VC CHILLERS AND PV PANELS: A GENERIC PLANNING TOOL PROVIDING THE OPTIMAL DIMENSIONS TO MINIMIZE COSTS OR EMISSIONS

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ABSTRACT
We developed a design optimization tool for a primary HVAC plant consisting of vacuum compression chillers and PV panels. If provided with weather data, hourly cooling demand, and PV area limitations, it yields the optimal PV panel dimensions and the number of chillers, as well as their nominal capacities. Additionally, it provides the costs and the emissions resulting from utilizing such plant to supply the thermal distribution network of the building. The tool is based on a quasi-static system simulation, which calculates objective function values to be evaluated by the optimization algorithm. It targets preliminary building design and planning.

INTRODUCTION
Over the years the cooling demand is gaining more significance in Europe. Namely, the requirement to actively cool the building space during the summer is expanding in northern direction. Since the demand largely coincides with the solar radiation profile, the simplest approach to reduce the energy consumption for space cooling, while still utilizing the conventional vacuum compression chillers, is to cover part of the chiller power demand using on-site generated photovoltaic (PV) power.

A tool for quantifying the performance of the introduced plant configuration aiming at planning processes has been developed (Grahovac 2012). It is a design optimization tool for a plant consisting of vacuum compression chillers and PV panels, which enables providing the following information. Firstly, it yields the optimal:

- PV panel dimensions and
- The number of chillers to be utilized, as well as their nominal capacities.

The PV panels can be placed on each of the following: building façade, its roof and an optimally tilted area, regarding the user provided limitations. Secondly, it provides

- Primary and final energy savings; and
- Costs and emissions resulting from utilizing such plant to condition the building.

The latter is helping the planner to become aware of the benefits of utilizing the provided optimal configuration.

An optimization procedure based on the hourly plant simulation has been developed, which is able to account for the intermittent PV power generation. Moreover, the chiller plant is coupled with the PV power profile and wet cooling towers, the performance of which also depends on the current ambient conditions. It being an unknown to the planner, the suitable number of chillers is defined automatically based on the provided load. A competent chiller load allocation strategy, which adapts to any number of chillers, has been developed. The power generated by PV, which coincides with the demand, is consumed by the chillers themselves, while its lack or excess is bought from or sold to the grid. Chiller, cooling tower, and PV component models are configured to enable performing the simulation upon providing the following data: the ideal building demand profile, the weather data set, and dedicated PV areas on stated building surfaces. The simulation is executed in each iteration step of the optimization procedure in order to tests the combination of component sizes prescribed by the optimization algorithm. Two algorithms are offered as solvers, the Global Bounded Nelder Mead (GBNM) and the modified exhaustive search.

To demonstrate one way to utilize the tool, an example calculation for a simulated building located in Munich has been performed. The optimization aimed at minimizing the annual cost of electrical energy purchased to power the cooling system. The results demonstrate the interplay between the dynamic cooling demand and PV generation profiles.

The tool may find its application during preliminary building design. Namely, the further the design process progresses, the more limited is the choice of the position and the surface area of building mounted or integrated PV panels. Additionally, the tool can be applied to groups of buildings with a central chiller plant and distributed PV panels. Finally, it could highlight the potential benefits of applying this system configuration in larger areas, such as cities or even for an assessment at a regional or national level.

MATHEMATICAL MODEL
The general structure of the optimization and simulation processes is shown in Figure 1. Since the
targeted users are not required to know how to configure and dimension the system and its controls, the system simulation model is preconfigured within the tool using preset performance data. The optimizer passes the set of component dimensions (optimization parameters) to the simulator. The simulator evaluates the system model performance based on the given weather and building load data. Upon that, it determines the relevant system performance profiles in order to calculate costs and emissions, and defines the objective function. It returns the objective function value to the optimizer, which either defines a new set of component dimensions to be evaluated by the simulator in case the minimum has not been reached, or returns the optimal result. Among other performance related information, the result data contain:

- Optimal component sizes;
- Total, investment and running cost of such a system;
- energy savings;
- Carbon emissions; and
- Information on satisfying the demand.

The tool is developed in MATLAB (MathWorks, 2012).

External Input Data

Obligatory user input comprises of an ideal building cooling load and a weather data profile, as well as the area available for placing the PV panels.

