Optimal Control Based on Deep Learning Techniques for a Hybrid Solar-Biomass System for Residential Buildings

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Abstract

The EU-funded H2020 project SolBio-Rev aims to develop an energy system based on the use of solar energy and biomass with the objective to increase the share of renewable energy needed to meet heating, cooling, domestic hot water, and electricity demand in buildings. In this study, deep reinforcement learning techniques were applied for a SolBio-Rev system designed for a residential building (multi-family house) located in a Mediterranean climate in order to define an optimal control policy able to minimize the operating cost during summer and winter. Results showed that the smart control is able to reduce the cost of operation during summer compared to a standard rule-based strategy. Nevertheless, in winter the operating cost results slightly higher suggesting a further optimization for future studies.

Keywords: Deep reinforcement learning, optimal control, smart control, modeling, residential buildings, hybrid energy systems, biomass

1. Introduction

The reduction of energy consumption in buildings and the production of energy through efficient systems based on renewables are fundamental actions to achieve a substantial reduction of gas emission to the atmosphere. Indeed, buildings are responsible for almost 40% of the overall energy consumption and gas emission into the atmosphere (IEA, 2019), therefore immediate actions are needed. Energy systems that can integrate more renewable sources can overcome the problem of their intermittency providing high flexibility and increasing the total share of renewables in buildings. In the framework of the EU-funded H2020 project SolBio-Rev, an energy system based on the use of solar energy and biomass is being developed to provide heating, cooling, domestic hot water, and electricity to different building typologies located in different climates. The novel system developed combines different technologies including a reversible organic Rankine cycle (ORC)/heat pump, solar collectors with thermoelectric generators, and a biomass boiler. The potential of this system to achieve a 100% share of renewable was studied in (Palomba et al., 2020) and (Palomba et al., 2021) in both residential and non-residential buildings located in different EU climates.

In order to achieve the maximum efficiency of energy systems, the implementation of an optimal control is essential. Different control strategies can be found to manage energy systems. One of the techniques which gained attention recently is Model Predictive Control (MPC). However, one of the main constraints of this technique is the need of specialized solvers to find optimal solutions, which are limited to certain type of non-linarites. Amongst other techniques, Deep Reinforcement Learning (DRL) was proved to be a successful technique for solving complex control problems that is gaining interest in the field of energy system. In literature, it is possible to find DRL architectures approximating MPC on complex systems, or DRL algorithms that successfully control an HVAC (heating, ventilation, and air conditioning) system for a given user comfort requirement (Wei et al., 2017). A DRL architecture was also implemented in a previous study by the authors (Zsembinszki et al., 2021) to deal with the complexity of an innovative hybrid energy storage system and to develop high-level control policies that minimize the operating cost of the system. In this study, the same DRL techniques were applied for a SolBio-Rev system designed for a residential building located in a Mediterranean climate in order to build an optimal control policy that can minimize the operating cost during summer and winter.

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Selection and/or peer review under responsibility of Scientific Committee
doi:10.18086/eurosun.2022.16.15 Available at http://proceedings.ises.org

2. Methodology

The SolBio-Rev system optimized for Mediterranean climate is shown in Fig. 1 and is composed of the following main components with the respective functions:

- Solar collectors with thermo-electric generators (TEGs) providing (1) heat to a short-term storage tank that is connected to a sorption chiller, a biomass boiler, and a domestic hot water (DHW) distribution system, and (2) electricity to auxiliary system components (i.e., pumps).
- Biomass boiler that supplies heat for DHW and space heating (SH) to the storage tank.
- Sorption chiller that works in cascade with a reversible heat pump during summer operation.
- Reversible heat pump to provide heating/cooling.
- Dry cooler that provides evaporation heat to the heat pump during winter operation and dumps condensation heat to the ambient during summer operation.
- Buffer tank to decouple the heat pump and the short-term storage tank from the heating/cooling distribution system.

