# SIMULATION-BASED DESIGN OF PV COOLING SYSTEMS FOR RESIDENTIAL BUILDINGS IN HOT AND DRY CLIMATES

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## ABSTRACT

The contribution focuses on the simulate-based design and optimization of photovoltaic (PV)-driven cooling systems for residential buildings in hot and dry countries. The analyzed system includes the PV generator, the electric battery, the vapor compression chiller, the air-conditioned building and the controller technologies. Systems with split-devices for direct air-cooling and also water-based systems for cooling ceilings are considered.

The simulation studies are carried based on the Modelica library *BuildingSystems* and also in combination with the building simulation tool EnergyPlus and the framework for co-simulation BCVTB. In a first step, principal questions about the system design of photovoltaic-driven cooling systems under hot and dry climate conditions are analyzed, e.g. to find out matching system parameters like installed PV-power, battery capacity, vapor chiller cooling power taking into account the thermal capacity of the air-conditioned building. For this purpose, a pure Modelica system model with a simplified one-zone thermal building model is used. In a second step, a use case of a multi-zone building is studied, in which the building envelope is modeled with EnergyPlus and the air-conditioning system and the control strategy in Modelica. Both sub-models are integrated with BCVTB to the system model.

The simulation study was carried for the hot and dry location Hashtgerd in North Iran and the City El Gouna on the west coast of Egypt.

## INTRODUCTION

The development of solar assisted cooling systems for buildings was focused during the middle of the 90ths mostly on thermal processes (IEA TASK 38, 2011). Different technical solutions, based on open sorption processes (e.g. solar assisted DEC systems) and closed sorption processes (e.g. single or double lift solar assisted sorption chillers) were developed and tested in pilot project (BINE, 2004).

The drastically price reduction of PV modules from 2.62 €/$W_{peak}$ in May 2009 to 0.79 €/$W_{peak}$ in January 2013 for crystalline technology from Europe (or from 2.17 €/$W_{peak}$ in May 2009 to 0.54 €/$W_{peak}$ in January 2013 for crystalline technology from China)[1] makes air-conditioning systems with the direct photovoltaic driven vapor compression chillers much more attractive, especially a PV cooling systems can be much more easier constructed as a solar thermal cooling systems from the point of view of the system hydraulic. In a current simulation study the advantages and disadvantages about thermal and photovoltaic cooling systems for residential buildings in the MENA (**M**iddle **E**ast & **N**orth **A**frica) region were compared [Badran, 2012].

Now, first manufactures such as *Hot Spot Energy*, *Concept Sud* or *Split Cool* bring small PV driven split-unit-devices for residential buildings to the market (compare with Figure 1). Some of these systems work with DC machines for the compression chiller, which enables a direct use of the produced DC current from the photovoltaic generator without DC/AC transformation losses.

*Figure 1 Autonomous working PV-driven split cooling device with 4.4 kW cooling power and DC chiller technology (Source: Concept Sud)*

## CONVENTIONAL AND PV COOLING SYSTEMS FOR RESIDENTIAL BUILDINGS IN MENA COUNTRIES

The authors are developing energy concepts and technical solutions for the air-conditioning of residential building for the two MENA countries Iran and Egypt. Both countries have a high population growths over the last decades. For this reason, a lot of so called "New Towns" were built in Iran and Egypt to obtain the necessary living space. The hot climate in the MENA region leads to a relevant

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[1] Source: http://www.solarserver.de

cooling demand in the summer in residential buildings. The standard used active air-conditioning technologies in the MENA region are water evaporation coolers, often used for dry climate conditions and also electric-driven small vapor-compression chillers (split unit devices), especially in regions, where natural drink water resources are very restricted. Up to now, only fossil (natural gas, petrol) produced electricity is used for the operation of the compression chillers or the ventilators of the evaporating cooling systems.

As an alternative, the available high solar irradiation potential in the MENA region, for example 1.900 kWh/(m$^2$a) in Hasthgerd New Town (located in the northern part of Iran, 100 km west of Tehran) or 2.400 kWh/(m$^2$a) in El Gouna (located at the coast of the Red Sea, 500 km south of Cairo) could be used in the future to minimize the CO$_2$-emissions by fossil building air-conditioning. Within the Young Cities project different technical solution for building cooling were developed for a new planned 35 ha district for the New Town Hashtgerd (Huber and Nytsch-Geusen, 2011). One of the proposed technical solutions was a PV-based cooling system, which stores the produced electricity in a battery and the cooling energy in a cold water tank, before it is used for the room cooling (compare with Figure 2).

