Int. J. of Thermal & Environmental Engineering
Volume 11, No. 1 (2016) 1-4

Structural Optimization of Solar Driven Energy and Desalination Systems

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Abstract

Planning and dimensioning of desalination plants is usually done by engineers based on an estimation of the capacity of makeup water that is needed for a certain site. Planning a solar- powered system of water and energy supply is complicated and requires a lot of experience from the executing engineer. Optimization methods can support the process of planning complex energy and water supply systems in many ways. Structural optimization is a way to determine an optimized size and configuration for a given task.

In this paper a methodology is presented that allows for structural optimization of energy and water supply systems with a focus on a high share of solar energy use. The methodology has been implemented using a software framework that contains functionality for modelling, simulating, optimizing and analyzing energy and water supply systems. Based on load profiles for energy and water as well as technical and economical parameters of the components, a linear optimization is carried out in order to calculate an optimized structure of the system. Furthermore the optimization calculates the capacities of the desalination and energy conversion components and an optimized mode of operation depending on the primary energy prices and solar yield.

The methodology uses a MILP algorithm to solve the optimization problem based on linear component models. The linear optimization is coupled with an algebraic equation solver to allow solving of nonlinear equations as well, thus forming a hybrid simulation and optimization algorithm.

Introduction

The focus of this work is on the optimization of technical infrastructures that are capable of decentralized supply for fresh water, heat, cooling and electricity to a certain consumer. Typical fields of application would be large buildings with an access to waste or salt water in arid areas of the world (e.g. hotels, hospitals and office buildings). As in arid areas the yield of solar energy is typically very high, it makes sense to include devices that harvest this solar irradiation to produce electricity or heat. To model the supply of fresh water, cooling, heating and electricity different technologies have been modelled mathematically, to be used in the optimization later. The structural optimization is based on a superstructure that contains all possible technologies that may be used at the site. The optimization algorithm selects a reasonable configuration out of the superstructure that satisfies the loads in the most cost efficient way. The optimization minimizes overall annualized Costs. This means, it takes investment costs and operation costs into account. It is also capable of optimizing according to CO2-emissions or primary energy. The number of available technologies is constantly expanded. At the moment there are desalination units like reverse osmosis, multi-effect distillation and mechanical vapour compression. To represent heating supply conventional hot water boilers and cogeneration plants have been modelled. Furthermore it is possible to use concentrated solar power and flat plate collectors. To satisfy cooling loads compression and absorption chillers have been included. For the generation of electricity photovoltaic have been added. To enable a self- sustaining operation of the energy and water supply system, storages have been included for heat, cool, water and electricity. The methodology can be used to get an idea of a good structure and dimensioning of the different technical components. It does not replace the detailed planning process whatsoever.

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DOI: 10.5383/ijtee.11.01.001

Structural Optimization Using Mixed Integer Linear Programming

The structural optimization is based on a super structure that contains all possible combinations of technologies that should be considered by the optimization algorithm. Figure 1 shows a screenshot of a superstructure for such a system. The superstructure is modelled using a flow sheet editor. Components can be added or removed to describe the number of options for the optimization. In Figure 1 are demands for electricity, heat and water on the right side and supplies for electricity, heat and gas on the left side. In the middle are optional components to realize the energy conversion. These are in this case a CHP plant, a boiler, a multi-effect distillation and a reverse osmosis.

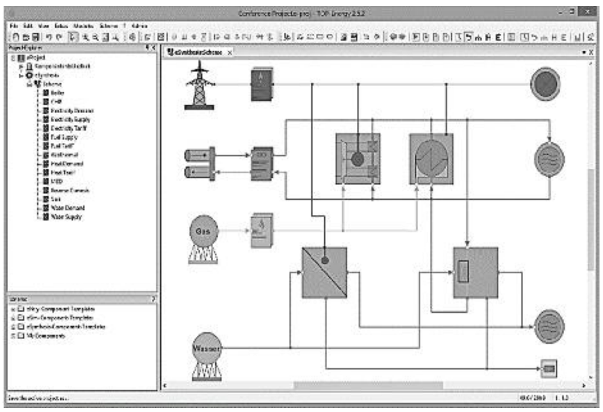

Figure 1: Superstructure of a Coupled Heating, Cooling, Electricity and Water Supply System

Every component in the scheme contains a set of linear equations. The lines between the components represent material of energy flows and are converted into linear equations as well. That way a MILP system of equations is described by the superstructure and the models of the components in it. This MILP system has the general form as follows:

$$\begin{aligned} \min_{x,y} z &= f(x,y) \\ s.t.\ \ h(x,y) &= 0 \\ g(x,y) &\leq 0 \\ x \in \mathbb{R}^n&, y \in \{0,1\}^m \end{aligned}$$