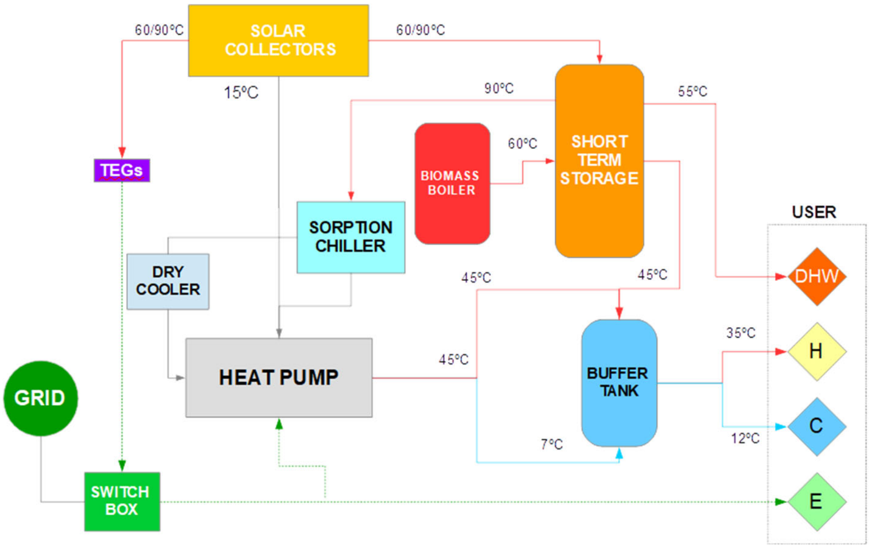

Fig. 1. System components for the SolBio-Rev designed for continental climate

The components were sized (Tab. 1) based on the energy demand obtained through simulations of a multi-family house located in Madrid. In this case, the multi-family house taken as a reference was the one from the EU project iNSPIRe (Dipasquale et al., 2014) with the U-values of a new/refurbished building according to the national building directive of Spain.

Tab. 1. Size of the SolBio-Rev system components

Component	Size
Sorption chiller	15 kW
Biomass boiler (without supplying heat to the ORC)	15 kW
Reversible heat pump	15 kW
Solar collectors with TEGs	50 m^2
Short-term storage tank	1500 litres
Buffer tank	800 litres

For each component, a detailed numerical model to be integrated in the DRL architecture was developed. In particular, the solar collectors model is based on a commercial AkoTec OEM vario 3000-20 collector and the solar thermal power was calculated based on the global solar radiation and the overall efficiency of the solar collectors. The TEGs were modelled considering the total thermal resistance of the TEGs system and calculating the power output through a linear function related to the temperature difference between input and output. The heat pump and the sorption chiller were modelled using performance curves given as polynomial functions based on equations for the cooling power and coefficient of performance (COP) as a function of operating temperatures. The biomass boiler was considered to operate at constant power with a 98% of thermal efficiency. The two water storage tanks were model using energy balance equations between the inputs and outputs.

The system modelling considered two different time scale slots: a finer time slot (3 minutes), to numerically compute the SolBio-Rev system behavior for inner model operations and, a second, longer time slot (15 min was considered), to manage the high-level control system. Within the longer time slot, any action decided by the control system will not change until any of the subsystem limits is attained. The input and system variables considered as an input to the control includes the level of solar irradiance, the ambient temperature, the status of the different subsystems, and the energy demand profile for heating, cooling, and DHW. The set of actions that are taken by the control algorithm are based on the combination of operational modes of each subsystem/component shown in Tab. 2.

Tab. 2. Operational modes of the system components

Component	State no.	Description
Solar collectors + TEGs	0	Off
	1	Setpoint 60 ºC (SH+DHW production)
	2	Setpoint 90 ºC (sorption chiller-assisted operation of the heat pump for cooling)
	4	Feeding TEGs for electricity generation
	5	Setpoint 15 ºC (solar-assisted operation of the heat pump for heating)
Heat pump	0	Off
	1	On for space heating using dry cooler
	2	On for space heating using solar collectors
	3	On for cooling using dry cooler
	4	On for cooling using sorption chiller
Biomass boiler	0	Off
	1	On for short-term storage tank charging at 60 ºC
Buffer tank	0	Not charging
	1	Heat provided from the short-term storage tank
	2	Heat provided from the heat pump
	3	Cooling provided from the heat pump