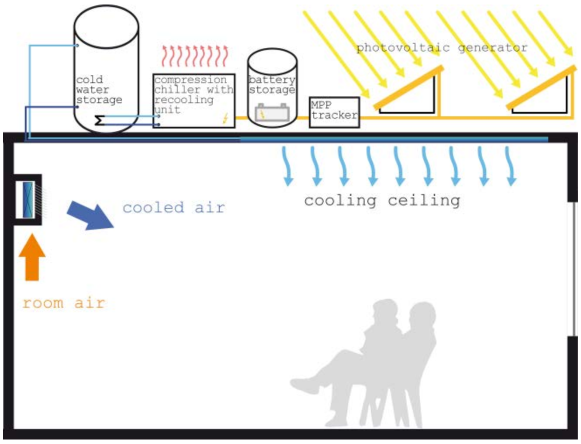

*Figure 2 PV-based cooling system for residential building cooling*

## USED MODELS, SIMULATION AND SOFTWARE TOOLS

For the simulation-based design of the PV cooling system a Modelica model library, the simulation tools Dymola and EnergyPlus and the software tools GenOpt and BCVTB were used stand-alone and also in combination:

### Modelica library Building Systems

The Modelica library *BuildingSystems* (Nytsch-Geusen et al., 2012) for object-oriented modeling and simulation of complex energetic building systems is being developed by the chair of building services technology at UdK Berlin. The models of the library cover a broad spectrum of the domains such as room and building, solar energy technologies (solar thermal energy, photovoltaic) and HVAC-technologies (compare library structure in Figure 3).

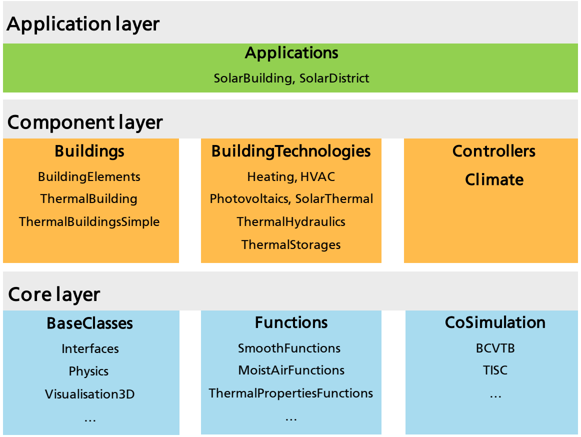

*Figure 3 Structure of the Modelica library BuildingSystems*

### Photovoltaic generator model

*Figure 4 Monitored PV-generator on the roof of the UdK Berlin building Hardenbergstraße 33*

Monitored data from the PV-generator (15.5 kW$_{peak}$), located at the roof of a UdK Berlin building (compare with Figure 4) were used for the validation of the PV model of the *BuildingSystems* library. The measured values such as air and module temperature, solar irradiation and electrical output were used as climate boundary conditions of the Modelica system model and as comparison values for the model (compare with Figure 5).

For the validation, one of the three strings of the photovoltaic field was modeled with a total peak performance about 5.6 kW$_{peak}$ (22 serial connected PV modules; type TSM-PC05 with 230 W$_{peak}$).

The simplified model of a PV module from the *BuildingSystems* library was used, which produced the electrical power P$_{MPP}$ for a MPP (maximum power point)-controlled PV module. This model is based on an electrical one-diode model with a calibration factor f$_1$=0.851 and an empirical thermal equation for the cell temperature T in dependency on the environment temperature T$_{env}$ and the total solar irradiation E with the factor $f_2$=0.043 (Nytsch et al., 2000):

$$I_{ph} = E \cdot \frac{\mathrm{I_{k0}}}{\mathrm{n_{cp}}} \cdot (1 + \propto_{ik} \cdot (T - \mathrm{T_S})) \quad (1)$$

$$U_l = U_{l0} \cdot (1 + \propto_{ul} \cdot (T - \mathrm{T_S})) \quad (2)$$

$$\mathrm{I}_{s1} = \frac{\frac{\mathrm{I_{k0}}}{\mathrm{n_{cp}}} \cdot (1+\alpha_{\mathrm{ik}} \cdot (\mathrm{T}-\mathrm{T_S}))}{e^{\frac{\mathrm{U_l}}{\mathrm{n_{cs}} \cdot \mathrm{U_t}}} - 1} \quad (3)$$

$$I_{MPP} = n_{cp} \cdot \left[ I_{ph} - I_{s1} \cdot \left( e^{\frac{U_{MPP}}{n_{cs} \cdot m_1 \cdot U_t}} - 1 \right) \right] \quad (4)$$

$$\frac{I_{MPP}}{n_{cp}} - \left( U_{MPP} - \frac{n_{cs}}{U_t} \right) \cdot I_{s1} \cdot e^{\frac{U_{MPP}}{n_{cs} \cdot U_t}} = 0 \quad (5)$$

$$P_{MPP} = I_{MPP} \cdot U_{MPP} \cdot f_1 \quad (6)$$

$$T = T_{env} + f_2 \cdot E \quad (7)$$

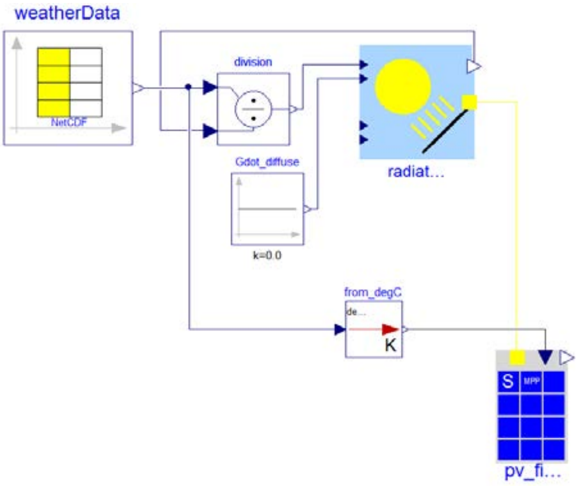

*Figure 5 Modelica model of the PV-generator*

Figure 6 shows the measured and the simulated values (temperatures and electrical power) of the string of 22 PV modules during three summer days. Both quantities have similar values for the real PV plant and for its simulation model. The cell temperature runs up two 20 K higher than the environment air temperature.

