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Demonstration of the new ESP-r and TRNSYS co-simulator for modelling solar buildings

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Abstract

The pursuit of innovative architectural designs and the development of novel and integrated energy conversion, storage, and distribution technologies presents a challenge for existing building performance simulation (BPS) tools. No single BPS tool offers sufficient capabilities and the flexibility to resolve all the possible design variants of interest. The development of a co-simulation between the ESP-r and TRNSYS simulation tools has been accomplished to address this need by enabling an integrated simulation approach that rigorously treats both building physics and energy systems. The capabilities of this new modelling environment are demonstrated in this paper.

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Keywords: building performance simulation, co-simulation, ESP-r, TRNSYS

1. Introduction

1.1. Motivation

The pursuit of zero-energy buildings [see 1, for definitions] is leading to more innovative architectural designs and is driving the development of novel energy conversion, storage, and distribution technologies. Increasingly, renewable energy systems are being exploited and energy systems are being integrated with the architecture of the building, such as with building integrated photovoltaic/thermal systems [see 2, for example]. These rapid innovations present challenges for the building industry. The accurate analysis of the energy benefits of these integrated designs and concepts requires the meticulous simulation of both the building physics and the performance of energy conversion, storage, and distribution systems. Furthermore, greater interaction between the building's architecture, occupancy, and energy systems means that it is not sufficient to treat each modelling domain disparately; rather, the entire system must be treated simultaneously and in an integrated manner. Simply put, integrated building designs require integrated modelling approaches.

Although building performance and energy systems simulation methods and tools have been under development for over four decades, the capabilities of existing tools cannot respond to the needs elaborated above. As argued by [3], no single tool offers sufficient capabilities and the flexibility to enable the rapid

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prototyping of innovative building and system technologies. State-of-the-art building performance (BPS) simulation tools such as ESP-r possess strengths in modelling building physics; but are less flexible in the treatment of innovative mechanical, electrical, and renewable energy systems. In contrast, tools such as TRNSYS, which was originally developed for modelling renewable energy systems, possess a structure and suite of component models that facilitate the simulation of renewable and other energy systems; but are less precise in treating building physics.

The run-time coupling (also known as co-simulation) of complementary tools such as ESP-r and TRNSYS offers the possibility of an integrated simulation that rigorously treats both building physics and energy systems.

1.2. Previous work

Numerous authors have investigated the coupling of simulation programs. In many of these previous works, the simulation programs have been coupled at the source-code level. With this, the source code from one simulation program is integrated into a host simulation program. Examples include: the integration of COMIS into TRNSYS [4]; the integration of COMIS into EnergyPlus [5]; the incorporation of some TRNSYS types (e.g. solar thermal collector) into ESP-r [6]; the adaptation of ESP-r micro-cogeneration models into TRNSYS [7]; and the development of a wrapper to enable compilation of individual TRNSYS types into ESP-r's plant domain [8].

As an alternative to integrating at the source code level, two simulation programs can be linked at run-time to exchange information as they march through time. This technique, which relies on the exchange of data between separate executables, has been referred to as co-simulation or external coupling [3]. In most instances of co-simulation to date, one simulation program serves as the master and controls the co-simulation while the other serves as its slave. Examples of such co-simulations include: the integration of Radiance with ESP-r [9]; FLUENT with ESP-r [10]; and TRNSYS and EnergyPlus [3].

Another approach to the direct coupling of two simulation programs, one which does not impose a master-slave architecture, has been proposed [11]. In the Building Controls Virtual Test Bed (BCVTB), a middleware manages the data exchange between different simulators, with each simulator acting as a client. The BCVTB's flexible design enables clients to operate on different computers and to exchange data with the middleware via the internet. The BCVTB offers numerous advantages over the direct coupling of two simulation programs. Despite these advantages, however, the BCVTB's flexible middleware design imposes a significant restriction in the control of convergence: no iteration between the clients is possible within a time-step. Hence, it is limited to co-simulation with what is referred to in the literature as *loose* coupling or *ping-pong* coupling [3].

1.3. Objectives and outline of paper

A design has been conceived and implemented to enable a co-simulation between the ESP-r and TRNSYS simulation programs [12, 13]. This exploits the strengths of both simulation tools to enable the modelling of innovative building and energy system configurations more accurately than either simulation program could achieve on its own. In this co-simulation, ESP-r treats the building domain, and potentially a portion of the mechanical and electrical energy systems; and TRNSYS resolves all or a portion of the mechanical and electrical energy systems. Importantly, the design enables the collaboration between ESP-r and TRNSYS in modelling HVAC systems through the exchange of data within the time-step, an approach that is referred to as *strong* or *onion* coupling in the literature.