The control policies of the smart control aimed at the minimization of the economic operational costs of the system (€) using a cumulative reward function calculated based on the costs associated to running the system in different operational modes. The objective function can be defined with the following equation:

$$Penalty\ (E_{dhw} - E_{dhw,supplied}) + Penalty\ (E_{sh} - E_{sh,supplied}) + \qquad \text{(eq.1)}$$

$$+ Penalty\ (E_{cooling} - E_{cooling,supplied}) + E_{boiler}Cost_{pellets} + E_{grid}Cost_{grid}$$

where *Penalty* (€/kWh) is an economic penalization for not supplying the energy demand, E_{dhw} (kWh) is the DHW demand, $E_{dhw,supplied}$ (kWh) is the energy supplied for DHW by the SolBio-Rev system, E_{sh} (kWh) is the SH demand, $E_{sh,supplied}$ (kWh) is the energy supplied for SH by the SolBio-Rev system, $E_{cooling}$ (kWh) is the cooling demand, $E_{cooling,supplied}$ (kWh) is the energy supplied for cooling by the SolBio-Rev system,E_{boiler} (kWh) is the energy provided by the biomass boiler, $Cost_{pellets}$ (€/kWh) is the economic costs of the pellets, E_{grid}

(kWh) is the energy consumed from the grid, and $Cost_{grid}$ is the price of the electricity (€/kWh). A cost of 0.30 €/kg (0.72 €/kWh) was considered for the pellets, while a cost of 0.15 €/kWh and 0.30 €/kWh was considered for the grid electricity cost during off-peak and peak periods, respectively. The DRL algorithm was trained using the energy demand simulated for the reference multi-family house shown above using the weather data obtained from Meteonorm database for the location of Madrid available in TRNSYS (TRNSYS18, n.d.).

The smart controller algorithm based on DRL developed minimized the objective function defined as cumulative reward of the whole season, providing the optimal policy of actions. To evaluate the performance of the DRL control policy, a rule-based control (RBC) policy was first implemented for the different operational modes. To assess the RBC policies, exactly the same number of training and testing data and the same time-step for the control management were used. In particular, the data sets were created taking 150 days for winter and 80 days for summer. From each season set, days were shuffled and 10 days were taken for testing and 10 days for validation. The remaining days of each set were kept for training the algorithm. The results shown in the next section correspond to the validation set.

3. Results

The actions done by the RBC policy and the DRL algorithm during summer are shown in Fig. 2 and Fig. 3, respectively. The results show that, due to the constant need of cooling demand, the heat pump is operating most of the time in both cases. However, using an RBC policy, the heat pump is mostly running using the dry cooler, but it also runs in the mode using the sorption chiller. On the other hand, the smart control never uses the cascade mode with sorption chiller. Moreover, the RBC policy uses the TEGs to produce electricity more often than the DRL policy. Despite of this, in summer, the total cost using the smart control is very similar to the cost using the RBC policy (55 € vs. 57 €). In winter, when solar radiation is lower, the RBC (Fig. 4) shows a high use of the biomass boiler to satisfy both DHW and space heating, and, during periods of highest solar radiation, solar energy is used to run the TEGs. The heat pump in solar-assisted mode is never used. However, the smart control using DRL algorithm (Fig. 5) reduces the use of the biomass boiler by enhancing the use of the solar collectors. Moreover, the TEGs are almost always OFF. In this case, using the policy detailed by the smart algorithm, it is possible to reduce the operating cost in winter for 10 days of operation from 37 € to 24 €.