The weather data consist of the solar radiation and ambient dry and wet bulb temperature profiles. The ideal building load profile can be created using building simulation software. If not enough building information is available, synthetic load profiles can be used. Any of the profiles can be scaled accordingly to represent a demand of a group of buildings or a settlement.

Component Models

Simplified empirical models for vacuum compression chillers, cooling tower and photovoltaic panels, directly adopted from the literature or slightly modified, are implemented. Short description of each of the models and their references are provided in following sections.

Vacuum Compression Chiller

Detailed models including physical descriptions related to all four thermodynamical processes of the refrigeration cycle do exist, but for the purpose of modeling space conditioning water chillers more simple approaches have shown good results. Various empirical and semi-empirical models based on measurements on the water side have been developed. They have been evaluated by Lee et Lu (2010). A similar data fitting approach is seen in TRNSYS and TESS models. EnergyPlus implements the DOE-2 (Hirsch et al., 1998) chiller model described in EnergyPlus Documentation (2011) and Hydeman et Gillespie (2002), as well as a slightly modified version of that same model, which is described in Hydeman et al. (2002). The latter two papers demonstrate both the validity of this regression model and its applicability to many commercially available chillers.

Here the DOE-2 chiller model described by Hydeman et Gillespie (2002), is adopted and implemented. It is an empirical model that determines the chiller power consumption based on condenser water inlet \(T_{\text{cool,in}}\) and evaporator chilled water return \(T_{\text{chil,out}}\) temperature. Three performance curves model the chiller performance. Implemented values of performance coefficients, minimal PLR (part load ratio) and reference condition performance are values for generic centrifugal and reciprocating chillers from EnergyPlus (2012). In case the chiller type is already known, the coefficients for many chiller types are readily available in the last stated source.

Cooling Tower

Since the cooling tower power consumption is small compared to the chiller consumption, the following simple model which approximates the electricity and water consumption of a cooling tower is implemented. The cooling tower design capacity, \(P_{\text{el,ct,d}}\), is proportional to the maximal chiller heat of rejection, \(HR\):

\[
P_{\text{el,ct,d}} = k_{\text{el,ct}} \cdot \text{mad}(HR)
\]

\(k_{\text{el,ct}}\) is thus the cooling tower sizing coefficient. The equation is adopted from EnergyPlus Engineering Reference (2011).

To determine the part load performance of the cooling tower, a linear approximation for single stage
fans found in Hydeman et al. (2001) is assumed, as well as the fan shut off for PLRs under 15%. As a result, the power consumption, $P_{el,ct}$, in each timestep can be written as:

$$P_{el,ct} = \begin{cases} 0, & HR < PLR_{min,ct} \cdot \max(HR) \\ k_{el,ct} \cdot HR, & HR \geq PLR_{min,ct} \cdot \max(HR) \end{cases}$$  \tag{2}$$

where $PLR_{min,ct}$ is the cooling tower fan shut off limit. The tower water flow rate is modeled as a linear function of the heat of rejection using the rule of a thumb from EnergyPlus Engineering Reference (2011). The water consumption is approximated as:

$$WC = P_{el,wloss} \cdot k_{wc} \cdot HR$$  \tag{3}$$

with $P_{el,wloss}$ being the cooling tower blowdown percentage (data a) and $k_{wc}$ the ratio between the cooling tower water flow rate and its load. The blowdown percentage of 0.1% has been adopted from Sydney Water (2008).

**Photovoltaic Panels**

Many models of PV performance have been identified in the literature, starting from very detailed theoretical models found on physical behaviour of a solar cell, to semi-empirical ones focusing on overall thermal and electrical performance of a PV module, to very coarse empirical models for annual solar energy production assessment. PVsyst (Mermoud et Villoz, 2012) is a software tool offering help in preliminary or project design of PV components. PVGIS (PVGIS, 2012) is a web-based PV performance estimator.

From the architect’s point of view, the areas covered with PVs and their positions on the building are the relevant design parameters. Hence, the area and its orientation are required as an input to the model and an hourly power generation profile is the result. With this in mind, DIN EN 15316 4-6 (2009) and both above mentioned tools have been used to propose a modified empirical model suitable for preliminary design. To verify its performance, the model has been compared with the TRNSYS photovoltaic model Type 562h (TRNSYS Documentation, 2009) for four different locations. The differences in annual cumulative energy production lied below 0.5%. The physical characteristics of the PV module accounted for within the model are:

- Reference efficiency and its change with the collector temperature;
- System efficiency (e.g. cable and inverter losses); and
- The building integration (the quality of module ventilation).