A multi-threading approach has been employed in the interests of computational speed and the co-simulation is controlled by a newly developed middleware called the *Harmonizer*. The Harmonizer is responsible for communicating data between ESP-r and TRNSYS, for assessing overall system convergence, and for controlling marching through time. The Harmonizer is freely distributed through an OpenSource license. The modifications to ESP-r to effect the co-simulation have been incorporated into the main release of that software, which is also freely distributed under an OpenSource license. Licensed TRNSYS users can access an updated version of that software that supports co-simulation with ESP-r while these features will be made more widely available when they are incorporated into the general release of TRNSYS in the near future.

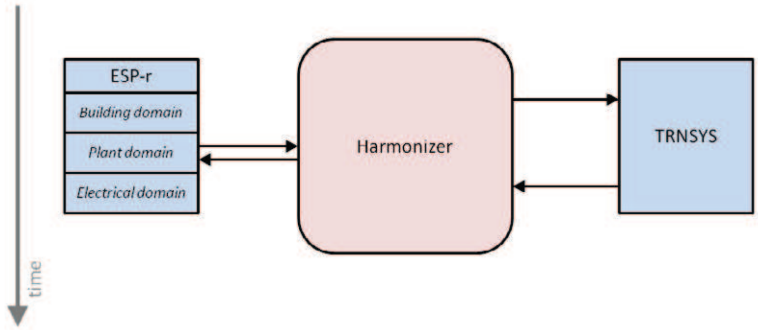

Fig. 1. Co-simulation program flow

Previous papers [12, 13] described the design and implementation of the co-simulator and demonstrated its application through a series of simple tests. The current paper complements this material by demonstrating how these new modelling capabilities can be used to simulate the performance of solar buildings.

2. Co-simulation between ESP-r and TRNSYS

There are significant differences in the simulation methodologies employed by ESP-r and TRNSYS. The interested reader is referred to [12] for a synopsis of each BPS tool's methods. A design was conceived that builds upon the strengths of each tool and allows each to exist and independently evolve.

Figure 1 illustrates the program flow. The Harmonizer controls the overall simulation, instructing each BPS program to march through time in a synchronous fashion. ESP-r employs a partitioned solution approach wherein customized solvers are employed for each modelling domain, e.g. building thermal, nodal air flow, plant (HVAC), electrical, etc. Once its plant domain has converged a solution for the current time-step, it communicates data to the Harmonizer through new plant components that have been designed for this purpose. The Harmonizer then passes these data to TRNSYS, where they are received by a new type, Type 130. Through TRNSYS's standard input-output mapping approach, these data are then communicated to the normal TRNSYS types and the TRNSYS simulation proceeds as usual for the given time-step. However, before the Harmonizer allows ESP-r and TRNSYS to march forward in time, it assess the state of data passed between the two simulators. If it concludes that these data have not stabilized, it imposes further *invocations*[1] within the time-step, as elaborated in [12] and [13].

With this design, the user creates models using both the ESP-r and TRNSYS interfaces and then invokes the co-simulation using the Harmonizer. As such, the user does not interact with the graphical interfaces of the ESP-r and TRNSYS simulators in the usual fashion to launch the simulations. Consequently, the user cannot examine the progress of the simulation through the *monitoring* function of ESP-r's Building and Plant Simulator module, or through TRNSYS's *online plotter* types. Rather, the Harmonizer invokes each simulator through a command window such as the Windows CMD prompt or a Cygwin xterm (see Figure 2). Each simulator can be configured to produce output files for post-simulation analysis.

The next section describes a case study that is used to demonstrate the use of the ESP-r / TRNSYS co-simulator.

3. Case study

This section demonstrates how simulations can be configured with the new facility and how its capabilities can be exploited for a highly resolved treatment of solar buildings. The focus is a detached low-energy

[1]Each simulator is forced to rewind its solution to the beginning of the time-step and repeat its solution process with the newly passed data from the other simulator.

