# A Model Predictive Control Approach for Long Term Planning of Capacity Investments in a District Heating System

Jose L. Mojica and John D. Hedengren
Brigham Young University

There is uncertainty in the power generation sector on the type, timing and stringency of potential air emission regulations. Coupled with uncertainties on fuel prices, future costs, and energy demand, stakeholders often delay large investment decisions in favor of incremental changes to meet regulations [1], [2]. Commercial and industrial end-users of energy also face similar challenges to fulfill growing energy needs and simultaneously comply with environmental regulations and constrained budgets. The contribution of this study is to investigate a dynamic optimization approach with a model predictive control (MPC) framework that gives an optimal long-term planning horizon outlook with uncertainty descriptions, intrinsic non-linear constraints, and system dynamics for capacity expansion of energy systems.

Models that account for uncertainty are known as stochastic models as opposed to deterministic models [3]. A notable amount of work has used multistage stochastic programming problems (MSSP) to address power generation capacity expansion and investment planning under uncertainty [2], [4], [5]. MSSP more specifically deals with problems that involve a sequence of decisions reacting to outcomes that evolve over time. With stochastic programming methods, the distribution of the parameters is assumed to be known instead of the actual uncertain parameters. This assumption causes the model size to grow rapidly thus limiting the potential use in real world applications [6]. Because of this curse of dimensionality, researchers simplify the models by reducing the number of stages and probability distributions to distribution trees that represent discrete scenarios that satisfy statistical properties [7]. The reduction of model complexity as well as the simplification of the stochastic properties to discrete scenarios in stochastic programming approaches motivates the need to explore other methods that can simultaneously take into account the short term dynamics of the system as well as the long term planning time horizon along with the uncertain inputs.

In this study, the capacity expansion of a district heating network is studied with the goal of evaluating the investment decision timing and type of capacity expansion. The study intents to find the optimal investment schedule over a 30 year horizon with the options of investing in traditional heating sources (boilers) or a next generation combined heat and power (CHP) plant that can provide heat and electricity to the user. In district energy systems, the investment decision on the capacity and type of system is dependent on demand side requirements, energy prices, and environmental regulations. The latter two are influenced by economic and political uncertainty, giving uncertainty to the investment planning problem.

The main contribution of this project is formulating the capacity planning over a time horizon as an optimal control problem. In this way, an initial system configuration can be modified by a “controller” that optimally applies control actions that drive the system from an initial state to an optimal state. Model predictive control (MPC) has the feature of making a plan of decisions over a future time horizon only to implement the present point.  As summarized by Qin and Badgwell, MPC has the objectives of preventing violations of input and output constraints, drive some output variables to their optimal set points while maintaining other outputs within specified ranges, and prevent excessive movement of the input variables [8]. Each of those features represents key objectives that decision makers would like to achieve for energy capacity expansion planning. Some of these key objectives include preventing violations of economic and environmental constraints, meeting the required energy demands while the planned capacity operates in an optimal manner, and limiting additional capital expansion projects. The robust solution considers the constraints and proposes a long-term investment strategy that accounts for irreversible decisions and high costs for system upgrades.

The prediction horizon of an MPC formulation is an optimized set of decisions that state the sequence of optimal decisions over the period of time being evaluated. The forecast information on important system variables provides a quantification of uncertainty and delivers a family of solutions that reflect a range of outcomes. The time horizon is also specified as part of the problem, thus the level of fidelity of the solution can be modified to achieve the level of temporal resolution that practically reflects the discrete time events where investment decisions can be made. By including time steps in the order of minutes and longer time-steps over the lifetime of the plant, an MPC approach has the capability of formulating a multi-scale problem that can reveal not only the long term planning horizon but also optimal operation in a smaller time scale. In a planning and scheduling problem where the objective is to reduce costs or maximize profit, the short time scale optimal solutions can reveal unforeseen savings or profits hidden within the dynamics of the system.

Results of this study confirm the value of the short time scale dynamics on the optimal capacity expansion for the long term horizon plan. When a CHP system is considered for capacity expansion or replacement, one of the most important drivers on the feasibility and size of such system is natural gas price. Because of the uncertainty in future prices, stakeholders fear that the investment may very soon be unprofitable or not cost effective as natural gas prices increase. Using a dynamic MPC approach reveals that such investments can still be made early on, and that the driver for continual profitability or cost savings can be drawn from the mode of operation of such system in the shorter time scale. The change in mode of operation comes in the form of winter/summer configurations, and “peak shaving” or “base load” following of the electric or heating demand. With short time scale dynamics, the optimizer finds the optimal capacity that is the most flexible in providing the energy demands but also at minimum cost. In this study, the optimization approaches that do not account for short time scale dynamics are compared with the dynamic MPC approach. The optimal capacity with no dynamics is consistently higher (wasted capacity with a worse economic objective function) and does not provide information on how the new capacity would most profitably perform with changing and uncertain input variables.

To solve this capacity investment planning problem containing over 42,000 variables and 37, 000 equations, APMonitor modeling platform was employed. The model is posed as a set of differential and algebraic equations (DAEs) and is solved with simultaneous methods. This approach for discretization of the differential equations allows a DAE model to be posed in open equation format and allows DAE models of index-1 or higher to be solved without rearrangement. The DAE system is converted to an algebraic equation representation through direct transcription or better known as orthogonal collocation on finite elements [9], thus facilitating the conversion of the problem to a Nonlinear Programming (NLP) problem and permitting the solution by large-scale solvers. The use of this technology allows for the efficient handling of large models with thousands of variables. This is necessary in solving MPC formulated problems in which points in the time horizon are solved simultaneously allowing for less compromise on the size and fidelity of the dynamic problem.

A model predictive control approach was applied to a capacity investment planning problem for a district heating system in which uncertainty was included with natural gas price forecasts on a 30 year horizon. Along with demand forecasts and system dynamics, the MPC formulation provided a solution that not only provides the timing and size of the capacity investment, but also on the mode of operation that would meet optimal economic objectives with the given capacity. Future extensions of this work may include multi-objective scenarios and discrete formulation of key variables.

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