DIN EN 15316 4-6 (2009) suggests following equation to calculate annual PV generated electrical energy, $E_{el,pv,out}$:

$$E_{el,pv,out} = \frac{E_{sol} \cdot P_{pk,perf}}{I_{ref}}$$  \tag{4}$$

where $E_{sol}$ represents the annual solar radiation energy, $P_{pk}$ is the peak PV power, $f_{perf}$ is a system performance factor accounting for annual system and temperature losses and the art of building integration, while $I_{ref}$ stands for the reference solar radiation on the PV module surface. In order to break this cumulative into hour-to-hour generated energy, the following needs to be considered. The annual solar energy $E_{sol}$ is to be replaced with the relevant hourly solar radiation profile, which is available from the weather data set for the given PV tilt. The PV temperature varies with the change in ambience conditions and thus so does the module efficiency. For that reason the factor $f_{perf}$ is split into the static system factor, $f_{sys}$, and the dynamic temperature factor, $f_{temp}$:

$$f_{perf} = f_{sys} \cdot f_{temp}$$  \tag{5}$$

Carlson et al. (2000) mention that crystalline silicon cells lose 0.4% of measured reference efficiency with each degree increase of the PV temperature in comparison to the reference. This temperature factor, $f_{temp}$, is thus linearly related to the temperature difference between the PV surface, $T_{pv}$, and the ambient:

$$f_{temp} = 1 + \beta_{pv}(T_{pv} - T_{amb})$$  \tag{6}$$

With the increase in module temperature the efficiency is dropping. To account for that, a linear approximation used in (PVGIS, 2012) is implemented:

$$T_{pv} = T_{amb} + k_T I$$  \tag{7}$$

where $k_T$ is the PV ventilation factor and $I$ is the total solar radiation on the PV module surface. Although in most of the PV applications the peak power, $P_{pk}$, is the primary design variable, in this case the area dedicated to PV by the architect dictates the peak power:

$$P_{pk} = \eta_{ref,pv} \cdot A_{pv} \cdot I_{ref}$$  \tag{8}$$

Where $\eta_{ref,pv}$ stands for the PV reference efficiency, $A_{pv}$ is the surface area of the PV panel. If the last four equations are introduced into the equation (4), modified to yield the hourly profile of photovoltaic energy generation, $P_{el,pv}$, the following equation is obtained:

$$P_{el,pv} = \eta_{ref,pv} \cdot f_{sys} \cdot (1 + \beta_{pv}(T_{amb} + k_T I - T_{ref}) \cdot A_{pv} I$$  \tag{9}$$

This equation models the PV panel power generation relying on four parameters, each having a distinct physical meaning:

- The reference efficiency $\eta_{ref,pv}$ – the module efficiency at Standard Test Conditions (STC: $I=1000$ W/m$^2$; $T=25^\circ$C);
- The system factor $f_{sys}$ – primarily accounting for inverter and cable losses;
- The temperature coefficient $\beta_{pv}$ – it accounts for the module performance sensitivity to module temperature; and
The ventilation factor $k_T$ – defines the difference between the module and the ambient temperature.

**System Performance and Control**

Figure 2 illustrates the scheme of the system. An arbitrary number of chillers, coupled with an autosized cooling tower, supply the building with the cooling energy following the provided set load. The optimizator will define the number of chillers. The performance of the plant is influenced by the weather conditions, and so is the power generated by PVs. In case of simultaneous demand and production, the PV power is consumed directly by the chiller plant. Otherwise the power is bought from, or excess PV power is sold to, the grid.

![General scheme of the plant.](image)

The control assumes condenser water and chilled water temperature reset. The outside air wet bulb temperature, $T_{amb,wb}$, from the weather data set, minimal ($T_{coo,in, min}$) and maximal ($T_{coo,in, max}$) cooling water inlet temperature from the chiller performance data, and the “approach” of 3°C ($T_{ap}$, relying on ASHRAE Handbook, 2008) define the condenser cooling water inlet temperature ($T_{coo,in}$). This temperature is thus equal to either the wet bulb (increased for the value of the approach) or the minimal cooling water inlet temperature, whichever is higher. If such a temperature exceeds the maximal cooling water temperature, the warning message is displayed stating that safe chiller operation cannot be granted. Since we do not explicitly model water flows, the assumed cooling water temperature is a linear function of wet bulb temperature between its limits:

$$T_{coo,in} = \min\{\max(\{\alpha T_{amb,wb} + \Delta T_{ap}\}, T_{coo,in, min}), T_{coo,in, max}\} \quad (10)$$

