approach. The TRusT approach considers the trade-off between expected costs in the nominal scenario and costs in the worst case while guaranteeing security of energy supply. Thereby, the TRusT approach identifies balanced robust energy supply systems which are cost-efficient in both the daily business and the worst case. The TRusT approach can be applied and solved efficiently. In a case study, we identify robust design options which ensure security of energy supply at low additional costs. Hence, the TRusT approach is a suitable tool to design cost-efficient and secure energy systems.

1. Introduction

Decentralized energy supply systems (DESS) are commonly designed using deterministic mathematical optimization models [1]. Deterministic optimization models, however, rely on the assumption of *perfect foresight*. Perfect foresight implies that input parameters (e. g., energy demands, prices for gas and electricity, or efficiency of the equipment) are known with certainty, when the optimization is performed. If the actual conditions differ from the deterministic parameters considered in the optimization, the obtained solutions will usually become suboptimal or even infeasible, as shown for general optimization problems [2] as well as for typical engineering problems, such as unit assignment [3], production planning [4], and DESS [5].

For DESS, infeasibility implies insufficient energy supply, for example, if the actual energy demand is higher than assumed in the design of the DESS. In practice, a pragmatic approach is often employed to aim for a reliable energy supply: Peak loads are taken into account in the optimization when considering average monthly values [6], typical days [7] or other typical periods [8]. Another pragmatic but expensive way to increase the reliability of energy supply is to install redundant equipment [9]. While security of energy supply can be achieved still assuming perfect foresight but with extraordinary high peak loads, the resulting system will be over-conservative: The peak loads are assumed to occur for certain and a corresponding energy system is built. Thus, the uncertain nature of demands has to be considered in the optimization to identify a cost-efficient robust energy supply system. The definition of a *robust energy supply system* is not used consistently in literature [10]. We expect a robust energy supply system to cover uncertain energy demands without regarding failure of equipment.

The contribution of our work is to show that a robust design which *ensures* security of energy supply can be cost-efficient at the same time. For this purpose, we introduce the ***T**wo-stage **Robu**stness **T**rade-off (TRusT)* approach. The advantages of the TRusT approach are twofold: First, the approach highlights the trade-off between nominal costs and worst-case costs for the robust design. The nominal costs represent costs obtained when uncertainties are neglected and perfect foresight is assumed. Second, the TRusT approach guarantees security of energy supply. Existing approaches often make compromises: The reliability of the system

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is reduced in order to receive a less expensive design, as shown in the following literature review.

If probability distributions of the uncertain parameters are available, stochastic optimization [11] can be applied. However, probability distributions are not known in general and have to be estimated. The uncertainty in the estimated probability distribution then impacts on the actual robustness of the design [12].

Robust optimization overcomes the need for uncertain probability distributions. A robust solution considers every possible scenario (i. e., every possible combination of parameter values) without relying on its probability of occurrence (for a review see Ref. [13]). *Strictly robust optimization* [14] ensures the feasibility of a solution for each scenario while minimizing costs for the most expensive scenarios. The concept of strictly robust optimization was introduced for linear programs by Soyster [14] in 1973 and restated by Ben-Tal and Nemirovski [15] in 1999. The resulting strictly robust optimal solutions are in general very conservative and, thus, expensive compared to the nominal costs. In order to reduce the degree of conservatism of robust solutions, the so-called Γ-*robustness* was introduced by Bertsimas and Sim [16]. Herein, not all uncertain parameters vary at the same time. The level of uncertainty Γ limits the number of parameters varying simultaneously and represents the degree of conservatism. For linear problems, the resulting Γ-robustness program can be transformed into a linear program. Robust optimization approaches have been applied successfully to the operation of decentralized energy supply systems (DESS): Dong et al. [17] use the Γ-robustness to derive a fuzzy radial linear programming model for planning robust energy management systems with environmental constraints. Akbari et al. [18] employ Γ-robustness to optimize operation. Additionally, they determine the Γ-robust structure and sizing of the installed heating and cooling components, considering renewable energy and storage. Renewable energy technologies in the design of energy systems are also considered by Moret et al. [19]. They classify the uncertain parameters to define adequate ranges of their variation. In general, Γ-robustness can only ensure security of energy supply if the conservativeness level Γ is set to its upper bound. However, using the upper bound for the level Γ leads to strictly robust optimization and thus unnecessarily expensive solutions which are not relevant for practical applications. Reducing the degree of conservatism in any way, however, compromises security of energy supply. This compromise can be measured by a robustness index analyzing the trade-off between investments and achievable targets [20].