### Battery model

The battery model is strongly simplified, because it stores electric energy with a constant conversion rate. This parameter is set in the following simulation analysis to 80 percent, a typical value for current battery technologies. Further the model has a maximum electric capacity and a loss factor, which is proportional to the stored energy.

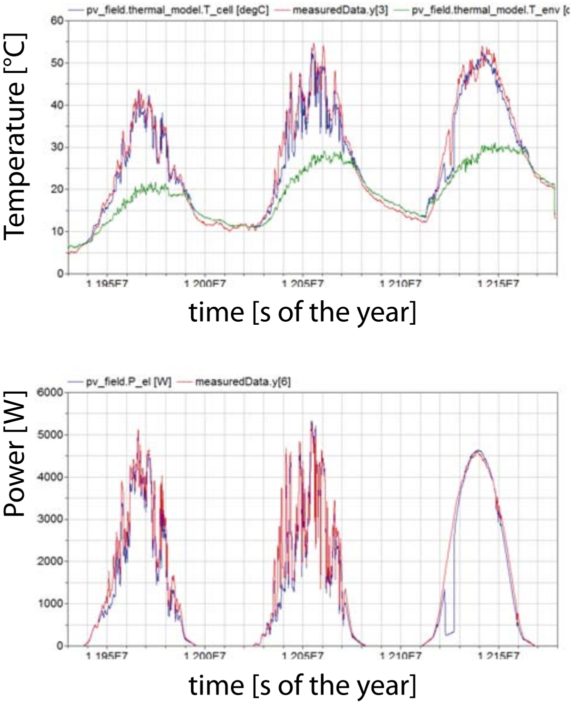

Figure 6 Simulated and measured module temperature and electrical power of the string of 22 modules during three days of June in 2012

### Compression chiller model

The COP (**c**oefficient **o**f **p**erformance) of the compression chiller model is calculated as the product of the ideal efficiency of a left-handed circular process, multiplied by a factor $\zeta = 0.5$, which includes the irreversibilities of a real chiller (inner losses and temperature differences between the refrigerant and the cooled water respectively to the waste-heat side and also the losses from the electrical machine of the chiller):

$$COP = \zeta \cdot \frac{T_{cool}}{T_{env} - T_{cool}} \quad (8)$$

With the COP and the given electrical power $P_{el}$, the produced cooling energy $\dot{Q}_{cool}$ and the waste energy $\dot{Q}_{env}$ are determined:

$$\dot{Q}_{cool} = COP \cdot P_{el} \quad (9)$$

$$\dot{Q}_{env} + \dot{Q}_{cool} + P_{el} = 0 \quad (10)$$

### Thermal building model

Also the used transient thermal building model is strongly simplified to obtain a fast system model for the often repeated simulation runs for the optimization analysis. The model works with only one thermal zone and three thermal capacities: One for all thermal masses in contact to the surrounding air (facades, roof, windows, ...), one for the whole thermal masse which is in contact to the ground (ground plate, ...) and one for all thermal masses which are in contact the air within the building (interior walls, storey ceilings, ...). The building model has also an unlimited number of transparent surfaces with a incident angle dependent calculation of the transmitted solar radiation (compare with Figure 7):

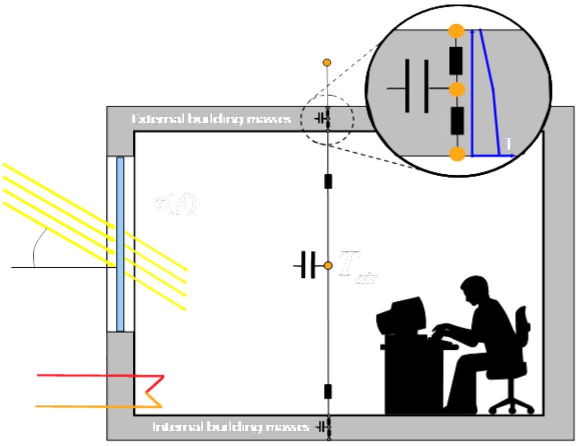

*Figure 7 Simplified thermal building model*

The authors showed within a previous analysis, that this fast model calculates similar energy heating and cooling demands as much more detailed thermal building models such as EnergyPlus (Huber et al. 2012).

