DREEM: A New Dynamic High-resolution Demand-side Management Model for Quantifying Benefits of Demand-flexibility in the Building Sector

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Abstract

Existing climate targets suggest energy transitions that fundamentally re-envisage the electricity system. To this end, increasing shares of renewable energy sources (RES) and reducing total demand are of paramount importance. However, one of the main challenges of a transition based on a high RES penetration is integrating these variable energy sources without jeopardizing the security and the reliability of the electricity system. Key solutions forward include the introduction of demand-side management (DSM) and flexibility functions, to absorb increased shares of dispatchable RES. However, so far DSM modeling at the building sector has been proven challenging, as the distributed and fluctuating nature of the consumption behavior can lead to misleading modeling assumptions. Addressing that, this paper presents a new Dynamic high-Resolution Demand-side Management (DREEM) model. The novelty of the model lies mainly in its modularity, as its integrated structure allows for the model components’ output variables to be appropriately correlated.

Keywords: Renewable Energy Sources, Energy Conservation in Buildings, Energy Systems for Power Generation, Modelica, Smart Home, Demand Response.

1. Introduction

Demand-side management (DSM) modeling at the residential sector is beneficial for testing demand-response (DR) schemes that could be offered to residential customers and could provide directions for the development of products and services related to the smart grid paradigm.

There is already a plethora of a literature consensus addressing DSM at the residential sector through state-of-the-art computational modeling and simulation tools [1–10]. However, most of the existing DSM models do so partially or in a simplified manner, used most of the times for forecasting purposes. The main challenge of DSM models is being flexible enough, while at the same time including all important aspects of end-use. An indicative set of key features and guiding principles of a DSM model to judge what should be incorporated and/or omitted or simplified in the interests of computational efficiency is:

- Bottom-up structure,
- Capability to be integrated with other models and easily re-used,
- Capability to produce outputs at a high resolution (i.e. one minute),
- Seasonal variability to reflect the changing level of demand between winter and summer,
- Computational efficiency to simulate large numbers of buildings, with the appropriate diversity of demand,
- Considering the coupling of the grid system model to market pricing models through practical control strategies,
- Modular structure to reduce simulation complexity owing to multidisciplinary nature and input data requirements,
- Capability to link the energy system to economic development and technological breakthrough (i.e. inclusion of alternative energy technologies or other energy carriers at a later date).

To address modeling gaps in the existing literature we present in this work a new Dynamic high-Resolution Demand-side Management (DREEM) model. The model serves as an entry point in DSM modeling in the building sector, to assess the benefits and limitations of demand-flexibility, primarily for consumers, and then for other power actors involved. Its novelty lies mainly in its modularity, as its integrated structure allows for the model components’ output variables to be appropriately correlated. This approach is more flexible in terms of possible system configurations and control strategies [11]. It also provides the ability to consider
future technology changes, such as the inclusion of heat pumps or electric vehicles, in view of energy transitions envisioning the full electrification of the heating and transport sectors.

To demonstrate the applicability of the model we used it to explore benefits of demand-flexibility for consumers in the residential sector of Greece. Note that, although its applicability is demonstrated for the case of Greece, the DREEM model can be configured and used for different geographic and socioeconomic contexts, given appropriate historical data-observations and market-related parameters, to fill-in knowledge gaps from an international and cross-country perspective.

2. Model Description

The DREEM model is composed of multiple components, as presented in Table 1 below, and its overall architecture makes it flexible to be extended in the future.

<table>
<thead>
<tr>
<th>Components</th>
<th>Description</th>
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<tbody>
<tr>
<td>1. Weather-Climate</td>
<td>Generating weather data and boundary conditions.</td>
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<tr>
<td>2. Building envelope</td>
<td>Modeling different building typologies.</td>
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<tr>
<td>3. Electricity demand</td>
<td>Defining and setting of the parameters for the behaviour and the activities of the occupants. Generating energy demand profiles from appliances and HVAC system.</td>
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<tr>
<td>4. Thermal comfort</td>
<td>Determining, based on international standards, appropriate thermal conditions and temperature ranges that result in thermal satisfaction of occupants.</td>
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<tr>
<td>5. Flexibility management</td>
<td>Determining PV generation based on the position of the sun and recorded irradiation data for the location of interest.</td>
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<td>6. Demand-Response</td>
<td>Simulating DR mechanisms that motivate the consumers to respond to real-time price signals.</td>
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<tr>
<td>7. Control strategies</td>
<td>Energy management supervision strategy that, given the time-shifting events of demand and the occupancy signals, aims at achieving energy savings and cost-effectiveness.</td>
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2. Case Study

