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Cogeneration planning under uncertainty. Part II: Decision theory-based assessment of planning alternatives

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ABSTRACT

This paper discusses specific models and analyses to select the best cogeneration planning solution in the presence of uncertainties on a long-term time scale, completing the approach formulated in the companion paper (Part I). The most convenient solutions are identified among a pre-defined set of planning alternatives according to decision theory-based criteria, upon definition of weighted scenarios and by using the exceeding probabilities of suitable economic indicators as decision variables. Application of the criteria to a real energy system with various technological alternatives operated under different control strategies is illustrated and discussed. The results obtained show that using the Net Present Cost indicator it is always possible to apply the decision theory concepts to select the best planning alternative. Other economic indicators like Discounted Payback Period and Internal Rate of Return exhibit possible application limits for cogeneration planning within the decision theory framework.

1. Introduction

This paper completes the formulation of the general framework introduced in the companion paper [1] by dealing with the details of taking into account large-scale uncertainties in the long-term time frame. In the multi-year time horizon for cogeneration planning, it is difficult to envision the expected trends of evolution of energy loads and, even more, of electricity and gas prices. Hence, proper alternative techniques of assessment of the foreseeable solutions have to be identified and applied. Literature studies have been based on sensitivity analyses of specific indicators (typically economic variables [2]) with respect to electricity and gas price variations. For instance, the simple payback period and the Internal Rate of Return have been used as indicators in [3] to carry out sensitivity analyses with respect to the variation of electricity price, fuel price and investment cost, for a Combined Heat and Power (CHP) application. Similarly, a deterministic approach has been used in [4] to find the most convenient technological alternative among a set of pre-defined candidate alternatives through minimization of the annualized total costs. Then, a sensitivity analysis has been performed to address the effects of upgraded performance of the equipment, reduction in the initial capital costs, and reduction in the electricity and gas prices. Sensitivity analyses have also been performed in [5] to test the robustness of the optimal solutions found for cogeneration systems coupled to cooling generation devices in the presence of large variations of energy market prices.

In general terms, sensitivity analyses are useful to get indications on the effects of pre-defined scenarios of variation of relevant variables. However, they give no information on how to combine the results obtained from different individual scenarios, and on the effects of actual occurrence of a scenario after the plant is installed. In order to get additional insights in this direction, different levels of involvement of the decision-maker can be considered [6]. In particular, the decision-maker can actively participate in the decision process, for instance choosing the scenarios to be analyzed and assigning to each of them a relative weight on the basis of specific expertise or personal preferences. In this way, the characteristics of alternative planning solutions available to the decision-maker can be explained by looking at the results obtained in each combined scenario considered. Approaches moving in this direction have been proposed for distributed generation siting and sizing in [7,8]. The nature of the results to be obtained (e.g., deterministic or probabilistic) is a further element driving the choice of the type of analysis. For instance, when taking into account uncertainty, the results can be conveniently expressed in probabilistic terms, providing the probability distributions of the planning outcomes. In this respect, it is possible to exploit the framework proposed in [1]. Instead of evaluating only best or worst cases, the hazard to which the decision-maker is exposed because of uncertainty is represented by the probability of occurrence of the outcomes. The relevant aspect is the evaluation of the probability of

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List of symbols

a	(index) technological alternative
b	generic real number
c	Net Present Cost instance (€)
e	(subscript) electrical
f	objective function
j	(index) Monte Carlo extraction
$n\%$	percentage of exceeding probability
p	probability
r	generic random number (instance of the RV $\mathbf{r}$)
t	(subscript) thermal
x	(index) scenario
y	(index) *long-term* time frame (year)
A	number of technological alternatives
C	cost (€)
C_{AB}	investment cost of the Auxiliary Boiler (€)
C_{CHP}	investment cost of the CHP system (€)
$F_{\mathbf{r}}$	Cumulative Distribution Function of the RV $\mathbf{r}$
J	number of Monte Carlo extractions
R	regret felt by the decision-maker (€)
X	number of scenarios
Y	number of *long-term* time frames (years)
α	weighting factor for the optimist–“pessimist” criterion
$\gamma^{(y)}$	fuel price at year y (€/kWh)
δ	discount rate
$\kappa_{\mathbf{r}}$	annual rate of increase for the RV $\mathbf{r}$
$\mu_{\mathbf{r}}$	expected value of the RV $\mathbf{r}$
ν	dummy variable
ϑ	Discounted Payback Period instance (years)
ς	(subscript) price
υ	availability coefficient of the CHP unit
ξ	control strategy of the CHP unit
ω	planning alternative
Φ	cash flow (€)
Ξ	number of control strategies
Ω	number of planning alternatives
$\mathbf{r}$	(RV) generic random variable

occurrence of a specific outcome, compared to a threshold level of exceeding probability defined by the decision-maker, as typically done within the domain of application of risk analysis techniques [3,9–12].

