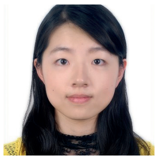
MODELICA FOR DESIGN OF BUILDING AND DISTRICT ENERGY SYSTEMS

IEA EBC ANNEX 60: RESEARCH PROJECTS DEMONSTRATING THE BENEFITS/UTILIZATION OF MODELICA

Under the umbrella of the International Energy Agency's Energy in Buildings and Community Programme (IEA EBC), a team of 41 institutes from 16 countries started collaborating in 2012 on the development and demonstration of new generation computational tools for building and community energy systems. The IEA EBC Annex 60 is based on the Modelica language and the Functional Mockup Interface (FMI) standards and is planned to end in 2017. This article briefly introduces the Annex 60 structure and objectives and presents some contributing projects carried out by the Computational Building Performance Simulation (CBPS) research group from Eindhoven University of Technology (TU/e) in the validation and demonstration sub-task related to the design of building and district energy systems.

J.I.(Ignacio) Torrens, Unit Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology



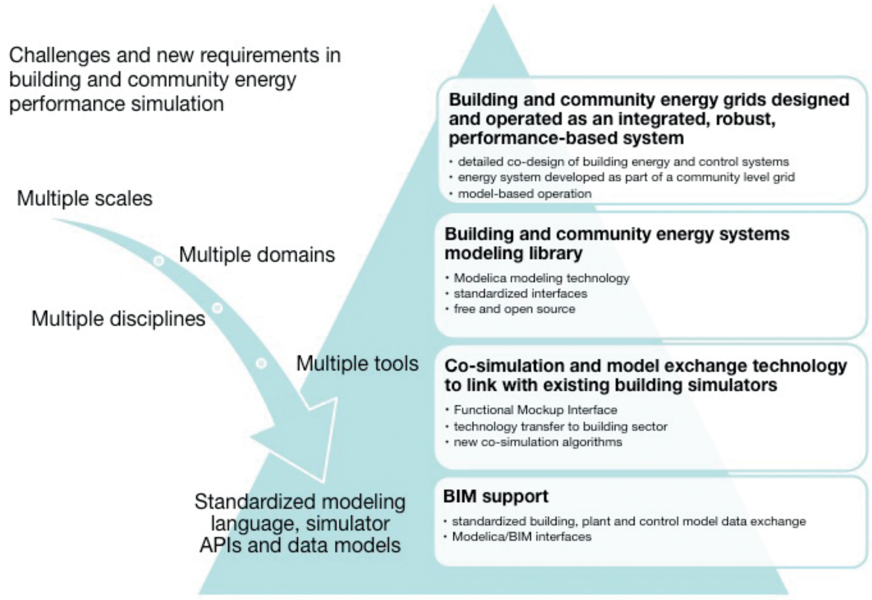
L. (Luyi) Xu MSc, Unit Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology

prof. dr. ir. J.L.M. (Jan) Hensen, Unit Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology

INTRODUCTION TO THE IEA EBC ANNEX 60

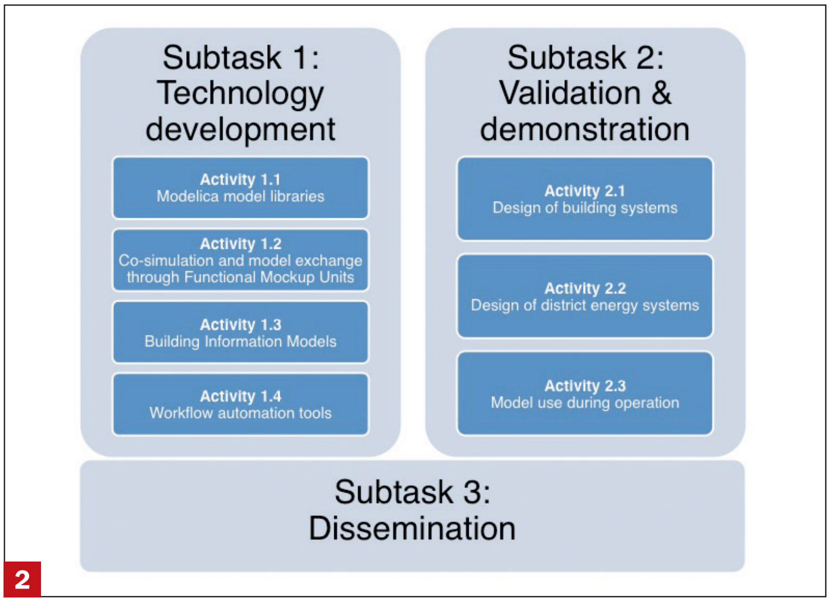
As buildings become increasingly integrated to reduce energy and peak power and to increase occupant health and productivity, new challenges are posed to engineers when using building simulation programs to support decision making during product development, building design, commissioning and operation. New requirements that were not yet recognized 20 to 40 years ago when the development of current building simulation programs started include:

- *Model-based design of integrated building systems* by design firms and of products by equipment and controls providers to optimize energy-efficiency and peak load, and to reduce time-to-market for components, systems and advanced control systems.
- Design processes based on *Building Information Models (BIM)* which become increasingly used by design firms.
- *Integrated design* of building envelope, HVAC systems and control strategies by design firms.
- *Model use to support operation*, for control providers as part of an energy or smart-grid aware controller, for commissioning agents to provide a reference for the expected building operation, for fault detection and diagnostics providers to provide a reference model that can be used to classify fault signatures, and for urban planners and utility companies to develop design and operation strategies for energy grids with dispatchable distributed loads, generation and storage.