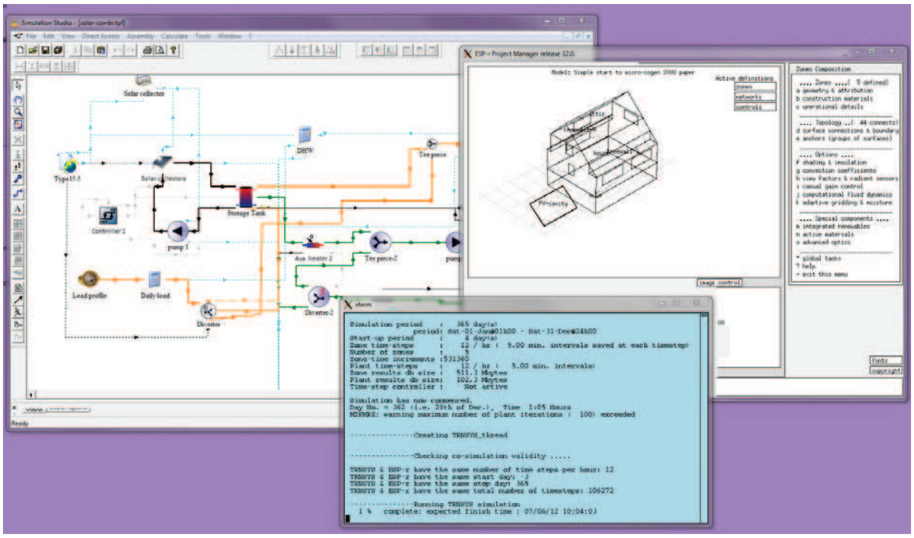

Fig. 2. Co-simulation session: model inputs created through ESP-r and TRNSYS interfaces with a co-simulation running in a Cygwin xterm

house served by a solar-thermal combination space heating and hot water system (solar combi-system), and by a photovoltaic/thermal (PV/t) system.

The house has about 140 m^2 of floor area in its $1\frac{1}{2}$ above-ground storeys and is built upon a full-height 80 m^2 basement foundation (see top right of Figure 2). It has a wood-framed construction with 140 mm of fiberglass insulation between the wood studs and an additional 25 mm of polystyrene insulation behind the cladding. A similar level of insulation is placed upon the internal surface of the basement's concrete walls. The ceiling under the pitched roof is insulated with 210 mm of loose-fill fiberglass while the basement floor is uninsulated. The house contains 23.1 m^2 of clear double-glazed windows, 40% of which is south-facing.

A schematic representation of the active solar systems is shown in Figure 3. (Note that tempering valves are not shown here for the sake of clarity.) A 600 L water tank with two immersed heat exchangers serves as the system's thermal store. Domestic hot water needs are met by drawing water from the top of the tank (black loop in figure); cold make-up water is supplied through a port at the base of the tank. The tank is charged through a 20 m^2 array of evacuated tube solar-thermal collectors through an immersed heat exchanger located near the bottom of the tank (red loop).

Air is circulated through the cavity formed behind a 15 m^2 PV/t array to cool the panels (this increases electrical conversion efficiency) and to capture thermal energy (green loop). This thermal output from the PV/t array is transferred to the house through an air-to-air heat exchanger that has return air from the house circulating over its cold side (house air supply loop shown in orange). Once the return air is warmed by the PV/t system (if energy is available), it passes over a water-to-air heat exchanger to extract energy from the solar-thermal system (blue loop). The warmed air is then supplied to the house to provide space heating.

Auxiliary electric-resistance heaters are located in the black and blue loops to meet thermal demands when the tank's state of charge is insufficient.

It is worth noting that this system has not been optimized for the house, nor is it implied that its configuration is the most appropriate for a solar house. Rather, it is used here simply to demonstrate the new modelling capabilities that are afforded by the ESP-r / TRNSYS co-simulator.

4. Co-simulation model of case study

As mentioned earlier, with the co-simulation it is ESP-r that treats the building domain. Consequently, an ESP-r model was configured to represent the building's geometry and the thermal characteristics of the