### EnergyPlus

EnergyPlus (EnergyPlus, 2012) is a entire building energy simulation program for multi-zone-thermal building simulation and energy plant simulation. It is the successor of the two older thermal building simulation programs BLAST and DOE-2. With EnergyPlus the modelling of heating, cooling, lightning, ventilating and other energy fluxes is possible. The modelling description input is based on text files. The software has no own 3D-geometry modeller, but external 3D modellers such as Design Builder or Autodesk Ecotect can produce input files for EnergyPlus. Energy plus supports co-simulation by the use of BCVTB.

### GenOpt

GenOpt (Wetter, 2011) is software for the reduction of a cost-function of an external simulation program. GenOpt varies predefined parameters and starts the simulator (for example Dymola, EnergyPlus, TRNSYS or IDA-Ice). The simulator returns a cost function back to GenOpt (after one simulation periode), which varies the parameters after the predifined optimization algorithm.

### Building Control Virtual Test Bed (BCVTB)

The Building Control Virtual Testbed (Wetter, 2010) is a software environment for co-simulation of different simulation programs, e.g. Modelica/Dymola or EnergyPlus. It supports also real time simulation, where hardware devices for building control are coupled with thermal building simulation and energy plant simulation models. The graphical editor of BCVTB shows the structure of the coupled system model on the top level.

## SIMULATION STUDIES

The PV cooling system for residential buildings from Figure 1 is analyzed and optimized at two different locations in the MENA region. The simulation period over the whole summer has a duration of 174 days (May to September).

### Environmental conditions

The first location is Hashtgerd in Iran, the second location is El Gouna in Egypt (see Figure 8).

*Figure 8 Map of the MENA region with the regarded locations Hashtgerd and El Gouna*

The air maximum temperatures in Hashtgerd and El Gouna are nearly the same (41 °C), but the mean temperature during the summer periode (between the two black bars in Figure 9) in El Gouna (30.4 °C) is much higher than in Hashtgerd (26.0 °C).

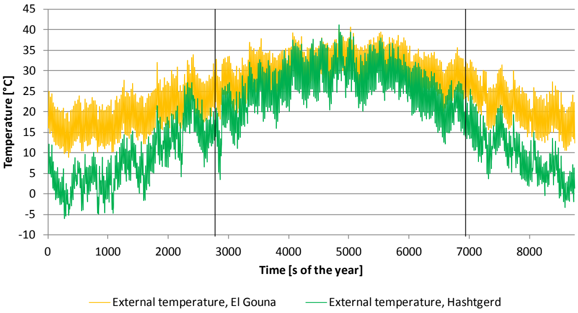

*Figure 9 External temperature in Hashtgerd and El Gouna (Source: Meteonorm)*

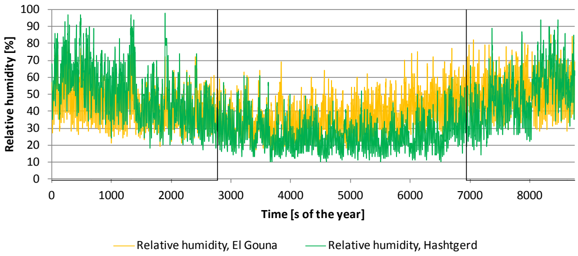

*Figure 10 Relative humidity in Hashtgerd and El Gouna (Source: Meteonorm)*

The relative humidity in El Gouna during the summer periode is eleven percent higher in the middle than in Hashtgerd (see Figure 10).

The yearly sum of global horizontal solar radiation is in Hashtgerd 1,800 kWh/m$^2$a and in El Gouna 2,400 kWh/m$^2$a.

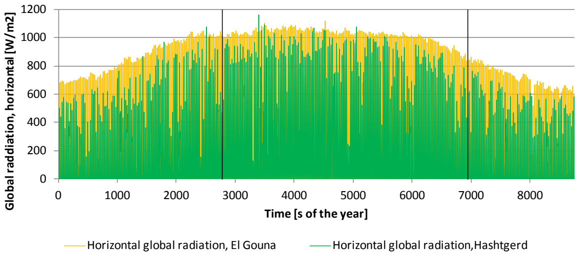

*Figure 11 Global irradiation on the horizontal in Hashtgerd and El Gouna (Source: Meteonorm)*

### Building Model

The regarded residential building has space for two families, each with 6 persons (278 m$^2$ net floor area). This building is modelled with 5 thermal zones, one public and 4 living zones (for each family one zone per storey) (see Figure 12).

*Figure 12 Ground plan of the regarded residential building.*

Figure 13 shows the 3D-geometry of the building model, embedded within its neighbourhood and also in detail with its 5 thermal zones.

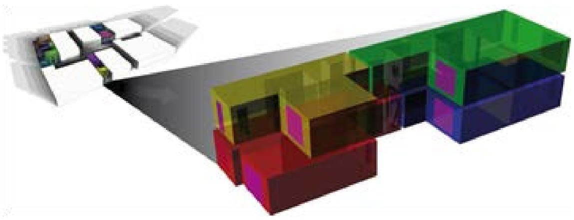

*Figure 13 3D-thermal Building model of the residential building, which includes also the detailed neighbourhood shading*

The mean U-values of the thermal envelope (walls, windows and roof) are 0.593 W/m$^2$K and of the ground plate 0.350 W/m$^2$K. The PV modules are mounted on the upper roof with its 135 m$^2$ area.