In this paper, an approach based on *decision theory* concepts [13] is used to enable the decision-maker to maintain a significant level of interaction in drawing the scenarios to be analyzed and in interpreting the results obtained. Decision theory has been applied to cogeneration planning by the authors in [14] by considering a single objective to be minimized (the expected value of the Net Present Cost). This paper extends the analysis in different directions to model and discuss the large-scale uncertainty issues identified in [1]. The comprehensive mathematical formulation provided is used with different objective functions (to be minimized or maximized) and different decision criteria (minimum expected value, minimax weighted regret, and a mixed optimist–pessimist criterion). The planning outcomes are then expressed with their probability distributions, enabling the decision-maker to choose the level of exceeding probability to be considered.

The proposed framework is applied to select the most convenient CHP solution (type, size and control strategy) among a predefined set of alternatives, considering the multiple scenarios of long-term evolution of energy loads and prices identified by the decision-maker. A business-as-usual case is considered as the reference alternative, with separate production (SP) of electricity from the electricity distribution system (EDS) and heat generated in conventional boilers. The other technological alternatives include different cogeneration technologies such as microturbines (MTs) or internal combustion engines (ICEs), with specified electrical and thermal rated power. Each technological alternative is operated under one of the control strategies (or operating modes [15]) described in the companion paper [1], namely, on–off operation, electrical load-following and thermal load-following.

This paper is organized as follows. Section 2 illustrates the formulation of the optimization problems in the long-term time frame. Section 3 describes the decision criteria adopted to cope with large-scale uncertainty. Section 4 shows and discusses the results obtained in the application case defined in [1] with specific technological alternatives, control strategies, economic indicators, and decision theory criteria. Section 5 summarizes the concluding remarks referred to the application of the decision theory concepts within the comprehensive multiple time frame approach.

2. Formulation of the optimization problem in the long-term time frame

The input information to formulate the optimization problem is based on the random variables (RVs) obtained through the approach illustrated in [1] for short- and medium-term time frames. These RVs represent typical economic indicators adopted for the analysis of investments in the cogeneration sector, such as the Net Present Cost (*NPC*), the Net Present Value (*NPV*), the Discounted Payback Period (*DPP*), and the Internal Rate of Return (*IRR*) [2,16]. This section illustrates how the various economic indicators can be adopted in the formulation of optimization problems in the decision theory-based planning framework to deal with the long-term time frame issues. Specific limitations in the use of the *DPP* and *IRR* indicators within this framework are further discussed in Section 4.5.

A *planning alternative* $\omega = 1, \ldots, \Omega$ is defined as the pair (a, ξ) given by the technological alternative a with the associated CHP control strategy ξ, in addition to separate production from the EDS and from the auxiliary boiler (AB).

Considering an economic indicator (RV $\mathbf{r}$ with $n\%$ exceeding probability) to be minimized (as for *NPC* and *DPP*), the optimization problem is formulated as

$$\breve{\omega}_{\mathbf{r},n\%} = \arg\min_{\omega=1,\ldots,\Omega}\{f(a,\xi,\mathbf{r},n)\} \tag{1}$$

If the economic indicator has to be maximized (as for *NPV* or *IRR*), the minimization indicated in (1) has to be changed into maximization.

The constraints associated to the optimization problems refer to the equipment limits in the various control strategies, as shown in Section 3.4.3 of [1].

In the optimization problem formulation, the equipment investment costs, namely, C_{AB} for purchasing the AB and $C_{CHP}^{(a)}$ for purchasing the CHP system for the ath technological alternative, are considered as deterministic entries and are referred to the beginning of the period of analysis.[1]

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[1] This direct type of investment is one of the possible investment strategies, selected here for comparing the planning alternatives. More refined strategies of investment such as sequential ones, in which multiple equipment is purchased at different times, can be developed, also depending on price volatilities [18]. The analysis of these strategies is outside the scope of this paper.