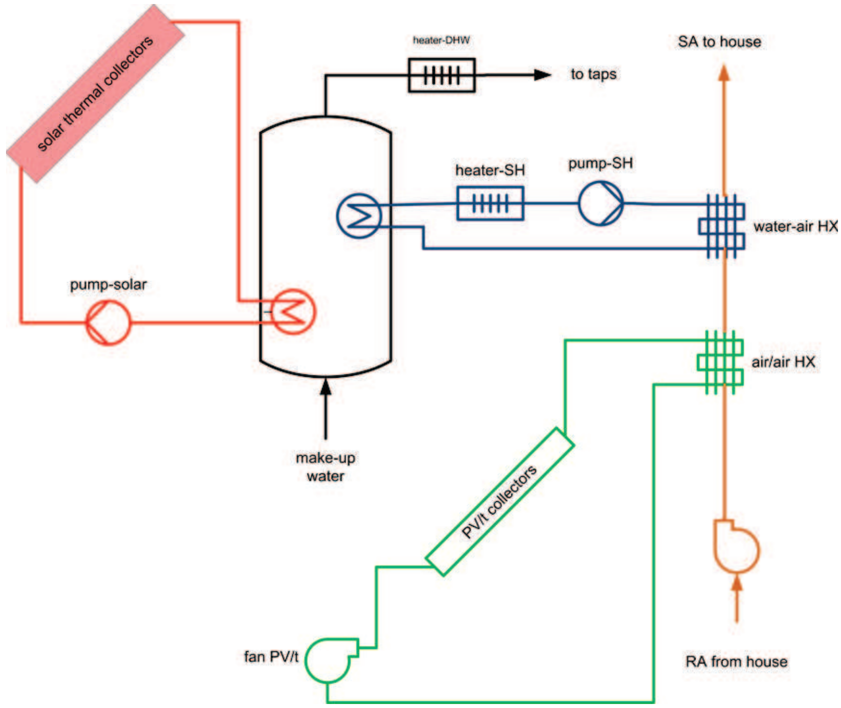

Fig. 3. Schematic of solar-thermal and PV/t system supplying space and DHW heating

building envelope (see top right of Figure 2). Air infiltration due to stack and wind pressures was modelled using ESP-r's optional AIM-2 model [14] using airtightness and leakage areas typical of low-energy houses. The below-grade heat transfer was treated using ESP-r's optional BASESIMP model [15].

It is possible for ESP-r and TRNSYS to cooperatively model the mechanical and electrical systems. With this, some components are treated in ESP-r while others by TRNSYS and data is exchanged between the simulators to predict the performance of the complete system and its interaction with the building. For this demonstration, it was decided that ESP-r would treat the PV panels using its WATSUN-PV model (see, for example, [16]). With this, the electrical output of the array is calculated as a function of irradiance as well as the temperature of the panel. ESP-r resolves the energy balance[2] between the incoming solar radiation and the convective heat transfer resulting from the air motion imposed by the fan (refer to green loop of Figure 3) to establish the temperature of the PV array.

For this demonstration, ESP-r also models the two fans and the water-air heat exchanger. The components of the active solar and thermal distribution system that are modelled by ESP-r are shown in red in Figure 4.

The components that are modelled by TRNSYS are shown in blue in Figure 4. TRNSYS models the solar-thermal collectors using Type 1, the water tank using Type 534 from the TESS libraries, and the pumps using Type 3. Although now shown in Figures 3 and 4, TRNSYS Type 11 is used to model the flow diverters and mixers for tempering the water streams. The air-to-air heat exchanger is modelled in TRNSYS using Type 91 and the damper control that ensures that heat is only transferred from the PV/t loop to the house (and not the opposite) is also accomplished in TRNSYS through a user-defined equation and Type 11 components.

Controllers are established within the TRNSYS network to control the components treated by TRNSYS

[2] All other significant modes of heat transfer are considered in this balance, such as longwave radiation to the sky, convective heat transfer to the outdoor air, and transient conduction in the PV array and supporting structure.