### Analyzed PV cooling system

The analyzed PV cooling system should work independent of an electric grid (autonomous system). It is modelled in Modelica by the use of the *BuildingSystems* library and it consists of following seven main parts (see Figure 14):

1. The weather integration and the conversion to the different surfaces (PV and building facades)
2. The PV generator system
3. The battery system
4. The compression chiller with its recooling unit
5. The cold water storage
6. The thermal building model
7. The controllers

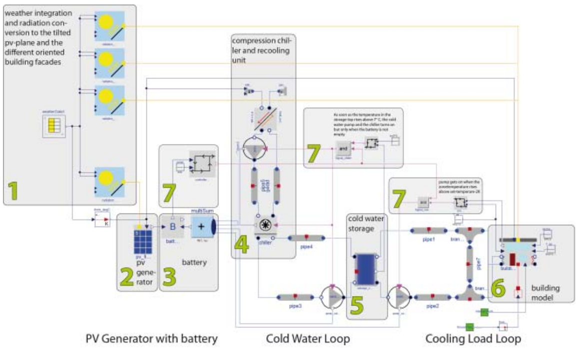

*Figure 14 Modelica model of the PV cooling system*

Several controllers are implemented within the system model. The first controller manages the cooling load pump. This pump gets on if the room air temperature reaches the set temperature with an offset of 2 K. The second controller measures the water temperature in the top of the cold water storage. If the temperature rises above 7 °C, the compression chiller, the re-cooling pump and the cold waterloop pump turns on, but only if the battery load state is not lower than 20 percent (discharge protection).

### Optimization of the Modelica system model

In the first step, the pure Modelica system model with the simplified thermal building model is used to carry out the parameter optimization for the system design with GenOpt (see Figure 15).

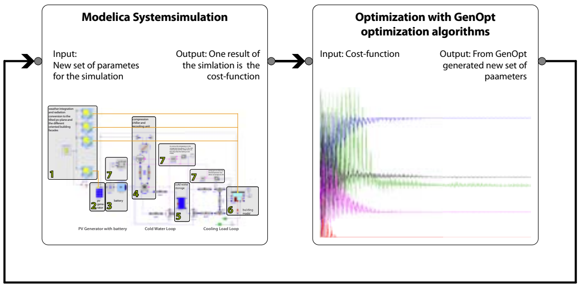

*Figure 15 Principle of the Optimization with GenOpt*

For this reason, the most important system parameters have been selected.

These chosen optimization parameters are

- the number of PV modules (1 – 83),
- the capacity of the electric battery (1 – 80 kWh),
- the nominal power of the vapor compression chiller (0.1 – 5.0 kW) and
- the volume of the cold water storage (0.1 – 10.0 m$^3$).

As the optimization criteria for GenOpt a cost-function $f(x)$ with three different design criterias is used (multi-criteria optimization):

$$f(x) = f_1 \cdot intovertemp + f_2 \cdot investmentcosts + f_3 \cdot chillerswitches \quad (11)$$

**Over temperature**: The first criteria is to avoid overheating in the thermal zone for an optimal thermal comfort. If the air temperature $\vartheta_{air}$ exceeds the set temperature $\vartheta_{set} = 26\,°C$ then the difference $\vartheta_{air} - \vartheta_{set}$ (over temperature) is integrated over the time:

$$intovertemp = \int_{t_o}^{t_1} \begin{matrix} if\ \vartheta_{air} - \vartheta_{set} > o :\ \vartheta_{air} - \vartheta_{set} \\ else: 0 \end{matrix}\ dt \quad (12)$$

**Investment costs:** The second criteria is to reduce investment costs. Following assumptions to the specific investment costs were taken:

- PV generator: 0.7 €/W$_{peak}$
- Battery: 600 €/kWh
- Compression chiller: 0.4 €/W$_{el}$
- Cold water storage:

$$costs\ (volume)\ [€] = 1649.81 \cdot volume[m^3]^{-0.464} \quad (13)$$

**Durability of the components**: The third criteria is the reducing of switching events of the DC vapor compression chiller with its recooling unit.

These three criterias are weighted within the constfunction with the factors $f_1 = 1$, $f_2 = 1$ and $f_3 = 2$. Electricity costs are not regarded, because the PV cooling system works grid-independent (autonomous system).

### Co-simulation Modelica / EnergyPlus

The system model which was optimized with GenOpt is finally transformed into a co-simulation model, which consists of a Modelica energy plant model and a EnergyPlus thermal building model. The co-simulation is realised with the framework BCVTB (Figure 16).