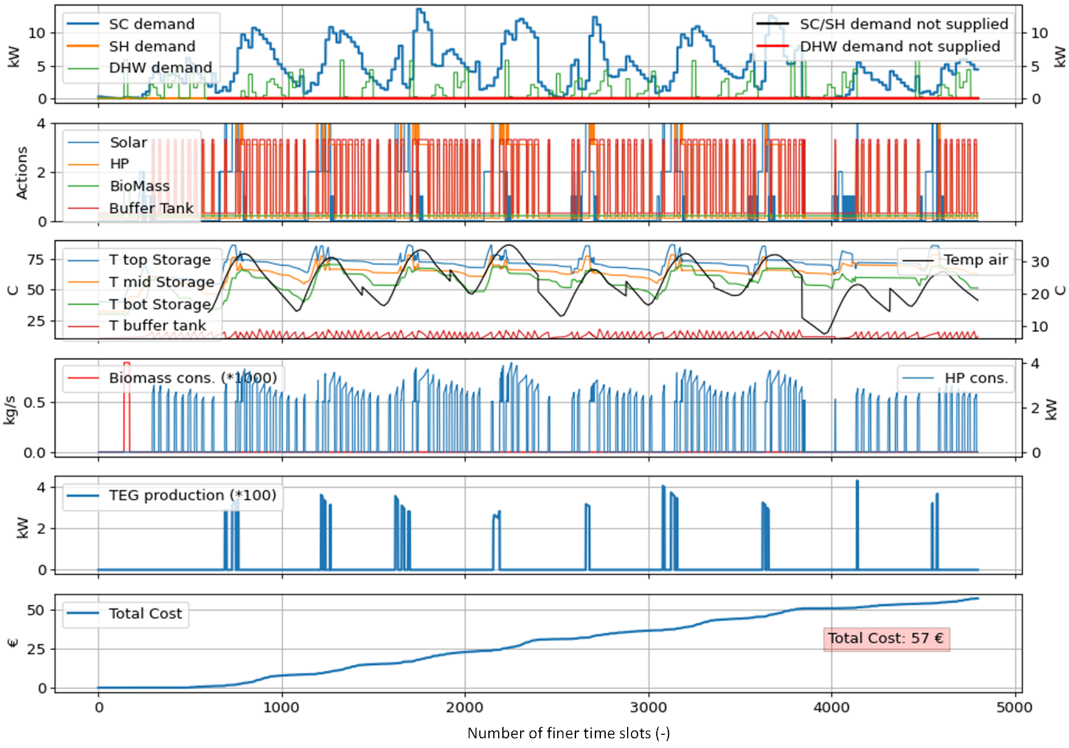

Fig. 2. RBC policy for summer season

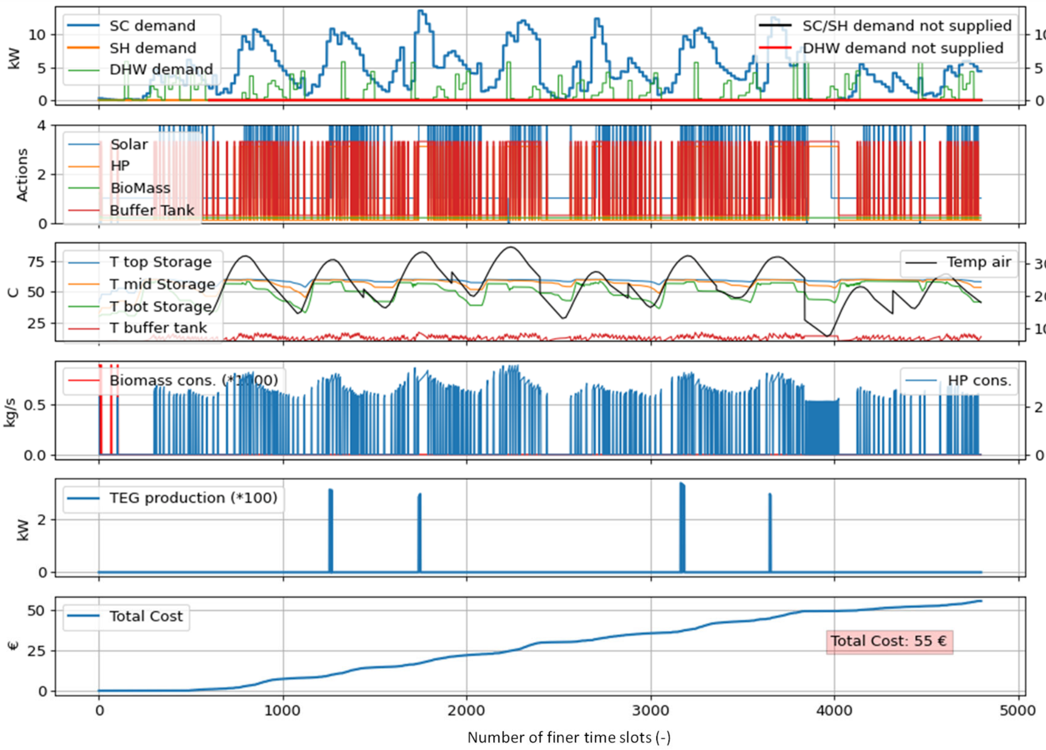

Fig. 3. Optimal control for summer season

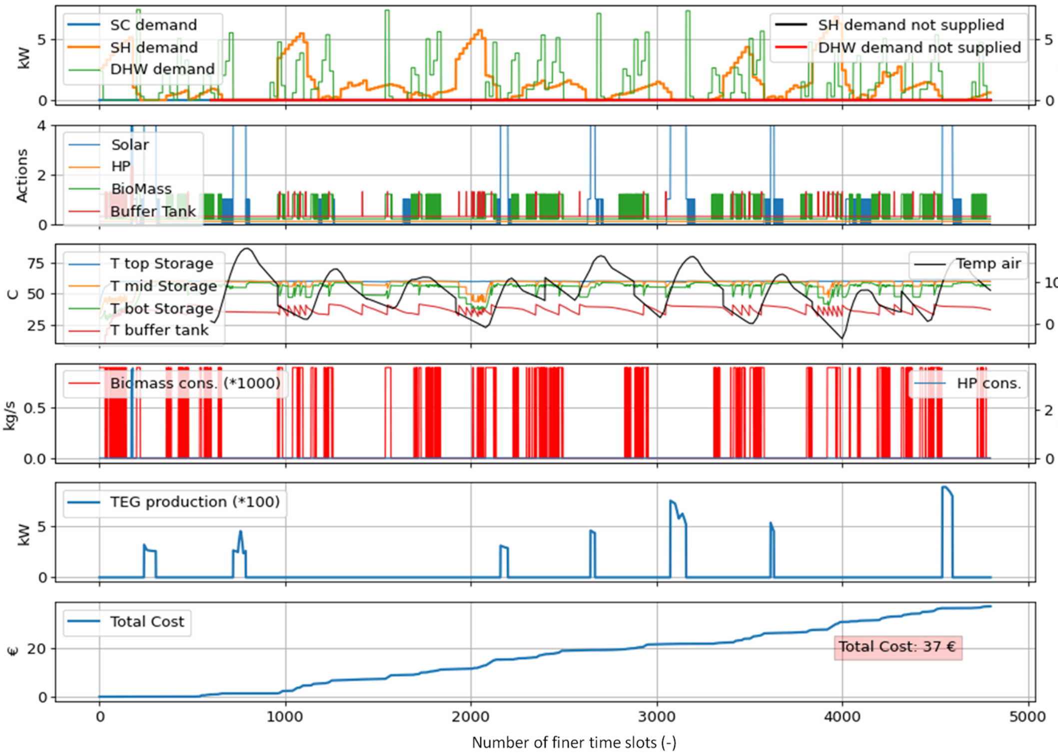

Fig. 4. RBC policy for winter season

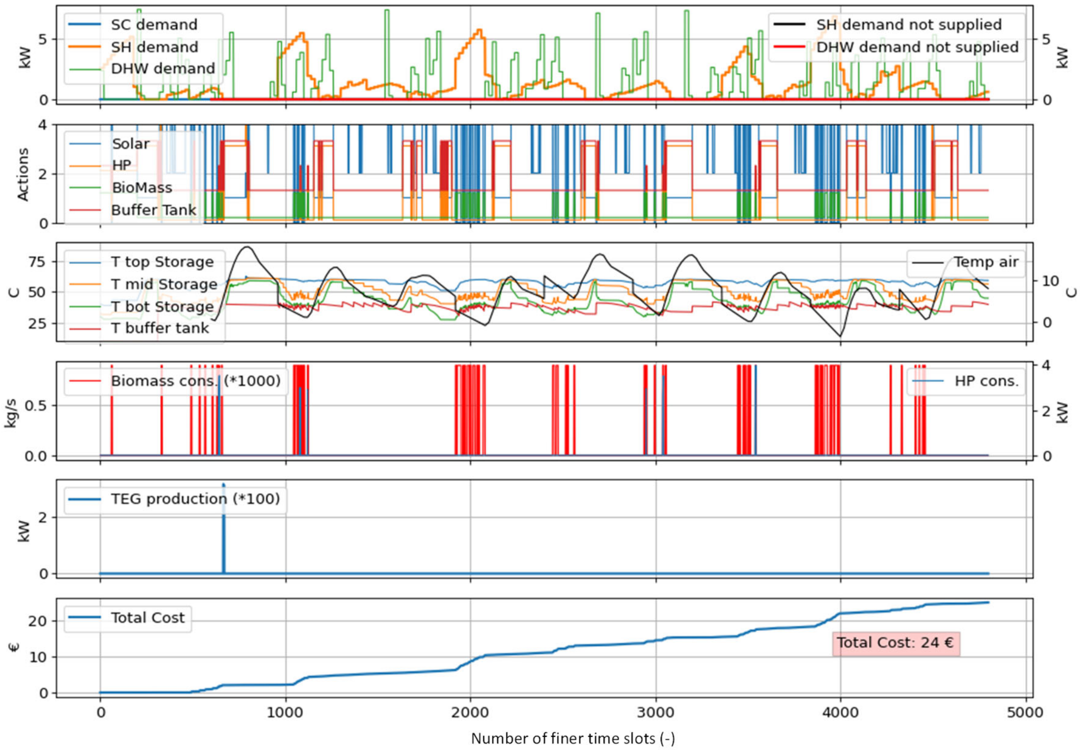

Fig. 5. Optimal control for winter season

4. Conclusions

In order to enhance flexibility of systems based on renewables sources, hybrid energy systems have a high potential to increase the total share of renewable energy used to satisfy the energy demand in buildings. The system developed within the SolBio-Rev project uses solar energy and biomass to provide heating, cooling, domestic hot water, and electricity for different building typologies in different climates. In this study, deep reinforcement learning (DRL) techniques were used to develop optimal control policies of the SolBio-Rev