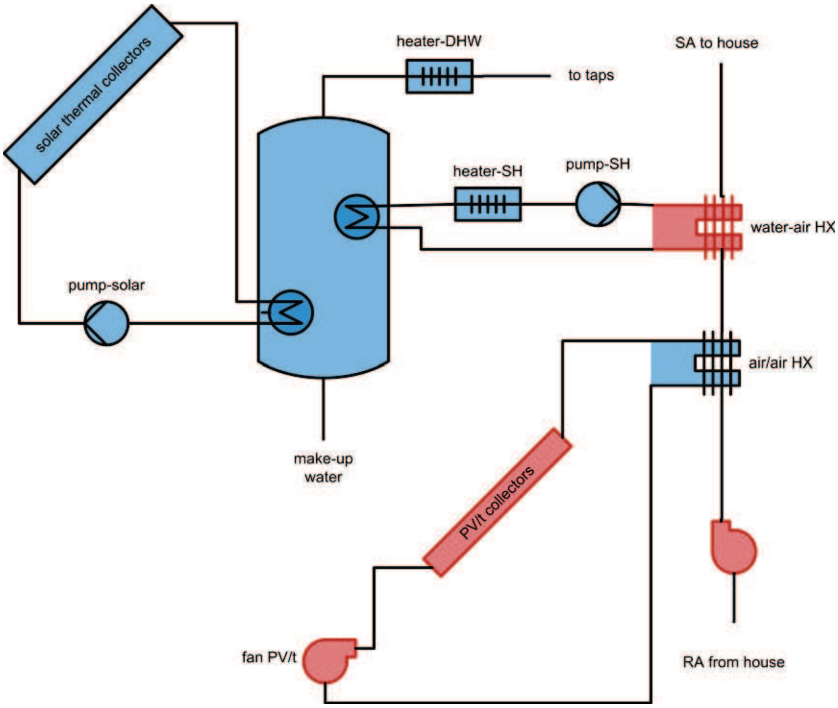

Fig. 4. Cooperative simulation of system by ESP-r (components shown in red) and TRNSYS (components shown in blue)

(although these also sense thermal conditions predicted by ESP-r). Likewise, the fans modelled by ESP-r and controlled by ESP-r.

From the user's perspective, the co-simulation is first configured by creating separate models in ESP-r and TRNSYS (see Figure 2). A TRNSYS network was created using the Studio; types corresponding to the blue components in Figure 4 were added and connected in the usual manner. The new Type 130 was also added to the network to support the coupling to ESP-r and this type was connected to the other types, as can be seen in Figure 5. For example, consider the pump that circulates hot water from the tank and auxiliary heater to the water-air heat exchanger in Figure 4. This is represented in TRNSYS by a connection from *pump-SH* to Type 130 in Figure 5. And the cooled water returning from the water-air heat exchanger is represented in TRNSYS by a connection from Type 130 to the tank.

The model of the house was constructed with ESP-r's Project Manager interface in the usual manner, and a plant network configured to represent the red components in Figure 4. The new plant components designed for coupling with TRNSYS were then inserted and connected to the other components. Consider again the pump that circulates hot water from the tank and auxiliary heater to the water-air heat exchanger. From ESP-r's perspective, this is seen as a stream of hot water that is received from TRNSYS. The new *hydronic coupling component* was added to the ESP-r plant network to represent this stream of hot water and it was connected to ESP-r's water-air heat exchanger. This can be seen in Figure 6, where the coupling component has been labelled *HCC-R-1* (any label can be provided by the user) and the heat exchanger has been labelled *water-air-HX* (see second yellow highlight). Another hydronic coupling component is used to return the cooled water stream to TRNSYS (first yellow highlight in figure).

The PV/t system is handled in a similar manner. Recall that ESP-r is sending two streams of air to TRNSYS (see Figure 4): return air from the building's convective heating system and warm air from the PV/t heat recovery system. These streams originate from thermal zones in ESP-r and are communicated to TRNSYS through two instances of ESP-r's new *air coupling component*. These streams are received in TRNSYS by Type 130 where they are directed to the cold and hot sides of the air-to-air heat exchanger (see