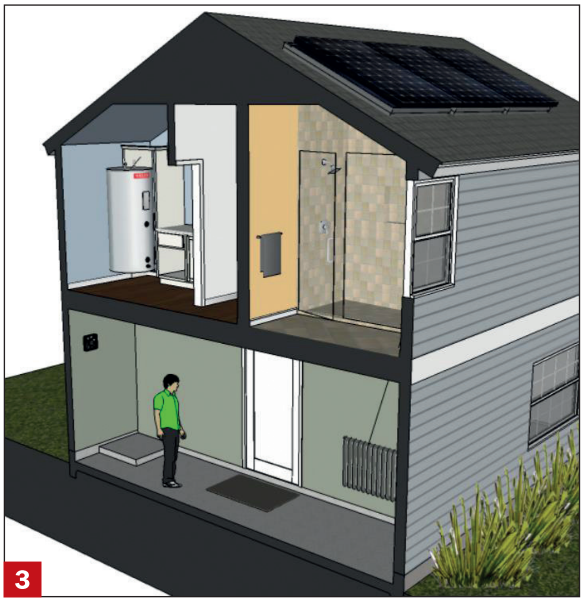
1

Overview of challenges and outcomes of Annex 60



2

Annex 60 Subtasks and activities structure



3

Full home system schematic

These applications require the integration of multiple domains (air-flow, thermodynamics, controls, indoor environmental quality, and electrical grid) and multiple disciplines (HVAC/energy consultant, architect, controls engineer, electrical engineer). They use a variety of tools that represent building systems across largely varying time scales from seconds to years, and length scales from building components to urban districts [1].

The IEA EBC Annex 60 will develop and demonstrate new generation computational tools for building and community energy systems based on the non-proprietary Modelica modeling language [2] and Functional Mockup Interface (FMI) standards. The anticipated outcomes are open-source, freely available, documented, validated and verified computational tools that allow buildings, building systems and community energy grids to be designed and operated as integrated, robust, performance based systems with low energy use and low peak power demand.

Validation & Demonstration: Design of building and district energy systems.

The IEA EBC Annex 60 is structured in three sub-tasks [3], as shown in figure 2.

- Subtask 1 focuses on the development of the necessary software technology, leveraging the dispersed work that already exists.
- Subtask 2 focuses on the validation, verification, demonstration and deployment of the developed software technology in the context of whole building and community energy performance design and operation.
- Subtask 3 will develop a guidebook, organize special tracks at professional conferences, and ensure effective collaboration with professional organizations.

The Computational Building Performance Simulation (CBPS) research group from Eindhoven University of Technology (TU/e) contributed to two of the validation and demonstration activities: 2.1:"Design of building systems" and 2.2: "Design of district energy systems" with a number of research projects that will be introduced and described in the following sections.

DESIGN OF BUILDING SYSTEMS

Development of a testbed for building integrated renewable energy sources

General description

With the increased penetration of the energy efficiency measures and the renewable energy systems in the built environment, buildings are moving from being energy-consumers to being active and complex producers of energy. The increased complexity of building systems imposes the need for flexible, multi-domain simulation models to be applied during the design phases in order to accurately predict the performances.

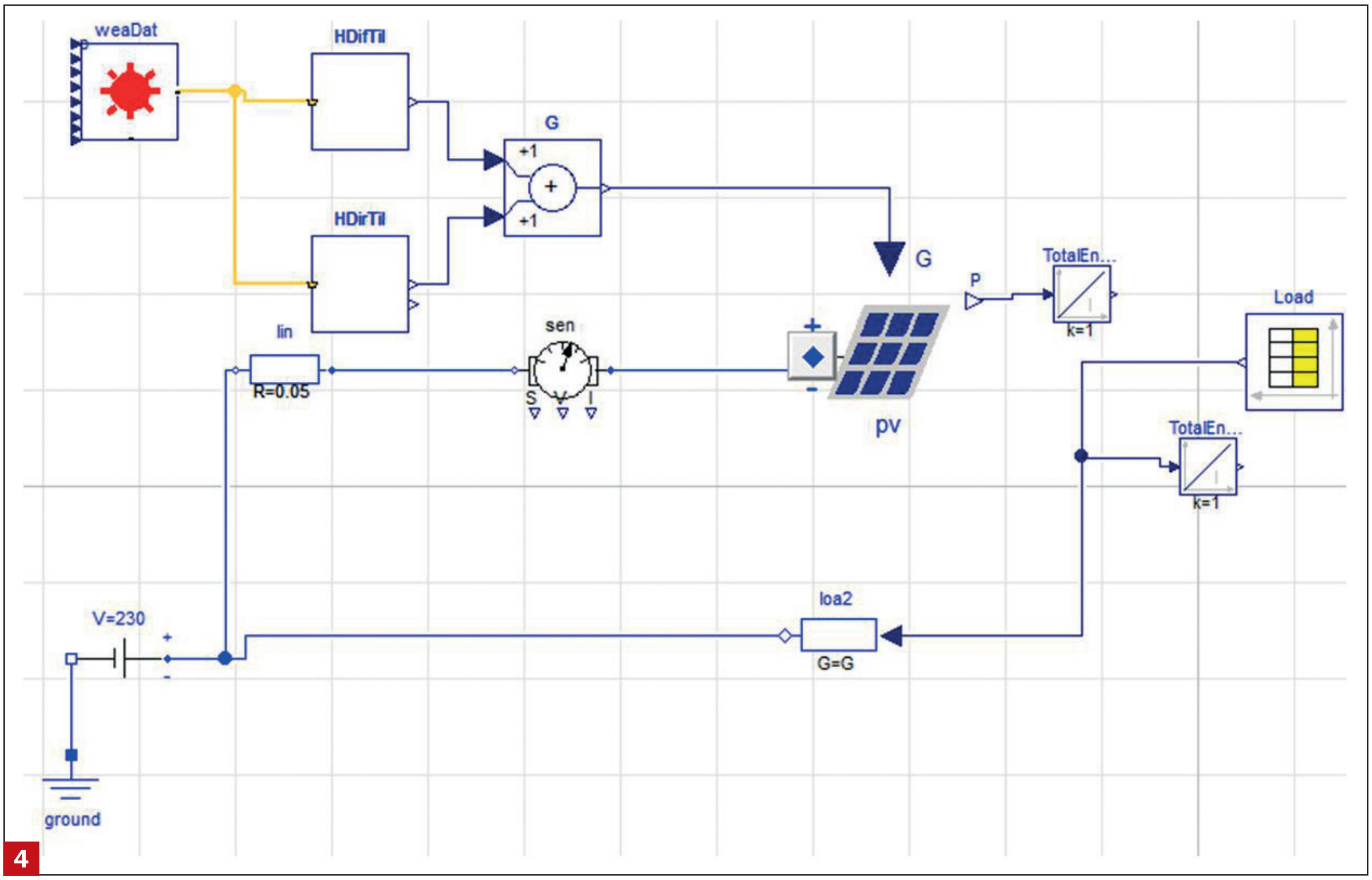
With the emergence of the Modelica language, building simulation using this language is turning out to be very attractive with all the multi-domain advantages that it presents. In this work, a virtual computational test-bed for building integrated renewable energy solutions is developed using Modelica. This test-bed [4] will help assessing the full scale performance potential of existing products based on pilot scale testing results from the Eindhoven University of Technology (TU/e) campus and simulations which are calibrated using the pilot scale testing measurements.