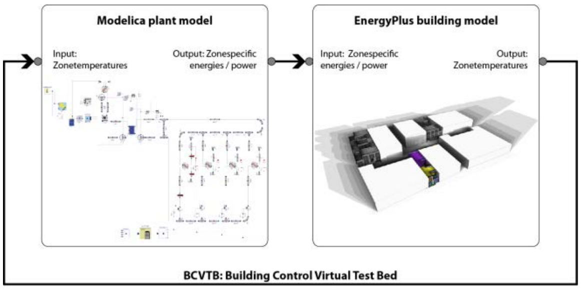

*Figure 16 Principle of the co-simulation framework BCVTB*

The input parameters of the building model (geometry, building construction, user behaviour etc.) are identical to the simplified Modelica building model. But now, in EnergyPlus the building is divided into 5 thermal zones (compare with Figure 12). In addition, this multi-zone building model has more realistic detailed shading and neighbourhood boundary conditions (e.g. shading from surrounding buildings).

The plant model of the PV-based cooling system was adapted to the interface of BCVTB and is shown in Figure 17.

The values between EnergyPlus and Modelica/Dymola were syncronized every 600 seconds by BCVTB.

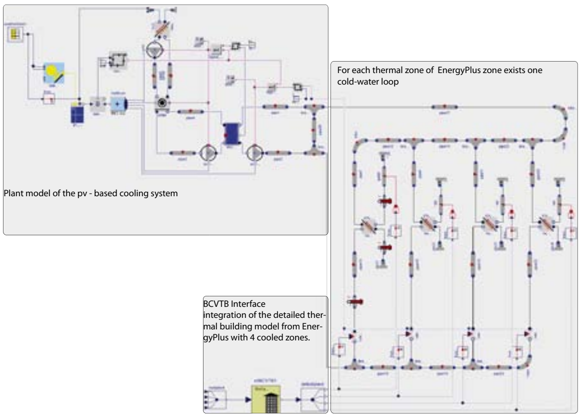

*Figure 17 Modelica model of the co-simulated PV cooling plant model*

## RESULTS:

### Optimization of the Modelica system model

GenOpt started at both climate locations Hashtgerd and El Gouna with the same parameter set

- number of PV modules (70),
- capacity of the electric battery (40 kWh),
- nominal power of the chiller (1.0 kW),
- volume of the cold water storage (5.0 m$^3$),

which leads to a significant different value for the cost-function for after the first simulation run (see Figure 18).

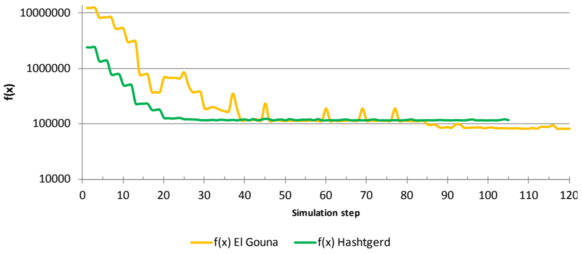

*Figure 18 Optimization runs of the problem with Modelica and GenOpt. Cost-function for El Gouna and Hashtgerd*

At the end oft the optimization (after 120 simulation runs) the cost-function for both locations are in the same region.

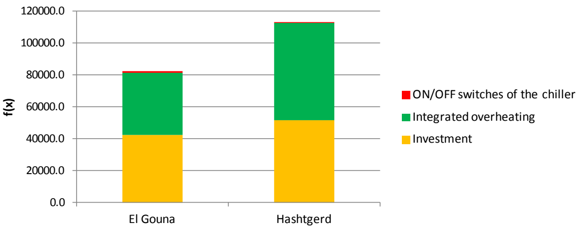

*Figure 19 Final cost-function value and its composition for El Gouna and Hashtgerd*

Because the climate of Hashtgerd differs more than in El Gouna during the year, also the cooling load shows in Hashtgerd higher peaks. The yearly amount of cooling energy in El Gouna is higher than in Hashtgerd, because the mean temperature at the Egyptian location is higher than in Iran. The maximum temperature during the summer is nearly the same at both locations.

For this reasons, the optmization algorithm has found for Hashtgerd the same number of PV modules (83), this is the maximum value of posible modules because of the needed roof area.

The location ElGouna with a higher mean temperature and cooling demand needs greater storage capacities for cooling energy. The daily and yearly timeline of the solar irradiation is more balanced in comparison to Hastgerd. So the optimization prefers a greater and cheaper cold water storage (6.1 $m^3$ instead of 5.5 $m^3$) and reduces the capacity of the electric battery (40 kWh instead of 55 kWh).

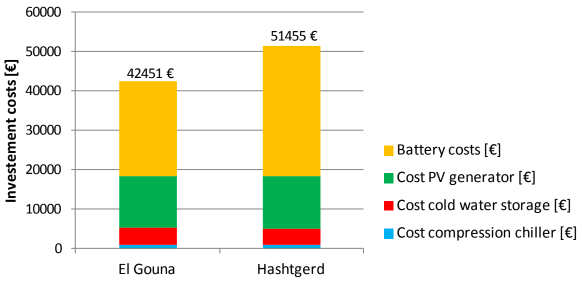

*Figure 20 Investment costs in €for both locations*

Figure 20 shows the detailed investment costs for both locations. The main costs are from the battery and the PV generator. The costs of the cold water storage and the chiller are not so significant.