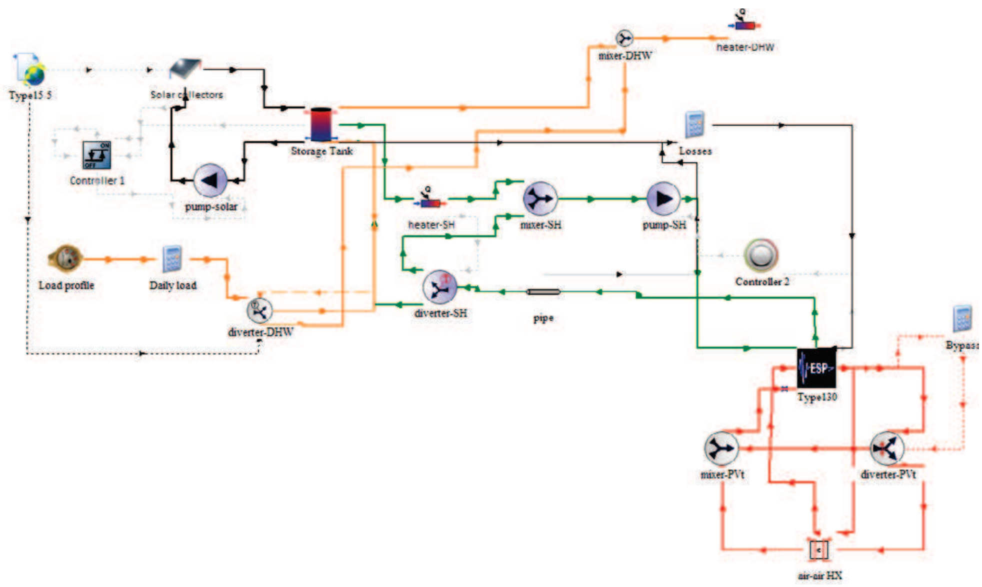

Fig. 5. TRNSYS network including Type 130 for coupling to ESP-r

the red loop in Figure 5), respectively. A user-defined equation (labelled *Bypass* in Figure 5) receives the temperatures of these air streams from ESP-r and takes a control decision for the bypass valve to determine whether or not the PV/t system can supply heating at the current time-step. Once the heat exchange between the air streams has taken place, TRNSYS returns the two streams to ESP-r via Type 130 and the Harmonizer, where they supply two more instances of ESP-r's *air coupling component*.

5. Simulation results

A co-simulation of the house and its system was conducted by invoking the Harmonizer (see Figure 2). In this case, the simulation was performed for a full year (plus 4 start-up or conditioning days) at a time-step of 5 minutes using Ottawa CWEC weather data [17]. Each simulator produced its own results files for the portions of the model it was responsible for.

Some representative examples of these simulation results are presented here to demonstrate the types of analyses that have been enabled by the new co-simulator. Two representative winter days were selected for this purpose: February 6 and 7.

Figure 7 illustrates how the system is able to condition the house, whose air-point temperature is plotted in the graph. The oscillations in the house temperature in the hours of darkness are a result of the deadband control on *pump-SH*, which cycles on to deliver energy from the solar-thermal and auxiliary heating system in response to the house temperature. The thermal contribution of the PV/t system can also be seen in this figure. During the sunrise hours, the air delivered by the PV/t system to the air-air heat exchanger rises and the impact upon the building can be seen by a slight overshoot of the house's air-point temperature. The rise in the PV/t air temperature is closely related to the system's electrical production, as expected.

The contribution of solar energy to heating the house is illustrated in Figure 8. This plots the instantaneous passive solar gains through windows, the thermal energy contributed to the house by the PV/t system, as well as the energy transferred to the house from the solar-thermal loop (note that the latter also includes the contribution of the auxiliary heater *heater-SH*. As can be seen, on these two winter days the contribution of the PV/t system is limited to a couple of hours each day, centred around noon. The input from the solar-thermal loop cycles in response to the deadband control and is only called upon during the hours of darkness when there are no passive solar gains or input from the PV/t system.

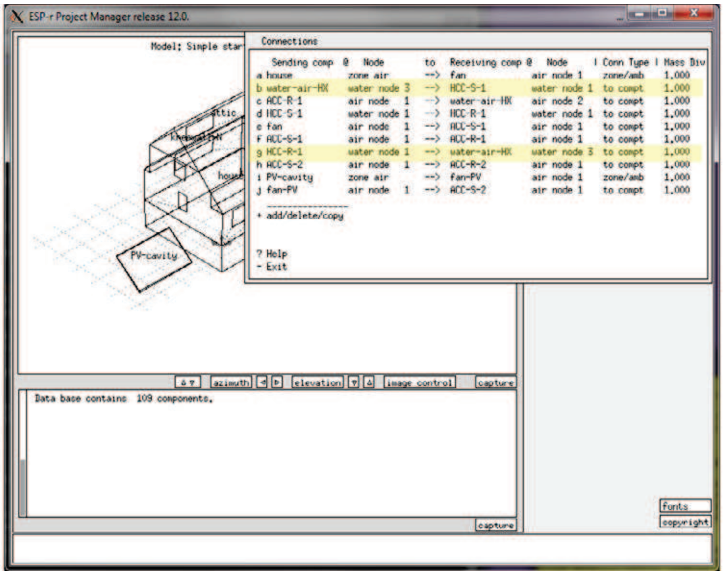

Fig. 6. ESP-r plant network connections including couplings to TRNSYS

Figure 9 plots the performance of the system on these two days from the perspective of the water tank. The evolution of the temperature profile in the tank is shown (see left-hand vertical axis). As can be seen, the temperature at the the top (node-1), middle (node-2), and bottom (node-3) of the tank rises to 90^{o}C following periods of solar gain in the absence of loads. The controller in the TRNSYS network was configured to stop the pump when this condition occurs, reducing the system's ability to capture solar energy. The energy added to the tank by the solar-thermal collectors is also plotted (see right-side vertical axis) as are the thermal demands placed on the tank by the DHW and space-heating systems. Over these two days, the amount of energy added to the tank by the solar collectors equals 72% of the amount of energy extracted to supply the DHW and space-heating loads. Clearly, a greater solar contribution could have been realized on these days if the storage tank had more capacity, thus preventing the tank temperature from reaching its high-limit cut-out.