The pilot scale testing facility is a cooperation known as SolarBEAT [5], which has been established between the TU/e and the Solar Energy Application Centre (SEAC), an independent research organization. The facility is situated on the roof of the Vertigo building, home of the Department of the Built Environment at TU/e and it consists of dummy buildings with building-integrated photovoltaic/thermal (BIPVT) solar collectors.

▶

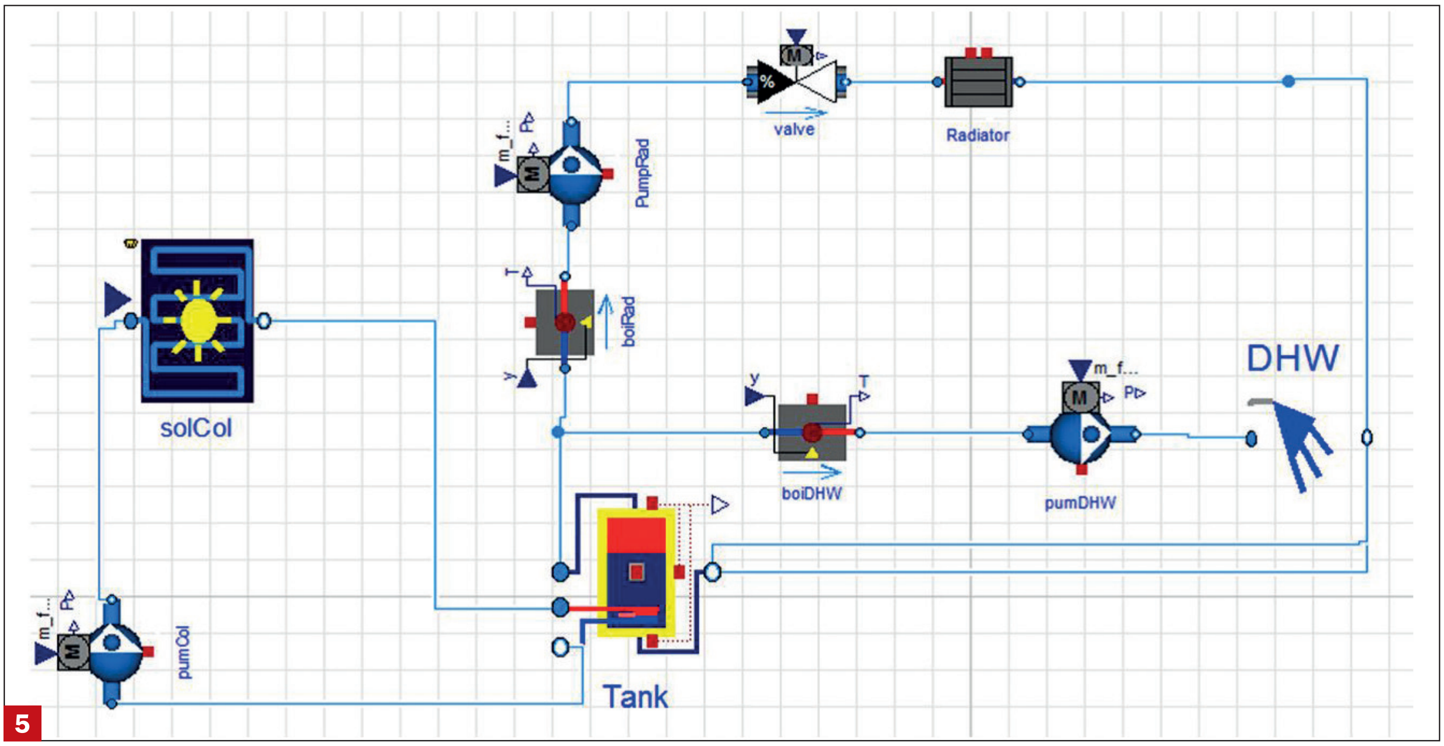
Table 1: Performance analysis of different PV technologies

Solar Panels Type	Thin film	Polycrystalline	Monocrystalline
Annual Energy produced (kWh)	699	1198	1797
Area to match consumption (m2)	50	29,3	19,5