The net present value of the optimized energy system is a well suited criterion for an optimization that takes the operation costs as well as the investment costs into account [1]. Therefore, the function to be minimized is the negative net present value. That means the net present value is maximized. The operation costs are weighted using the present value factor as shown in the equation below.

$$NPV = \frac{(i+1)^T - 1}{i(i+1)^T} R_t - \sum_n I_n$$

The net present value is calculated from the interest rate (i), the number of periods (T), the net cash flow per period (R_t) and the investment costs of all technical devices that are newly installed ($\sum_n I_n$). This function has to be maximized by an optimized structure, size and operation of the devices. This means, the primary energy costs and the investment costs have to be calculated based on the size of the devices and the mode of operation.

$$\max_{\dot{V}_{nt}, \dot{V}_{N,n}} NPV = \frac{(i+1)^T - 1}{i(i+1)^T} \sum_n \sum_t c_{PE_n} \dot{PE}_{nt}(\dot{V}_{nt}, \dot{V}_{N,n}) \Delta t - \sum_n I_n(\dot{V}_{N,n})$$

The net present value is calculated using a linear function ($\dot{PE}_{nt}$) that depends on the required energy and fresh water loads ($\dot{V}_{nt}$) as well as the nominal installed capacity ($\dot{V}_{N,n}$) which is optimized as well.

The component models of the devices in Figure 1 contain linearized functions for the investment costs. Furthermore, transfer functions $\dot{PE}_{nt}$ between primary energy and required energy/water are included for all the devices in the superstructure. Some of them will be shown in more detail in the next chapter.

Modeling of the Desalination and Energy System

To implement linear models of desalination systems a linear or linearized relation between the driving energy (heat or electricity) and the amount of makeup water is used. The characteristic of this relation usually depends on the concentration of salt in the makeup water and the salt water. As the solver is used to optimize the structure of the energy system and the capacities of the devices as well, investment costs have to be included for all technical devices that are contained in the superstructure.

Reverse Osmosis

Reverse osmosis is a water desalination technology that uses a semipermeable membrane to remove solved molecules (salt and metal ions) and bacteria from natural water sources. A pressure higher than the osmotic pressure is applied so that the water flows in the reverse direction to its natural osmotic flow direction. The required energy is proportional to the amount of dissolved molecules in the water. The amount of electrical energy needed per cubic meter of fresh water can be calculated from the osmotic pressure at 0% recovery [5]:

$$W_0 = -\frac{RT}{\dot{V}_W} \ln a_W$$

Where W_0 is the osmotic pressure, $\dot{V}_W$ is the molar volume flow rate and a_W the feed water activity with dissolved NaCl. The activity can be calculated from the molality (m) as $a_W = -0.0338m + 1.0004$ according to [[1]]. The molality is a parameter that is calculated from the salt concentration in the water assuming that it consists only of water.

According to [[5]] the actual energy demand of RO plants is usually three to four times higher than the minimum theoretical calculated energy, due to the extensive pre-treatment of the feed water and the concentrate.

Multi-Effect Distillation

Multi-effect distillation is a vacuum distillation process that consists of multiple stages arranged consecutively at a decreasing pressures and temperatures. In the first stage, external steam is used to initiate the desalination process. The

feed water is sprayed onto the surface of the heat exchanger surface causing it to be flashed due to the heat released by the condensing steam in the heat exchanger tube. The number of stages or "effects" has a reasonable influence on the investment costs and the energy efficiency of the process. The more effects a device has, the lower is the specific energy consumption.
The specific energy consumption is depends on certain parameters that are not variable in the optimization. These parameters are the number of effects, the top brine temperature of the first effect, the temperature difference between the effects, the temperature at condenser exit as well as feed and brine salinity.

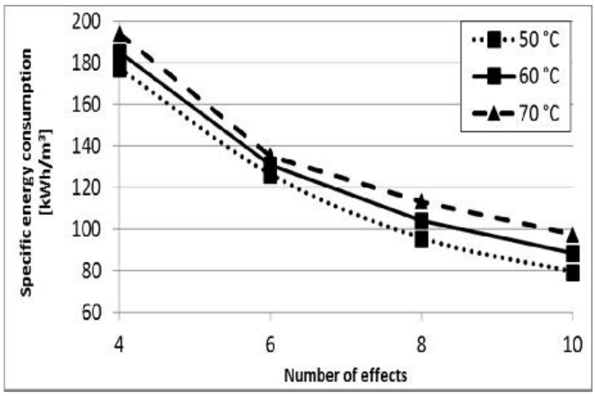

Figure 1: Specific Energy Consumption for Multi-Effect Distillation

The figure above shows the dependency between the specific energy consumption of the MED and number of effects at different top brine temperatures. The specific energy consumption decreases as the number of effect increases. The specific energy consumption increases with increasing top brine temperatures.