6. Conclusions

This paper has demonstrated how the newly developed ESP-r / TRNSYS co-simulator can be applied by focusing upon a case study of a low-energy building serviced by a solar-thermal and PV/t system. It has shown how this co-simulation environment is an effective tool for studying and designing solar buildings, particularly when architectural and energy conversion and storage systems are integrated.

The design of the co-simulator exploits the strengths of both simulation tools to enable the modelling of innovative building and energy system configurations more accurately than either simulation program could achieve on its own. ESP-r treats the building domain, and potentially a portion of the mechanical and electrical energy systems; and TRNSYS resolves all or a portion of the mechanical and electrical energy systems. Importantly, the design enables the collaboration between ESP-r and TRNSYS in modelling HVAC systems through the exchange of data within the time-step, an approach that is referred to as *strong* or *onion* coupling in the literature.

The co-simulation is managed by a new program called the Harmonizer. Development of the Harmonizer is complete and this tool is now freely available under an OpenSource license. Likewise, the changes to ESP-r to effect the co-simulation are now available in the general release of that OpenSource tool (as of Version 12.0). Licensed TRNSYS users can now acquire a package for Version 17.1 to add support for the co-simulation and the next general release of that tool will include the co-simulation features.

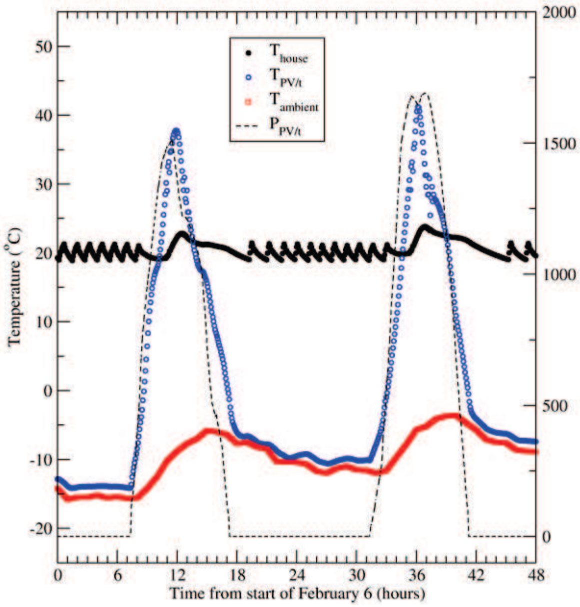

Fig. 7. Air temperature in house and in PV/t system over two days in February

References

[1] A. Marszal, P. Heiselberg, J. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero energy building - a review of definitions and calculation methodologies, Energy and Buildings 43 (4) (2011) 971–979.

[2] M. D. Bazilian, F. Leenders, B. Van der Ree, D. Prasad, Photovoltaic cogeneration in the built environment, Solar Energy 71 (1) (2001) 57 – 69.

[3] M. Trčka, J. L. Hensen, M. Wetter, Co-simulation of innovative integrated HVAC systems in buildings, Journal of Building Performance Simulation 2 (3) (2009) 209–230.

[4] V. Dorer, A. Weber, Air, contaminant and heat transport models: integration and application, Energy and Buildings 30 (1) (1999) 97–104.

[5] J. Huang, F. Winkelmann, F. Buhl, Linking the COMIS multi-zone airflow model with the EnergyPlus building simulation program, in: Proc. Building Simulation '99, Kyoto Japan, 1999, pp. 1065–1070.

[6] E. Aasem, Practical simulation of buildings and air-conditioning systems in the transient domain, Ph.D. thesis, University of Strathclyde, Glasgow UK (1993).

[7] I. Beausoleil-Morrison (Ed.), An Experimental and Simulation-Based Investigation of the Performance of Small-Scale Fuel Cell and Combustion-Based Cogeneration Devices Serving Residential Buildings, IEA/ECBCS Annex 42 Report, 2008.

[8] W. Wang, I. Beausoleil-Morrison, Integrated simulation through the source-code coupling of component models from a modular simulation environment into a comprehensive building performance simulation tool, Journal of Building Performance Simulation 2 (2) (2009) 115–126.