The chilled water return temperature ($T_{chi, return}$) is assumed a linear function of the set load ($L$) between its limits ($T_{chi, out, min}$ and $T_{chi, out, max}$ - defined within the chiller model data set):

$$T_{chi, out} = \frac{(\max(L) - L(t))}{\max(L) - \min(L)}$$

Once the set load and the temperatures are defined, the chiller full load performance can be determined. In each timestep the chiller is able to deliver any load between its minimum PLR multiplied by the full load capacity under current temperature conditions and that full load capacity (assuming the full load PLR equals 1). Hence the load imposing strategy in case of single chiller utilization is:

$$D(t) = \begin{cases} \frac{PLR_{min,CAP_{full}} \cdot L(t)}{P_r} & \text{if } \frac{PLR_{min,CAP_{full}} \cdot L(t)}{P_r} < 1 \\ \text{else} & \end{cases} \quad (12)$$

In order to allow multiple chiller utilization, an optimal chiller load allocation algorithm responsible for an hour-to-hour optimal chiller loading has been developed and implemented. Under assumption that the chiller COP increases with its PLR, the load is allocated to achieve as high as possible PLR of all active chillers throughout the simulation.

![The chiller COP is assumed to rise with the PLR.](image)

**Costs, Emissions and Optimization**

Since the dimensions of the components, as well as the power consumption resulting from the performance simulation are known, costs and emissions can be calculated. An annuity cost calculation method complying with EN 15459 (2008) and VDI 2067 (2010) has been implemented. The optimization goals are the annual cost or the emission (power consumption) minimization, both optionally combinable with a desired target solar ratio. The optimization objective is a simulation based non-linear and non-convex function. Two algorithms, robust enough to identify the global minimum of such an objective, are implemented in the optimizer:

- Global Bounded Nelder-Mead (GBNM), since it only evaluates the value of the function, and not its derivatives; and
- Exhaustive search, since the components are only manufactured in certain sizes. It is modified to exclude the sets of optimization parameters already known not to be able to yield the optimum.

More details on cost calculation and optimization can be found in Grahovac et al. (2011).
DEMONSTRATION EXAMPLE

Goals and Procedure
To evaluate and demonstrate the capabilities of the proposed method, it is implemented to an example building. The goal is to evaluate the interplay between the decentral electric power generation (by building integrated photovoltaic - BIPV) and power consumption by the cooling energy generation system. Since targeting building design and planning, the method firstly performs the design optimization, determining thus the optimal chiller capacities and PV areas. The optimization target is to minimize the annual amount of electrical energy purchased from the grid to power the compressors of electric chillers and cooling tower fans. The resulting optimal components yield the annual electricity bill which is, following, compared to the case where no PV panels are installed. The feed-in strategy is to consume the own generated PV power whenever it occurs simultaneously with the cooling system demand.

Two scenarios are studied. For comparison purposes, both are evaluated with and without PV utilization.

- The first scenario evaluates a cumulative power consumption profile of: chillers and cooling towers.
- The second scenario power consumption profile additionally includes the thermal distribution network power consumption. The fact is that the thermal distribution has not been explicitly modeled. However, it undoubtedly consumes a significant amount of energy to power the supply and return fans and chilled water pumps. Thus a simple approximation of the auxiliary power consumption as 50% of a chiller compressor power consumption profile has been implemented. The selected factor relies on data presented in Brodrick et Westphalen, (2001). Consequently, the overall power consumption of the second scenario is expressed as:

$$P_{el,ch,el,aux}(t) = P_{el,ch}(t) \cdot 1.5 + P_{el,ct}(t) \quad (13)$$

Although the results are represented as annual values, they rely on an hourly time domain simulation, thus encapsulating the intermittent nature of solar power production and cooling demand.

User Input Data
An ideal building cooling load and the weather data profiles need to be provided in order to perform the optimization. Additionally, the user provides an information on the area available to place the PV panels. Currently the panels can be placed on a horizontal roof, vertical facades and an optimally tilted surface (the tilt depends on the location).