4

Schematic of the PV system model



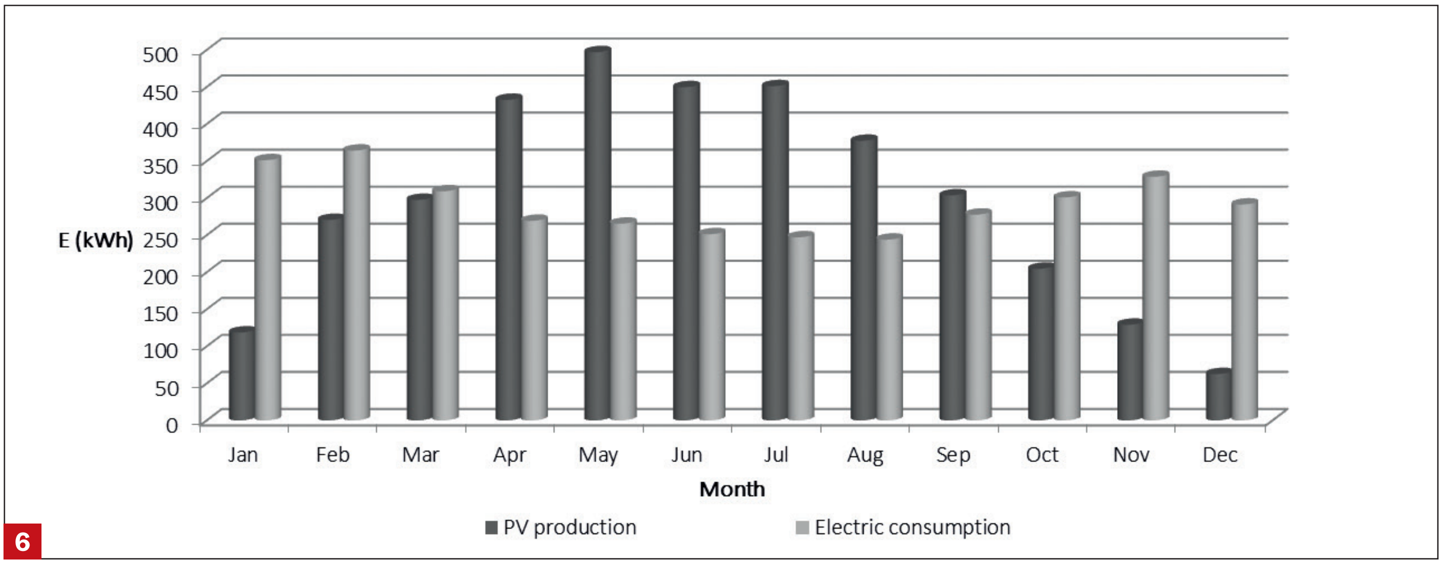
5

Schematic of the Solar-thermal model

Modelica system model

The end product will be a complete building system simulating photovoltaic modules, solar thermal collectors, occupancy, ventilation, infiltration, heating system, domestic hot water demand and heat storage as shown in figure 3.

It helps assessing different technologies in order to predict their performance. Those technologies will consist of BIPVT systems from different companies which are interested in testing their products and predicting their performance. The hardware topic will be part of the Solar-BEAT project installations whereas the software part will be the test-bed developed in this work. This will facilitate



6

Energy production versus consumption of a 20 m^2 monocrystaline PV solution

the calibration and validation of models and will help in the performance prediction for those products with different parameters and geographic locations.

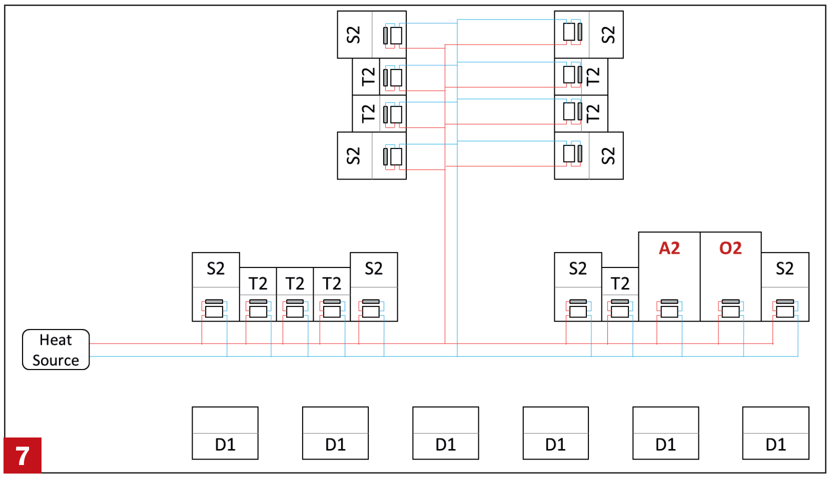
The building is based on a typical Dutch detached single family house [6]. It is assumed that the dwelling has 10 thermal zones: 3 zones at the ground floor including the kitchen, living room and the entrance, 5 zones in the first floor including 3 bedrooms and the second floor/attic which is divided into 2 rooms. The different zones are connected to each other thermally through the common walls and through the doors which can be controlled to be open or closed.

The building is assumed to have 4 occupants. The heat gains for lighting are the same for the whole building and are taken to be 12 W/m2. The heat gains from occupants differ from one room to the other, moreover, they are divided into convective and radiative heat transfer. The infiltration is equal to 0.2 ACH for each zone. The ventilation is a scheduled ventilation which varies from one zone to another. In addition, the domestic hot water demand is taken into account and it is assumed to have a constant flow of 200 L/day.

The Modelica model consists of three major parts: the PV model (figure 4), the solar thermal mode (figure 5) and the house model. The house model is used to model the heating demand of the home. The first two models are used to model the generation of renewable energy for the given location of interest. Using the combined simulation, we are able to analyse the dynamic interaction between the renewable generation systems and the energy demand of the home. The house is heated using typical radiators which are connected to the water heating system.