Mechanical Vapour Compression

Mechanical vapour compression is a vacuum distillation technology in which a compressor is used to increase the pressure and temperature of the evaporated steam. The superheated vapour generated is used to heat the fresh sea water in the evaporator.
The desalination process consumes electrical energy for pumping and for the compressor. According to [[1]], the specific energy consumption of the compressor can be calculated from the specific enthalpy of the superheated compressed vapour (H_S) and the specific enthalpy of the inlet vapour (H_V).

$$W_c = H_S - H_V$$

The energy needed for the compressor is divided by the motor efficiency ($\eta_{M,C}$). The energy consumption of the pump is assumed to be 25% of the compressor energy. This is divided by the pump efficiency ($\eta_{M,P}$). The specific overall energy consumption is then calculated as follows:

$$W_{MVC} = \frac{W_c}{\eta_{M,C}} + \frac{0.25 * W_c}{\eta_{M,P}}$$

Example

The methodology will be used to calculate an optimized energy system for a hotel in Germany. The hotel consumes electrical energy, heat, water and cooling. The load profiles were roughly estimated based on different published load profiles and experience with other residential objects. Overall yearly consumption and peak load consumption of the different energy forms and water are shown in Table 1.

Table 1: Energy and Water Demands of the Hotel

	Electricity	Heat	Cooling	Water
Consumption	5055 MWh/a	3303 MWh/a	1916 MWh/a	41975 m^3/a
Peak Load	763.8 kW	905 kW	841 kW	18.45 m^3/h

To be able to solve the optimization in a reasonable time, the number of time steps was reduced to 36 by using standard load profiles for winter, summer and transition days in a time resolution of 2 hours.

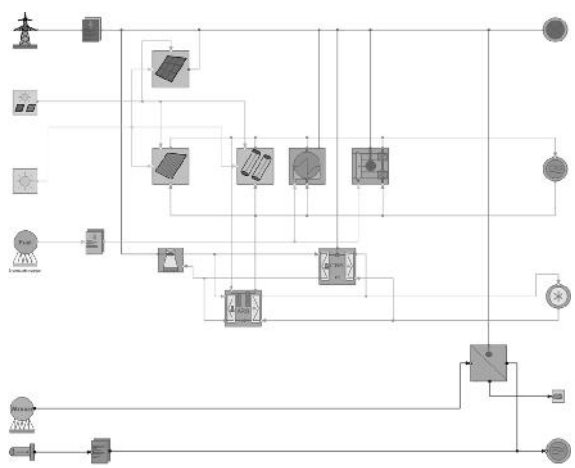

Figure 3: Superstructure for the Optimization of a Supply System of a Hotel

The aim of the structural optimization is to investigate the use of solar irradiation for the electricity generation and the use of desalination technologies to produce water. The superstructure that was used to optimize is shown in Figure 3. It contains a connection to the electricity grid, the gas grid and the water grid (left hand side). The demands for electricity, heat, cooling and water are shown on the right hand side. The hotel has an available area of 200 square metres on the roof for the installation of PV, flat plate collectors or concentrated solar power (upper left side). To supply the heat demand an additional boiler and a cogeneration heating plant are included in the superstructure (upper middle). To supply the cooling load, a compression chiller and an absorption chiller are included in the structure in the lower middle. The makeup water supply can be satisfied using the water grid in the lower left or the reverse osmosis plant on the lower right side of the scheme.
The optimization method chooses a configuration of devices and the corresponding size of each device in a way that maximizes the net present value. For the NPV calculation 10 periods are considered and the interest rate is set to 4%. The price for electricity is set to 21 ct/kWh and the feed in tariff is 6 ct/kWh. Natural gas costs 12 ct/kWh and the price for water from the grid is 5.5 ct/m^3.

Results

The optimization takes about 10 seconds on a common desktop PC using a state of the art MILP solver. The results for the sizes and energy production of the different devices are shown in the table below.

	Photo-voltaic	*Boiler*	*Cogeneration heating plant*	*Compression Chiller*	*Reverse Osmosis*
Capacity	$65 kW_p$	$227\ kW_{th}$	$642\ kW_{el}$	$841\ kW_c$	$147\ m^3/day$
Energy/ Vol.	$95\ MWh_{el}/a$	$465\ MWh_{th}/a$	$2690\ MWh_{el}/a$	$1915\ MWh_c/a$	$31696\ m^3/a$

An installation of the other devices in the superstructure is economically not feasible. This means, solar thermal use of irradiation as well as absorption chillers are not chosen by the optimizer.

Conclusion

Using the describe methodology, a structural optimization of solar-driven coupled energy and water supply system can be carried out. The software framework TOP-Energy has been used to make it accessible to practitioners. This way the users can perform optimizations without in-depth knowledge of the mathematical representation. The TOP-Energy Software is delivered with component models for many different technologies. Using these models in optimization superstructures, many different structures can be investigated efficiently.

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