An ideal cooling load for a 12 floor commercial building located in Munich has been simulated using TRNSYS (TRNSYS Documentation, 2009). The building has an office area of approximately 10800 m$^2$. The building has been simplified into three zones. All peripheral offices have windows facing either north or south, forming thus a south and a north zone. Each of these two zones comprises of 15 offices of 20 m$^2$ per building floor. The rest of the building area belongs to an internal zone between the north and the south zone. The cooling set point temperature of 26°C was applied during office hours between 8-18h, with a constant 1/h air exchange. The objective here is not to further evaluate the building characteristics, but rather to generate a realistic hourly cooling demand profile. The simulation resulted in an annual cooling demand of 10.6 kWh/m$^2$.a. Since an ideal indefinite cooling source has been assumed, before feeding this load to the described tool, the peak loads have been shaved and redistributed to subsequent hours.

Furthermore, it has been assumed that the PV panels are allowed to cover maximally 200 m$^2$ of each of the following areas: horizontal, optimally tilted, and southern façade. The optimal tilt for Munich is 36°. An overview of the relevant building data is given in Table 1.

The Meteonorm (Meteonorm 2012) TM2 weather data for Munich has been used to provide the temperature and solar radiation profiles.

<table>
<thead>
<tr>
<th>Conditioned Area, m$^2$</th>
<th>Cooling demand, kWh/m$^2 \cdot a$</th>
<th>Peak cooling load (secondary), kW</th>
<th>Maximal building area available for PV, m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10800</td>
<td>10.6</td>
<td>328</td>
<td>200</td>
</tr>
</tbody>
</table>

Implemented System Performance and Cost Data
Data sources have been referenced in the section describing the component models.

Vacuum Compression Chillers
The utilized DOE-2 Generic vacuum compression chiller model requires the following data: coefficients for performance curves, reference performance, and reference and limit conditions. The parameters for generic reciprocating and centrifugal chillers have been utilized and are available in EnergyPlus documentation. During design optimization all chillers of capacities lower than 400 kW are considered to be reciprocating, while larger chillers are modeled as centrifugal.

Cooling towers
Implemented parameters are given in Table 2.
Table 2
Factors describing cooling tower electrical energy and cooling tower water consumption

<table>
<thead>
<tr>
<th>Sizing coefficient, $k_{ct}$</th>
<th>Turn off limit, $PL_{min,ct}$</th>
<th>Blowdown, $\beta_{ct, min}$</th>
<th>Water flow ratio, $k_{w,ct}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0105</td>
<td>0.15</td>
<td>0.1</td>
<td>0.194</td>
</tr>
</tbody>
</table>

Photovoltaics

Implemented parameters are given in Table 3.

Table 3
PV model parameters

<table>
<thead>
<tr>
<th>Ref. Efficiency</th>
<th>System factor $f_{sys}$</th>
<th>Temp. coeff. $T_{ref}$, °C</th>
<th>Vent. factor $k_{a,ct}$, °C/(W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>0.78</td>
<td>-0.004</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Costs and Carbon Emissions

Data used to calculate for the results presented in the next section are given in Table 4. The utilized feed-in tariffs for photovoltaic power generation can be found at Bundesnetzagentur (2012). The electricity tariff for a commercial building consuming more than 100000 kWh/a is subject to an individual agreement and has thus not been determined, so the utilized price of 20 €/kWh represents a demonstrational value. Water costs are assumed linearly proportional to the water consumption. The value is taken from SWM (2012). According to the publication of the Umweltbundesamt (2012), the German power plant portfolio generates 560 g/kWh of CO₂.

Table 4
Data utilized as PV feed-in tariffs, utilities and power related carbon emissions.

<table>
<thead>
<tr>
<th>PV Feed-in Tariffs, €/kWh</th>
<th>Prices</th>
<th>Carbon Emissions, g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;$30</td>
<td>$&gt;$30</td>
<td>$&gt;$100</td>
</tr>
<tr>
<td>20.76</td>
<td>19.75</td>
<td>18.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.5836$</td>
</tr>
</tbody>
</table>

Results and Discussion

The minimization of the annual power purchase from the grid yielded the results presented in Table 5. The optimization recommended two chillers, one smaller, reciprocial, of 60 kW, and a bigger, centrifugal, of 460 kW nominal capacity. As expected, the maximal PV area of 200 m² resulted for all three surfaces. With such a configuration, the chillers consume 157.5 MWh, while the PVs generate 70.9 MWh per year. The optimization is performed using exhaustive search. Figure 4 presents the surface formed by objective function values for the evaluated chiller size combinations, while maintaining maximal PV power. The valley formed by the values close to the identified minimum is surrounded by steep walls. They are formed by the supply penalty, in case the chiller power is insufficient, and the 400 kW border, where the chiller type changes from reciprocating to centrifugal, due to the significantly higher COP of the latter.