Results and conclusion

The testbed developed enables energy performance assessments of the demand and supply sides. The energy demand consists of the electric power demand and the heating and cooling demand whereas the energy supply consists of the supply of electric power through the PV and the supply of heat through the solar collectors. Both aspects combined are analysed to assess the feasibility of the total design solution.



7

District Heating system schematic (based on A2.2 Annex 60)

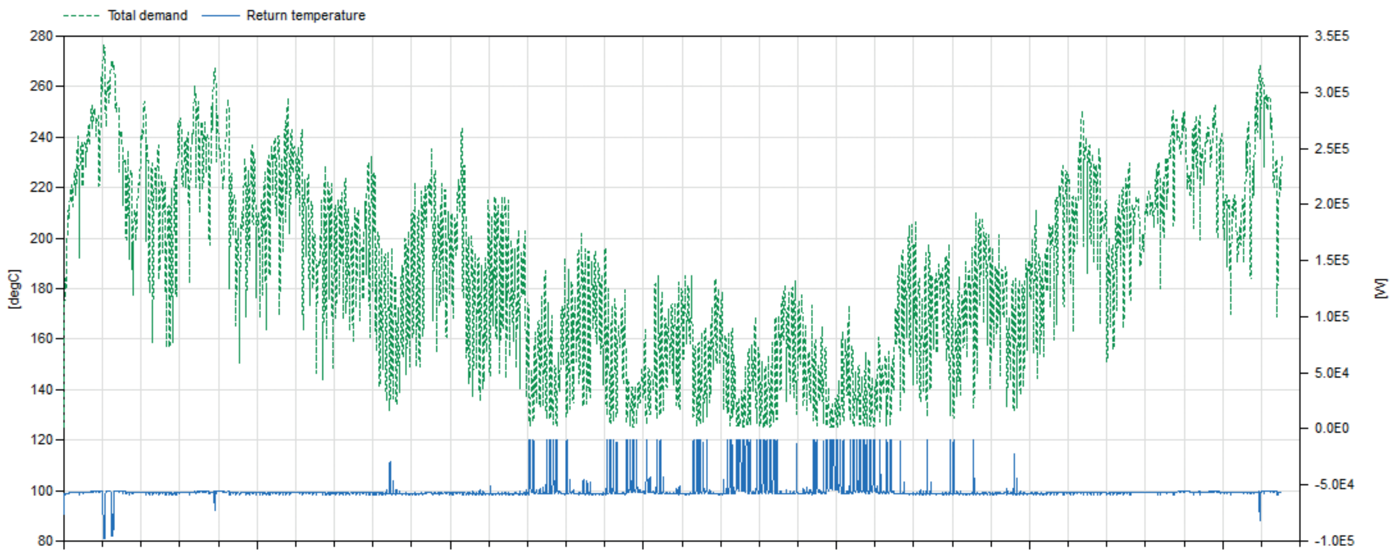
Table 2: Demand results for the Initial district

	Initial district	+6 houses	+12 houses
Peak power demand [kW]	432	482	
Annual E. demand [MWh]	890		
Demand satisfied [% time]	99,9		
Boiler at full charge [% time]	0,2		

In order to achieve annual electric zero energy designs, three different PV technologies were virtually tested. The energy produced and roof area needed to match the building energy demand is presented in table 1.

BIPV solutions and their interactions with buildings can be further investigated. Based on these results, the energy matching of the 20 m^2 monocrystaline solution can be, for instance, studied per month, as illustrated in figure 6.

▶



8

Total DH demand and Return temperature

Table 3: Simulation results obtained for the three demand-response strategies and the baseline operation

	Winter (Feb)			Summer (Aug)		
	Total DH demand (MWh)	Stored energy (MWh)	Storage active (h)	Total DH demand (MWh)	Stored energy (MWh)	Storage active (h)
Basis	293,85	-	-	17,63	-	-
Building	400,41	106,56	124	56,78	39,14	65
Battery	293,85	28,18	58	17,63	23,76	48
Building + Battery	400,25	129,72	124 + 52	55,83	61,51	64 + 47

A solution that is able to satisfy the energy demand on a yearly basis will not necessarily be able to do so when looking at shorter periods of time.

In conclusion, this project has created a testbed for validation and performance assessment of innovative BIPV solutions that supports design improvements as well as accelerates the process leading them to commercialization.

DESIGN OF DISTRICT ENERGY SYSTEMS

Two of the projects that benefit from the use of the Modelica simulation language in the context of the design/retrofit of DES are presented here.

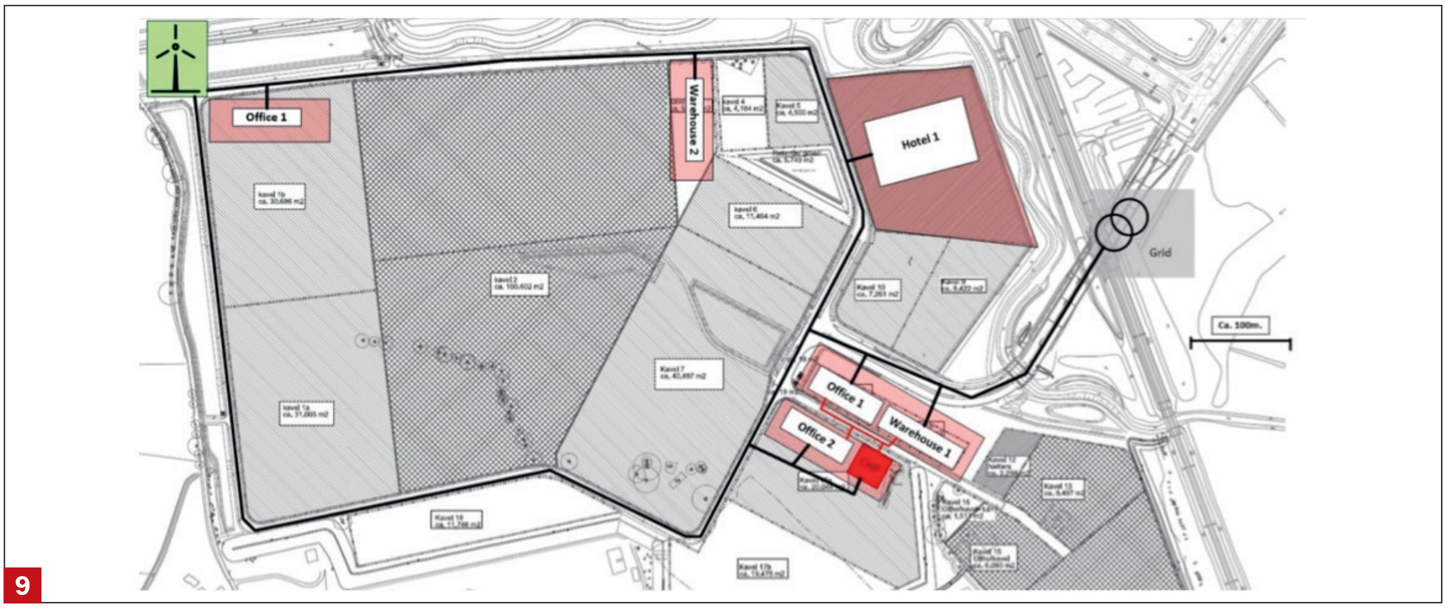
Retrofit solutions for a district heating system expansion