The applicability of the model was demonstrated for the case of Greece by exploring the energy performance of a single-family residence (two parents and two kids) in the city of Athens (Climate Zone B). Electricity interconnection of the islands with the mainland in Greece remains a continuous challenge, with the non-interconnected islands depend mainly on fossil-fueled units. As a result, Greece makes a reasonable selection for envisaging an electricity sector that relies on large-scale RES plants, decentralized RES generation and increased demand-side flexibility, especially at the residential sector.

The following modeling scenarios were considered:

1. **Reference Case (“Case1”):** The family consumes energy according to its daily needs, maintaining indoor temperature in comfort levels.

2. **A possible demand-response scheme (“Case2”):** The family invests in solar PV and electricity storage installations, a smart thermostat and an advanced control device that regulates the dwelling’s energy performance, while complying, if possible, to market dynamic pricing DR events.

The model allows also for seasonal simulations to account for the effects of weather and temperature on electricity demand. The two typical seasonal profiles considered to present our results are:

I. **Period 1 (hot weather):** June to September,

II. **Period 2 (cold weather):** December to March.

4. Results & Discussion

4.1. Reference Case (“Case1”)

To ensure thermal comfort the set points for indoor normal temperature are set to 23.2°C for Period 1 and to 22.1°C for Period 2. *Figure 1* and *Figure 2* below present the indoor temperature, the PMV values, the power consumption from the grid and the electrical energy consumed from the grid for both Period 1 and Period 2.

![Figure 1](image1.png)  
*Figure 1* Indoor temperature, PMV values, Power consumed from the grid and Electrical energy consumed from the grid for Period 1.
4.2. A possible demand-response scheme (“Case2”)

The DREEM model allows for simulating demand-response mechanisms that motivate the consumers to respond to real-time price signals, which are derived through a “real-world” situation, in which a central planner (e.g. supplier, retailer, etc.), that attempts to maximize flexibility value by issuing DR signals, is assumed. This entity learns the optimal policy that maximizes its revenues through an optimization approach based on Reinforcement Learning (RL) theory. Our RL algorithm suggests that the optimal policy for the retailer for both Period 1 and Period 2 is represented by the demand-response signals visualized in Figure 3 below.

To assess potential energy and cost savings for the consumer, we set normal and minimum indoor temperature at 23.1°C and 25°C respectively for Period 1 and at 22.1°C and 21.1°C respectively for Period 2. Figure 4, Figure 5, Figure 6 and Figure 7 below present the indoor temperature, the PMV values, the power consumption from the grid, the electrical energy consumed from the grid, the solar power sold to the grid, electrical energy sold to the grid, the Electrical energy stored to the battery and the State of charge of the battery for both Period 1 and Period 2.

Figure 2 Indoor temperature, PMV values, Power consumed from the grid and Electrical energy consumed from the grid for Period 2.

The costs for electricity consumption are €123.97 and €150.67 for Period 1 and Period 2 respectively.

To assess potential energy and cost savings for the consumer, we set normal and minimum indoor temperature at 23.1°C and 25°C respectively for Period 1 and at 22.1°C and 21.1°C respectively for Period 2. Figure 4, Figure 5, Figure 6 and Figure 7 below present the indoor temperature, the PMV values, the power consumption from the grid, the electrical energy consumed from the grid, the solar power sold to the grid, electrical energy sold to the grid, the Electrical energy stored to the battery and the State of charge of the battery for both Period 1 and Period 2.

Figure 3 Frequency of demand-response signals for both Period 1 and Period 2, according to the RL optimal policy, based on historical data of 2015 for the Greek electricity wholesale market.