[9] M. Janak, Coupling building energy and lighting simulation, in: Proc. Building Simulation '97, Vol. II, 1997, pp. 313–319.

[10] E. Djunaedy, External coupling between building energy simulation and computational fluid dynamics, Ph.D. thesis, Technische Universiteit Eindhoven, Eindhoven Netherlands (2005).

[11] M. Wetter, Co-simulation of building energy and control systems with the building controls virtual test bed, Journal of Building Performance Simulation 4 (3) (2010) 185–203.

[12] I. Beausoleil-Morrison, F. Macdonald, M. Kummert, T. McDowell, R. Jost, A. Ferguson, The design of an ESP-r and TRNSYS co-simulator, in: Proc. Building Simulation 2011, Sydney, Australia, 2011, pp. 2333–2340.

[13] F. Macdonald, R. Jost, I. Beausoleil-Morrison, M. Kummert, T. McDowell, A. Ferguson, A demonstration of the run-time coupling between esp-r and trnsys, in: Proc. SimBuild 2012, Madison, USA, 2012.

[14] I. Walker, D. Wilson, Field validation of algebraic equations for stack and wind driven air infiltration calculations, J HVAC&R Research 4 (2) (1998) 119–139.

[15] I. Beausoleil-Morrison, G. Mitalas, Basesimp: A residential-foundation heat-loss algorithm for incorporating into whole-building energy-analysis programs, in: Proc. Building Simulation 1997, Proc. Building Simulation 1997, Prague Czech Republic, 1997, pp. II.1–8.

[16] I. H. Rowlands, B. P. Kemery, I. Beausoleil-Morrison, Optimal solar-PV tilt angle and azimuth: An Ontario (Canada) case-study, Energy Policy 39 (2011) 1397–1409.

[17] Environment Canada, Canadian weather for energy calculations user's manual, Tech. rep., Toronto (2008).

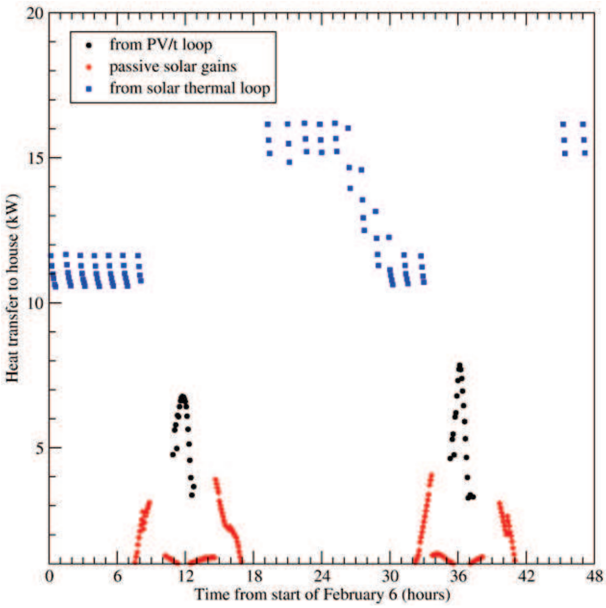

Fig. 8. Solar thermal, PV/t, and passive solar input to house over two days in February

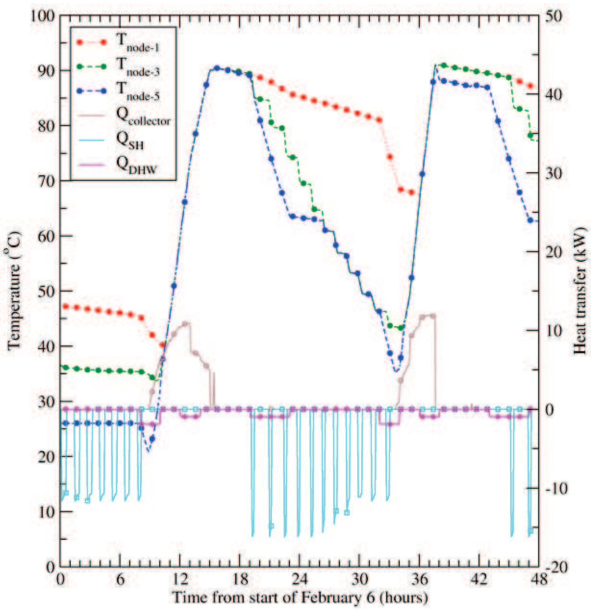

Fig. 9. Storage tank temperatures and energy flows over two days in February