General description

District heating (DH) networks may go through expansions that were not always planned during their design phase. This could be an addition of new demand, supply or even by the connection to other DH systems. In order to allow these systems to achieve more economic and efficient operation, it is imperative that they are designed from the start to enable growth. When this is not the case, it is crucial to assess the feasibility of the district expansion both from a technical and economical perspectives.

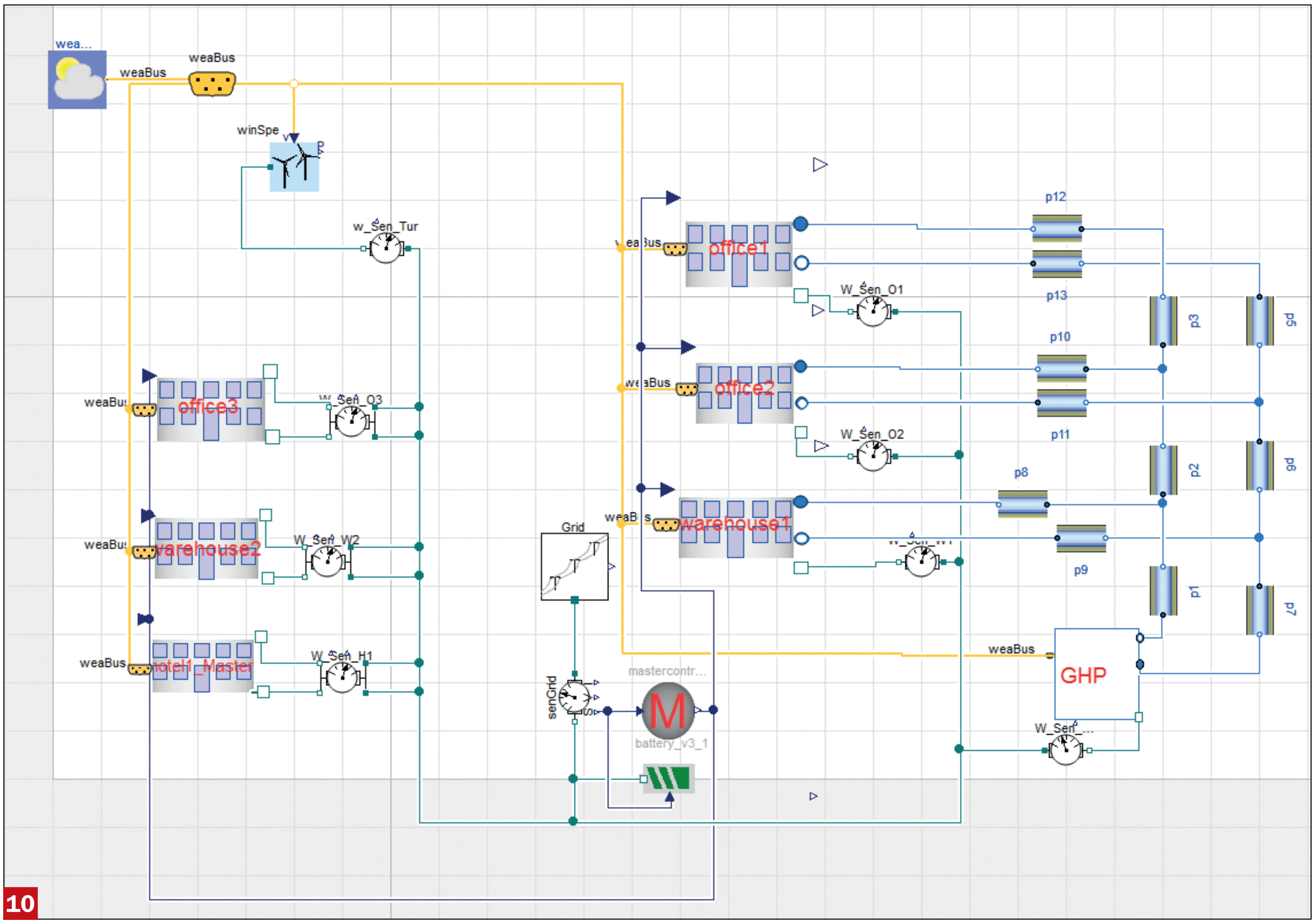
The scope of this research is to investigate the viability of an existing district heating system in the long-term, that is to assess the energy performance of a neighbourhood and evaluate the most cost effective retrofit opportunities (e.g. retrofit of building envelopes, centralized/decentralized thermal storage) so that the existing district system generation and network are able to supply a new group of buildings that will be added to the network. Summarizing, the objective is to find the most cost effective method for extending the existing district heating network while keeping the same generation source and distribution network.