Figure 4 Indoor temperature, PMV values, Power consumed from the grid and Electrical energy consumed from the grid for Period 1.

Figure 5 Solar power sold to the grid, Electrical energy sold to the grid, Electrical energy stored to the battery and State of charge of the battery for Period 1.

Figure 6 Indoor temperature, PMV values, Power consumed from the grid and Electrical energy consumed from the grid for Period 2.
As expected the benefits of self-consumption for consumers come due to less electricity absorbed from the grid and the use of smart devices and control management strategies. On the other hand, our results indicated that, due to a demand-response scheme, the central planner (e.g., supplier, retailer, etc.) assumed, can offset a part of its losses due to self-consumption. Based on historical data of the Greek electricity wholesale market for 2015, this offset was estimated at €152.06 million. Table 2 below presents the energy and cost savings for the “Case2” scenario, compared to the “Case1” scenario.

Table 2 Energy and Cost Savings for the “Case2” scenario, compared to the “Case1” scenario, for both Period 1 and Period 2 (negative values suggest savings).

<table>
<thead>
<tr>
<th></th>
<th>Period 1</th>
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<th>Period 2</th>
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<tbody>
<tr>
<td></td>
<td>Energy (%)</td>
<td>Cost (%)</td>
<td>Energy (%)</td>
<td>Cost (%)</td>
</tr>
<tr>
<td>“SC2”</td>
<td>-50.02</td>
<td>-60.50</td>
<td>-36.46</td>
<td>-41.32</td>
</tr>
</tbody>
</table>

Our findings have been already presented in the EC funded events “TRANSrisk Policy Lunch "Paris in Practice: Understanding the Risks and Uncertainties" - November 2018, Brussels” and “TRANSrisk & SET-Nav Regional Workshop: "Decarbonizing our energy system - Transformation pathways, policies and markets, with spotlight on Greece“ - November 2018, Athens”. During these events, the model has been exhibited to relevant stakeholders and energy experts from the power sector, and policymakers and practitioners have validated its usefulness, as a decision support tool that provides fast answers to “What-if scenarios”, through an extensive round of breakout and technical ‘hands on the tools’ sessions.

5. Concluding Remarks

To the best of our knowledge, most models in the scientific literature address DSM partially or in a simplified manner, used most of the times for forecasting purposes. Our work addresses this gap in the scientific literature by introducing the Dynamic high-resolution dEmand-sidE Management (DREEM) model. The novelty of the model lies mainly in its modularity, as its integrated structure allows for the model components’ output variables to be appropriately correlated.

To demonstrate the applicability of the model we used it to explore benefits of demand-flexibility for consumers in the residential sector of Greece. Our results have shown that the flexibility to increase self-consumption can be brought to the Greek market without a need: a) for significant changes in the current market design, and b) for consumers to sacrifice comfort and energy services. Additionally, our results indicated that allowing for a synergistic co-operation between the power provider and the prosumer, significant cost reductions and energy savings can be achieved. A fair allocation of these benefits can provide incentives to both sides, towards a decentralized electricity system.

Building on our findings, and considering current developments on the smart-grid paradigm, the DREEM model will be coupled with a computational monetary framework that uses the energy currency concept [12] to promote incentive schemes that are based on the idea of using energy as a monetary entity, in order to make people more aware of the dependence of energy consumption on their behavior. Such a study could shed light on how such schemes, promoting peer-to-peer transactions between consumers, could result in the mitigation of the energy consumed in a city, considering the immense potential of Information and Communication Technologies (ICTs). Important implications could be derived from this soft linking, including policies that could motivate people to regulate their energy consumption as a way to benefit financially from obtaining energy saving practices.

Finally, a decentralized vision of the future electricity system has as an important implication to be considered. Part of the infrastructure required will be developed from consumers’ direct investments in building-scale technologies for electricity generation using renewable energy sources. Increased adoption of these technologies requires that they become competitive with fossil-fuel alternatives, and, thus, business models that will increase their value are needed. To this end, the authors intend to link the DREEM model with another in-house agent-based model, that correlates technology adoption with its value to consumers, quantifying behavioural uncertainty, to explore adoption scenarios towards a European decentralized electricity system.

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6. References