The *minimax regret approach* (e. g., [21]) aims to identify a solution with low risk, characterized by the so-called *regret*. For each scenario, the regret is defined as the deviation between the occurring costs and the minimal possible costs for the scenario. The maximal possible regret is then minimized. To decrease the conservatism in minimax regret, Yokoyama et al. [22] allow a violation of the energy balance constraints and introduce a penalty term for the unmet energy demands in the objective function. The minimax regret approach is also successfully applied by Dong et al. [23] to determine power generation and capacity expansion for uncertain demands.

The design of decentralized energy supply systems can also be interpreted as a *two-stage optimization problem*. Two-stage problems are characterized by two kinds of variables [24]: *First-stage variables* have to be fixed in the beginning (so-called *here-and-now variables*). *Second-stage variables* (*wait-and-see variables*) can be revised later when knowledge on the scenario is available. In the design of energy systems, first-stage variables commonly correspond to design variables that determine which components should be installed at which capacity. The second stage defines the operation of the installed components. The concept of two stages has been introduced into robust optimization as *adjustable robustness* (also called *adaptive robustness*) [24]. The original concept was further extended by Thiele et al. [25]. Bertsimas et al. [26] propose a two-stage unit-commitment problem taking into account the failure of components. They consider unit commitment as first stage and dispatch as second stage. Adaptive robustness can be combined with a conservatism scaling factor to achieve less conservative solutions [3]. Applying adaptive robustness leads to complex problems which are hard to solve. Thus, special solving strategies are necessary, such as Bender's decomposition [27] and outer approximation [28]. Two-stage problem formulations are used frequently in stochastic optimization [11]. Recent advances in two-stage programming are reviewed by Grossmann et al. [29]. Applications to building energy systems [30] and to utility system optimization [5] showed that uncertainties have to be considered already at the design stage. In order to analyze the trade-off between the system economy and system failure, risk preferences of decision makers are introduced in stochastic approaches [31].

Most robust design approaches thus aim to be less conservative than strictly robust optimization, in order to obtain less expensive solutions. In return, however, they cannot guarantee security of energy supply. In this work, we propose the ***T****wo-stage* ***R****ob****u****stne****s****s* ***T****rade-off (TRusT)* approach which identifies robust design options ensuring security of energy supply. Cost-efficient design options can be chosen by analyzing the trade-off between nominal costs and robust costs. Thus, the proposed TRusT approach allows the designer to find solutions which are both, robust *and* cost-efficient.

Our approach builds upon the classical concept of strictly robust optimization stated by Soyster et al. [14]. Robust optimization can be efficiently applied to DESS design using MILP optimization. We extend the concept of strict robustness and introduce the TRusT approach. The TRusT approach recognizes the two-stage nature of DESS design: A two-stage bi-objective optimization is employed studying the nominal cost and the strictly robust costs simultaneously. Both objective functions employ *identical* first-stage variables representing design decisions. The second-stage variables, however, are adapted *separately* for the nominal and the robust objective function. Thus, the design decisions ensure that the system is feasible for every scenario. Operation can thus be adapted to each specific case, e. g., the nominal or worst-case scenario.

A related *bi-criteria approach to robust optimization* has recently been introduced by Chassein and Goerigk [32] for *single*-stage problems with uncertainties in the objective function. In their approach, the nominal and the robust objective function are minimized. Schöbel [33] generalizes the concept of *light robustness* [34] which selects solutions with the highest robustness among all solutions within a certain range of the nominal optimal objective function value. They show that the trade-off between robustness and nominal quality yields promising solutions. For stochastic programming, a similar concept has recently been proposed [35]: A stochastic analysis is performed for the expected and worst-case costs of residential cogeneration systems.

We apply the TRusT approach to a DESS design problem formulated deterministically in our earlier work [6]. The DESS design problem considers decisions on structure, unit sizing, and operation in a deterministic *mixed-integer linear program* (MILP). In this work, we assume uncertainties in energy prices and energy demands.

The resulting TRusT problem is formulated as bi-objective MILP. Thus, the problem is efficiently solvable without implementing special solution algorithms and the approach can easily be applied to DESS design problems. Thereby, the TRusT approach increases the acceptance for practical applications. Furthermore, we show

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