A case-study based on a modified version of the Annex 60, activity 2.2 neighbourhood district, shown in figure 7 will be used for this purpose. The buildings can have two levels of thermal insulation, i.e. (#1) denoting a level of insulation required by the EPB 2010 in Flanders and (#2) denoting a level of insulation similar to the one found on buildings of the period 1946-1970 in Flanders, based on the IEE TABULA project [7]. In this study, the municipality that is the ‘owner’ of the DH network also owns the apartment building (A2) and the office building (O2). They want to extend the network to supply space heating and DHW to the newly built detached houses (D1 × 6) without any change in generation capacity or piping network of the existing system.



9

Schematic of Deventer district energy system



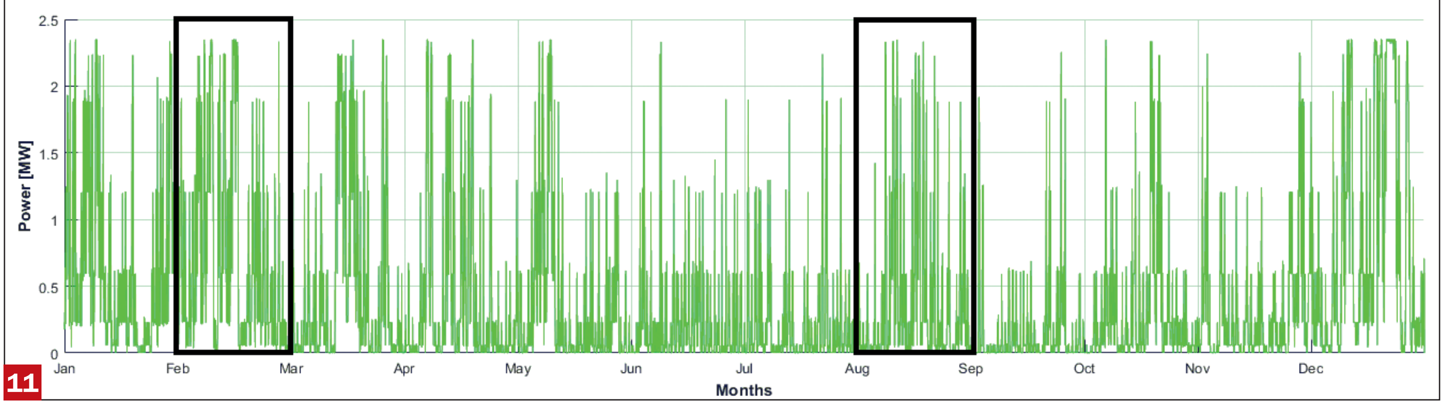
10

Modelica model schematic of the Deventer DES

Objectives

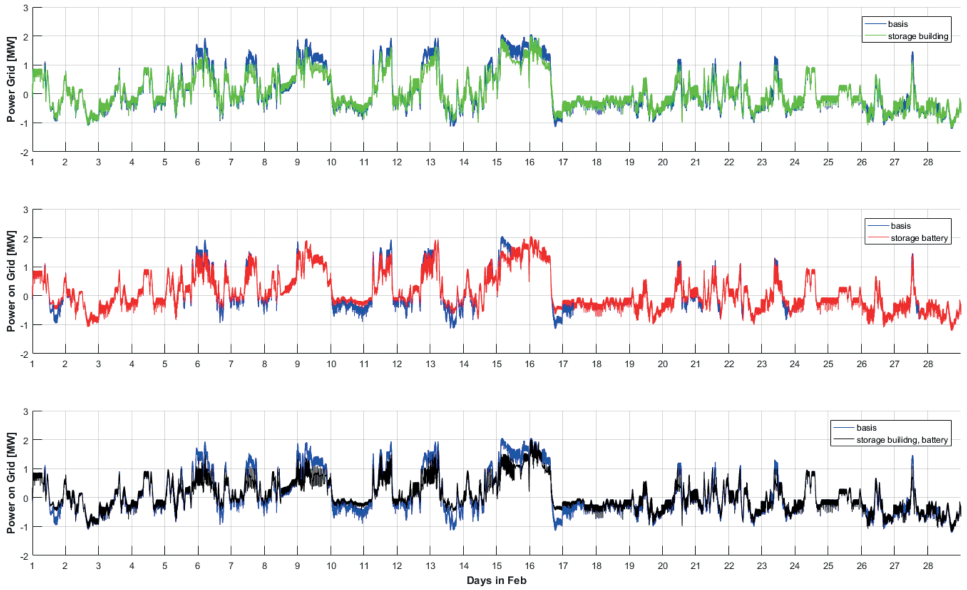
This ongoing research will try to firstly assess if the new buildings can be easily integrated into the existing network with the generation capacity available and understand what issues might occur as a result of an insufficient heat supply. If the energy demand of any of the buildings is not met, a set of retrofit measures applied to the municipality buildings or to the network will be assessed in terms of reliability and cost-efficiency. These retrofit solutions are the following:

- Improving thermal insulation of the building envelope (thermal insulation, windows, etc.) of the municipality buildings (A2, O2).
- Add centralized/decentralized thermal storage.



11

Wind turbine (2,35 MW) yearly generation profile



12

$L_{I;A}$ en $L_{I;A;k}$ in relatie tot vloeroppervlakte (slaapkamer)

Table 4: Reduction of re-delivered energy above 1 MW

% reduced	Building	Battery	Building + Battery
Winter (Feb)	62,8%	36,6%	81,3%
Summer (Aug)	18,5%	59,6%	69,2%

– Use the return water from the higher-temperature distribution network to supply the newly added low energy consumption buildings.