Table 5
Optimal component dimensions: Power consumption minimization. Annual energy generation.

<table>
<thead>
<tr>
<th>Chiller Design Capacity, kW</th>
<th>Photovoltaic, m²</th>
<th>Optimal Tilt (36° S)</th>
<th>Horizontal</th>
<th>South Façade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller 1</td>
<td>Chiller 2</td>
<td>50</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>60</td>
<td>460</td>
<td>27264</td>
<td>23807</td>
<td>19866</td>
</tr>
<tr>
<td>Annual production, kWh</td>
<td></td>
<td></td>
<td>Total:</td>
<td></td>
</tr>
<tr>
<td>8510</td>
<td>149980</td>
<td></td>
<td>70937</td>
<td></td>
</tr>
<tr>
<td>Total cooling:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>157490</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4
Power consumption minimization. Objective function values for chiller size combinations. Minimum identified at chiller capacities of 60 kW and 460 kW

Figure 5 illustrates two weeks (end of May, beginning of June) of system performance using the optimized dimensions. The demand is satisfied in each of the timesteps. On the Friday of the first week only the smaller chiller is on. The PV generation and chiller power consumption profiles indicate a high degree of concurrence.

Finally, the resulting annual consumption and production are evaluated in Figure 6. In each of the charts two scenarios are presented, as introduced in the beginning of the result section. In the first scenario, only the consumption of chillers and cooling towers is deducted (in each timestep) from the PV generated power, while the difference is bought from the grid. In the second one, the previously mentioned consumption profile is increased for an approximation of the auxiliary power consumption (fans and pumps).

The first chart indicates that, observing the first scenario, the installed PVs can reduce the power consumption almost three times. This reduction is a consequence of the on-site consumption of 18 MWh of the 70 MWh that were produced by PV panels. The second scenario consumes a slightly larger amount, 20 MWh, which accounts for almost a half of its demand. It is assumed that the rest of the PV
generation can be sold to the grid. Evidently, in a more realistic scenario the total building power demand includes further consumers apart from the cooling system. This would yield a different ratio between the grid feed-in and direct consumption. However, if a planner is evaluating an impact of a potential cooling system installation on an overall building consumption, the presented calculation provides a good insight.

In the second chart, the annual cost of purchased and sold electric power is presented. Since we assumed a simple linear power tariff, the results are proportional to the previous chart. Nevertheless, since in reality the large consumers have a customized tariff system, such a calculation represents an important factor within the cost optimization procedure.

Still observing the second chart, the second scenario is a more realistic indication of how the PV panel installation represents a suitable accessory to the building cooling system installation. Not only is the own consumption almost cut in half, but the earnings, resulting from feeding the PV power to the grid, exceed the expenses for purchasing the “cooling” power by a factor of two.

The third chart provides the power consumption related carbon emissions of a cooling system. Calculated as a saving related to substituting the grid purchase with on-site produced PV power, the observed cooling systems can prevent around 7 t of CO₂ emissions per year.

The investment cost has been omitted in this observation. Nevertheless, if up-to-date component and installation prices are available, the tool is prepared to calculate the investment costs and its annuities for a demanded time period, as indicated earlier in the model description.

CONCLUSION AND OUTLOOK
The presented method enables optimal design of vacuum compressor chiller building cooling systems supported by PV power generation. The performance of the system is simulated in an hourly resolution to account for weather dependent intermittent PV generation, building demand and chiller and cooling tower performance. Already during the early
planning phases, the system components can be dimensioned such to minimize any of the following: investment cost, running cost, or power consumption (emissions). Costs, consumption and emission calculation are provided. The optimization objective function values are generated using annual hourly system simulation and evaluated by the modified exhaustive search algorithm.

Due to the hourly resolution, the method can be used in existing buildings to predict the generation/consumption dynamics of a building equipped with PV panels, distributed on its roof and facades, and VCh chillers. Furthermore, the method could be meaningful for planning future prosumer buildings, which will be members of a smart grid. On a larger scale, the tool can be used to analyze how the cooling demand changes the power demand profile of a region, combined with the impact of decentralized BIPV plants.

REFERENCES


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