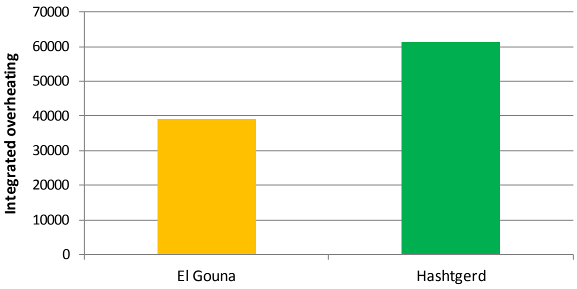

*Figure 21 Integrated overheating time*

The PV cooling plant causes in Hashtgerd higher overheated time (see Figure 25) as in El Gouna because of the higher cooling load peaks.

Because of the higher alternating external temperature, the chiller switches in Hashtgerd are a bit more (Figure 22).

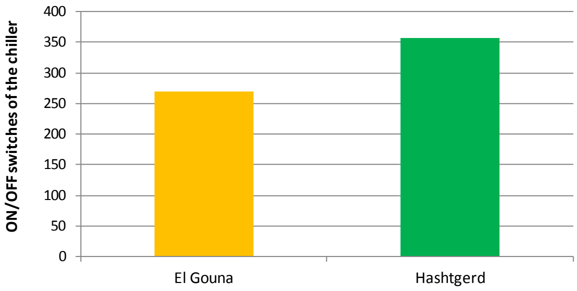

*Figure 22 ON/OFF switches of the chiller*

**Co-simulation Modelica / EnergyPlus**

The co-simulation was performed for the climate location Hashtgerd.

The simulation experiment for the summer-periode takes for the co-simulation case with BCVTB approximately 4 to 5 times more than the single (pure) Modelica simulation.

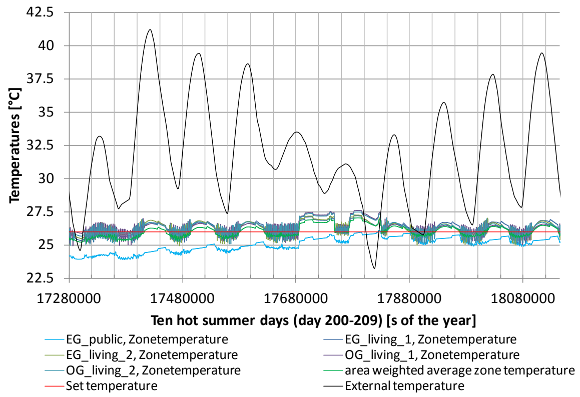

*Figure 23 Zone temperatures from the coupled multi-zone building for a hot summer week (EnergyPlus)*

Figure 23 shows the different zone temperatures of the detailed EnergyPlus building model in the hottest summer week. Because of the controllers and the thermal inertance of the zone, the zone air temperature rises a bit above the set-temperature in the sunlit zones.

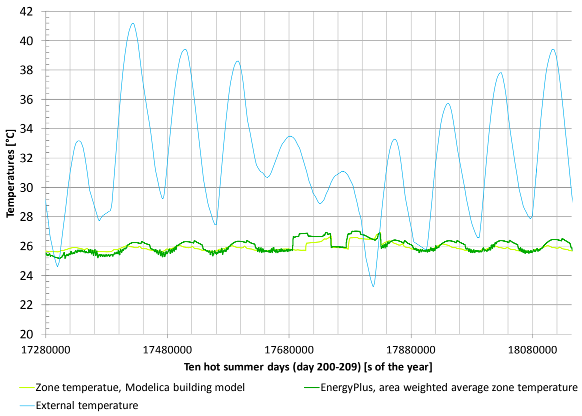

*Figure 24 Comparison of the zone temperature of the simplified building model (Modelica) versus the area-weighted average zone temperature of the multi-zone building model (EnergyPlus) for a summer week*

In comparative between the area-weighted average zone temperature of the detailed multi-zone EnergyPlus simulation and the single zone temperature of the Modelica building model can be seen a similarity (see Figure 24).

The EnergyPlus building model shows significant higher values for the integrated over temperatures for as the Modelica building model, because the simplified building model with only one common ideal mixed air volume calculates smaller (mean) values for the air temperature as the multi-zone-EnergyPlus model with five smaller air volumens (see Figure 25). The higher integrated over temperatures of 636,719 Ks are equivalent to a mean over temperature of 0.3 K, which is also not a critical value for a good thermal comfort.

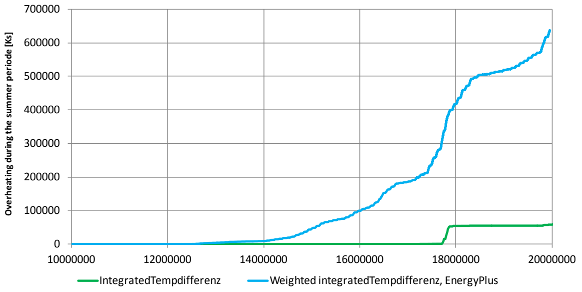

*Figure 25 Integrated over temperature (EnergyPlus: sum of all 5 zones)*

Figure 26 shows the thermal power, which is transferred from the building to the PV cooling system. The timelines of the pure Modelica simulations are continous, the co-simulation shows a more discrete behaviour.