Initial results and future work

Initial results show that the generation capacity of the original DHS is not able to meet the peak power demand required when including six extra detached houses.

The retrofit solutions assessed should be able to flatten the aggregated demand profile of the district so that the new buildings planned can successfully be served by the existing DHS. Finally, a combination of the retrofit strategies described to maximize the number of extra low-energy buildings that could connect to the existing DHS will be evaluated.

Reducing the power peaks re-delivered to the grid by a Renewable District Energy System

General description

Nowadays renewable energy sources are implemented at all stages of the electricity system. The electricity generation from renewable energy sources is of an intermittent nature. Electricity production that is not needed at the time when generated will introduce stress to the grid infrastructure, especially to the connections (i.e. transformer substations) between a district and the public grid. Increased electricity demand [8] in combination with renewable energy production requires investments in the power grid to accommodate these fluctuations. Investments such as transformers with greater capacity are of high cost.

Reducing high peaks on the grid connection to match the power production and consumption is possible through demand response strategies [9]. Peak loads can be shifted for instance, by storing electricity on-site during the time of surplus production to be reused at a later stage when the production is lower than demand. Storing energy on-site could be achieved per building, or centralized for a district.

Objectives and case-study

As a collaboration between TU/e and ENGIE [10], the objective of this project [11] is to reduce the power peaks on the grid connection to a level below 1 MW, assuming that, above this figure an upgrade on the infrastructure of the grid (i.e. increasing transformer's capacity) would be required. For this, the demand-response strategies selected for the study are based on:

- Storing energy on-site by using the buildings thermal mass (passively).
- Electric battery storage (5,4 MWh battery with a peak power of 500 kW).
- Combination of the two above.

The reduction of the power redelivery is analysed in the early-design phase of an all-electric business park with two on-site wind turbines. This case-study considers six buildings (three offices, two warehouses and one hotel); three buildings (Office 1, Warehouse 1 and Office 2) are connected to a district heating system (CHP and red network in figure 9, while the other three buildings are using individual solutions for providing their heating and cooling demand. All these systems are controlled by one master controller with the aim to reduce the peak loads. This configuration is analysed on the reduction of the power peak on the grid connection. Modelica was used to simulate this district energy system (figure 10).

Results and Conclusion

The annual energy production from the two 2,35 MW wind turbines, shown in figure 11, was analysed. Two characteristic periods with high frequency of peaks for the winter and summer periods were extracted.

Looking a bit more in detail at the winter period extracted (February) we can depict from the district model results how the simulated strategies are activated when the power re-delivered is greater than 1 MW, and their potential to reduce these power peaks. This is shown for the whole month in figure 12.

The results obtained from the simulation of the DES model in table 3
If we analyse the effect of the strategies simulated with respect to the reduction of the power peaks re-delivery, we can observe in table 4 that the significant thermal potential of the passive storage strategy in winter combined with active electric storage in summer is able to reduce the electricity re-delivered to the grid above 1 MW in a 81,3%

While using the mass of the building as thermal storage, a more detailed analysis of the comfort implications is needed to minimize possible overheating as well as to better design the control strategy. For the case-study analysed, it is expected that new additional buildings will be added to the district, although this will reduce the power peaks that are re-delivered to the grid, the model developed will allow the analysis of strategies to maximize the use of on-site energy generation.

CONCLUSION

The projects presented in this article, based on research in the context of Building and District energy systems, benefited from the Modelica simulation language through its comprehensive hierarchical structure, available libraries of components for various domains and the capacity to rapidly modify or create new models. Furthermore, the multi-domain nature of the language is able to effectively assist in these combined thermal-electric-logic(controls) problems.

Acknowledgements

We gratefully acknowledge the financial support by the Netherlands Enterprise Agency (RVO.nl) which enabled us to participate in this IEA ECB Annex.

We are also thankful to our colleagues John Bynum, Roel Loonen, Jad Al Koussa, Frank Soons, Tomas Pimentel, Fabio Batista, Carine Tran and Luis Ferreira whose contribution and expertise greatly assisted the research. ■

REFERENCES

▶ **[1]** Annex 60, http://www.iea-annex60.org
▶ **[2]** Modelica Association, Modelica-A unified object oriented language for physical system modeling
▶ **[3]**Wetter, M., Treeck, C. Van & Hensen, J., 2013, New generation computational tools for building and community energy systems
▶ **[4]** Koussa, J. A., 2014, Virtual Computational Testbed for Building-Integrated Renewable Energy Solutions, Building Physics and Services, Eindhoven University of Technology
▶ **[5]** SolarBEAT, http://www.sre.nl/projecten/energietransitie-in-de-brainportregio/gebouwdeomgev ing-zon/solarbeat
▶ **[6]** PRC B.V W/E adviseurs, Voorbeeldwoningen 2011-bestaande bouw, Brochure, Agentschap NL-NL Energie en Klimaat, January 2011
▶ **[7]** IEE Project TABULA, 2009 – 2012, "Typology Approach for Building Stock Energy Assessment", http://episcope.eu/index.php?id=169
▶ **[8]** EIA, 2013, EIA project world energy consumption will increase 56% by 2040, U.S. Energy Information Administration, Retrieved January 25, 2016, from http://www.eia.gov/todayinenergy/detail.cfm?id=12251
▶ **[9]** Mengmeng, Y., Seung, H.H., 2016, Supply-demand balancing for power management in smart grid: A Stackelberg game approach, Journal of applied enegery, vol 164, pp. 702-710, February 2016
▶ **[10]** ENGIE Netherlands, Business development division, http://www.engie.nl/
▶ **[11]** Hofstede, J., 2016, Reducing power peaks from renewable energy sources on the grid connection, Building Physics and Services, Eindhoven University of Technology