system to minimize the operating cost during all year. The SolBio-Rev system considered in this study was an optimized configuration for residential buildings located in Mediterranean climates. The smart control algorithm was trained using data of the energy demand of a multi-family house in Madrid obtained from simulations. In order to evaluate the goodness of the DRL control policy, a rule-based control policy was first implemented considering the different operational modes of the system components.

The results showed that the smart control is able to reduce the total cost in winter reducing the operation of the biomass boiler from 37 € to 24 € for 10 days of operation, due to a better operation of the solar collectors and a reduced use of the biomass boiler. However, in summer, the total cost using the smart control is very similar to the one achieved using the RBC policy. This can be explained by the low TEGs installed power and the fact that the reduction in the total energy consumption due to the coupling between the heat pump coupled and the sorption chiller is low. Further studies will aim to improve the DRL algorithm in order to define an optimal policy able to achieve higher savings in the energy cost in summer.

5. Acknowledgments

This project was funded by the European Union's Horizon 2020 Research and Innovation Programme under No. 814945 (SolBio-Rev). This work is partially supported by ICREA under the ICREA Academia programme. The authors would like to thank the Catalan Government for the quality accreditation given to their research group GREiA (2017 SGR 1537). GREiA is a certified agent TECNIO in the category of technology developers from the Government of Catalonia.

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