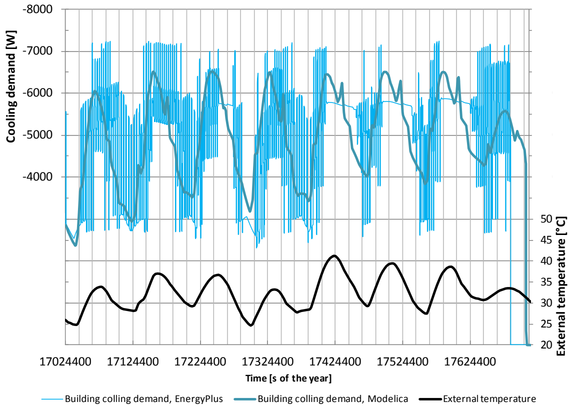

*Figure 26 Comparison of the cooling load for a summer week (EnergyPlus: sum of all 5 zones)*

The yearly needed cooling energy demand of both simulations is shown in Figure 27. The multi-zone building of EnergyPlus needs earlier cooling energy than the Modelica model, because the air temperature of the seperated modelled zones can touch earlier the limits of the set temperature, which leeds also to an earlier need of cooling energy. In total the co-simulation needs 16 percent more cooling energy than the pure Modelica simulation.

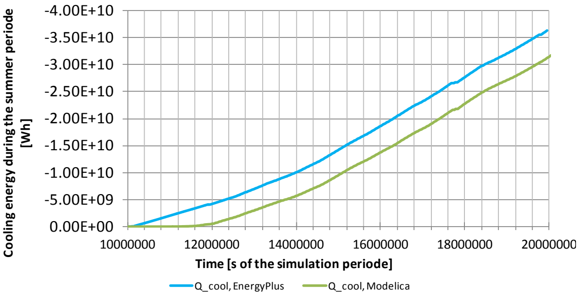

*Figure 27 Comparison of the cooling energy demand (EnergyPlus: sum of all 5 zones)*

## SUMMARY AND OUTLOOK

The simulation analysis of a PV cooling system for a 2-storey residential building has shown that the needed electricity can be produced by the building itself under climate conditions of the MENA region (locations Hashtgerd (Iran) and El Gouna (Egypt)). In this case the PV cooling system works autonomous without any connection to the electric grid by the use of an electric battery and a cold water storage.

With the help of a parametric multi-criteria optimization with GenOpt, adapted values for the design parameters

- number of PV modules,
- battery capacity,

- nominal power of compression chiller and
- volume of the cold water storage

could be found, which provide a compromise of reduced investment costs and also reduced over temperatures and chiller-switching events at a specific location (e.g. Hashtgerd or El Gouna).

A following BCVTB-based co-simulation analysis for the same problem, which includes a Modelica model of the PV cooling system and a EnergyPlus multi-zone building model - can produce much more detailed information, e.g. critical local temperature situations within the building or a more realistic operation behavior of the energy plant. But up to now the co-simulation model is to slow for parameter optimization such as GenOpt.

The next steps will be the set up of real test beds for PV cooling systems at the TU Berlin Campus El Gouna. With the help of these experimental devices measurement data will be gained as a source for further model validation on component level and also on system level.

## NOMENCLATURE

$\alpha_{ik}$ = Specific temperature coefficient for the short circuit current in 1/C
$\alpha_{ul}$ = Specific temperature coefficient for the open circuit voltage in 1/C
$COP$ = Coefficient of performance
$E$ = Specific solar irradiation in W/m$^2$
$f1$ = Calibration factor for internal PV module losses
$f2$ = Empirical factor for the irradiation dependency of the cell temperature in Tm$^2$/W
$I_{ph}$ = Photo current in A
$I_{s1}$ = Saturation current in A
$I_{k0}$ = Short circuit current (standard conditions) in A
$I_{MPP}$ = MPP-Current of the PV module on A
$m_1$ = Diode factor
$n_{pc}$ = Number of parallel cells
$n_{cs}$ = Number of serial cells
$P_{el}$ = Electrical input power if the chiller inW
$P_{MPP}$ = MPP-Electrical power of the PV module
$T$ = Cell temperature in K
$T_{cool}$ = Cold water temperature of the chiller in K
$T_{env}$ = Environment air temperature in K
$T_S$ = Cell temperature (stand. conditions 25 °C) in K
$\dot{Q}_{cool}$= Produced cooling energy of the chiller in W
$\dot{Q}_{env}$= Waste energy of the chiller in W
$U_l$ = Open circuit voltage in V
$U_{l0}$ = Open circuit voltage (standard conditions) in V
$U_t$ = Temperature voltage in V
$U_{MPP}$ = MPP-Voltage of the PV module in V
$\zeta$ = factor for irriversibilities within the chiller

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