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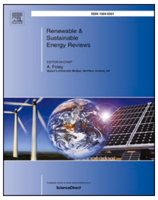

Co-benefits between energy efficiency and demand-response on renewable-based energy systems

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ABSTRACT

Driven by the recent trends towards a smart power system configuration, there has been a greater focus within the literature on the integration between supply and demand-side resources. The contribution of this research is multifold since it provides a timely and required study, offering valuable insights into how the integration between Demand-Side Management (DSM) resources with clean energy supply options might affect the long-term power planning strategies in high-renewable electricity systems. The innovative aspects of this study are strongly related to a framework proposal for assessing the co-benefits between energy efficiency and demand-response on renewable-based energy systems from a long-term perspective using a co-optimization modelling approach. Overall, the results indicate that a clear benefit of implementing DSM strategies is the percentage reduction of the new installed capacity (−1.0% to −20.6%), CO_2 emissions (−2.4% to −11.8%), and total system costs (−0.5% to −15.8%) for all scenarios compared to Business-As-Usual scenario. The evidence from this study suggests that investments in Energy Efficiency (EE) seem more economically valuable than investing only in Demand-Response (DR) strategies. However, integrating EE and DR would empower the overall power system benefits. Strong evidence for a higher potential to delay investments was found for all scenarios for the first ten years of the planning period. Our findings might provide valuable insights to both governments and policy-makers by delivering supportive information in scaling up EE investments. The methodology proposed offers essential contributions to the scientific community and would benefit energy systems research beyond the cases addressed in this paper.

1. Introduction

Energy transitions have a significant impact on society, the economy, and the environment [1], but their speed and scope would be dependent on a large-scale shift toward Renewable Energy Sources (RES) and Energy Efficiency (EE). The importance of gradually shifting the investments to both RES and EE to move from carbon-intensive energy systems towards a more sustainable energy future is, therefore, essential [2]. The International Energy Agency (IEA) supports that RES is projected to have the fastest growth in the electricity sector and might lead the way toward a sustainable future. The high integration of RES for electricity generation has been widely discussed worldwide to ensure long-term sustainable energy supply but also because the electricity sector stands out as a key driving force of global climate change. However, a large-scale shift toward RES might require a set of ambitious targets and policy changes from the current governments' energy plans. A new report from the International Renewable Energy Agency (IRENA) indicates that renewable energy jobs might reach 42 million by 2050 (out of 100 million), considering the "*energy transition*" scenario. Jobs related to EE were also reported to increase by 21% compared to the current plans [3]. Fig. 1 illustrates the six focus areas proposed by Ref. [2] where policy and decision-makers should act toward a sustainable future. The first focus area highlighted in Fig. 1, for instance, suggests the need to tap into the synergies between EE and RES for achieving a more sustainable and affordable pathway, which is also centred on other two main pillars, i.e., carbon neutrality and the

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so-called concept of a “*just*[1] *energy transition* [4]”.

Over the past years, recent changes have occurred in the global electricity sector. Several challenges for the power sector are also arising, for instance, from the wide range of alternative technologies development. This also means new techniques and strategies are required to operate and plan power systems to address the concerns of this novel and smart power system configuration [5]. The energy transition would require a set of shifts in investments, policy, planning, and cognitive (i.e., attitude and behaviour) issues [2]. New challenges have also been witnessed in the last couple of years for governments, utilities and system operators due to the disruptions in the electricity sector. These challenges include, for instance, the need for new techniques to address the intermittent generation from RES but also to meet global climate goals. Also, driven mostly by climate change concerns such as the Paris agreement - which attempts to limit the average global temperature rise below 2 °C in this century [6] - a holistic approach is required to address the challenge of reducing the overall level of greenhouse gas (GHG) emissions, notably carbon dioxide (CO_2) emissions, given its high contribution from the power sector perspective.

Climate change has been considered the most pressing challenge for many countries. In the wake of the climate-change[2] debate [7] and the “*just energy transition*” concept [4], the role of Distributed Energy Resources (DER[3]) has emerged as a potential contributor to addressing these challenges. The world has been moving towards renewable-based DER, mainly because of two main reasons (i) the decreasing costs of these technologies and (ii) the increasing need for new energy flexibility requirements in power systems [8]. The introduction of DER also holds the potential to address the three main conflicting variables (i.e., costs, the security of supply and CO_2 emissions reduction) faced by governments, municipalities, industries and communities in general, for which a holistic and integrated approach is required to meet these goals simultaneously. Regardless of all the benefits related to the development of DER (e.g., the grid losses reduction and the postponing of conventional investments in infrastructure), the growing insertion of these technologies implies more uncertainties on power demand projections and consequently in the optimal future countries’ energy mix [9]. The authors of Ref. [10] highlight that “*distributed energy resources (DER) are driving the need to change how the grid is managed*”. Therefore, DER represents a high disruptive potential and it can add up significant and systemic benefits to the power system but at the same time, it may significantly increase the power system’s complexity.

At the same time, adaptations in the current operation and expansion planning practices - including new normative-regulatory frameworks and market models that properly value the economic, environmental and social benefits - are still required to reap the systemic benefits offered by DER [9]. The potential of storage systems (e.g., Battery Energy Storage System – BESS) appears as a possible solution to absorb the excess renewable electricity production from Variable Renewable Energy (VRE) and to deliver electricity at a lower price during on-peak times, which may strongly contribute to the integration of higher shares of VRE into power systems. The emergence of DSM[4] strategies has also been recognised as one of the main potential contributors to addressing the challenges mentioned above and holds the potential to deliver significant advantages in future electricity supply systems. The benefits of combining EE and Demand-Response (DR) strategies may contribute significantly to the power system operation and defer investments in distribution and transmission systems. Therefore, evaluating the impact of DSM strategies in the short and long term is essential to identify the synergies and potentialities from the demand-side point of view.

Particularly for the past couple of years, the link between supply and demand-side has been at the centre of much attention. Many published studies (e.g., Refs. [11–13]) suggest that capital spending in DSM strategies would avoid investments in the supply-side. However, the most significant recent developments in this direction have been those of individual assessment, i.e., focusing on the unique contributions of EE (see, e.g. Ref. [14]) or DR strategies (see, e.g. Refs. [15,16]) only. The Electric Power Research Institute (EPRI) conducted a research that provided an insightful analysis regarding the synergies between EE and DR. It concluded that “*the combination of demand response and energy efficiency programs has the potential to reduce non-coincident summer peak demand by157 157 GW to218 GW*” which represents a reduction between 14% and 20% of the projected peak demand in the U.S. by 2030 [17].

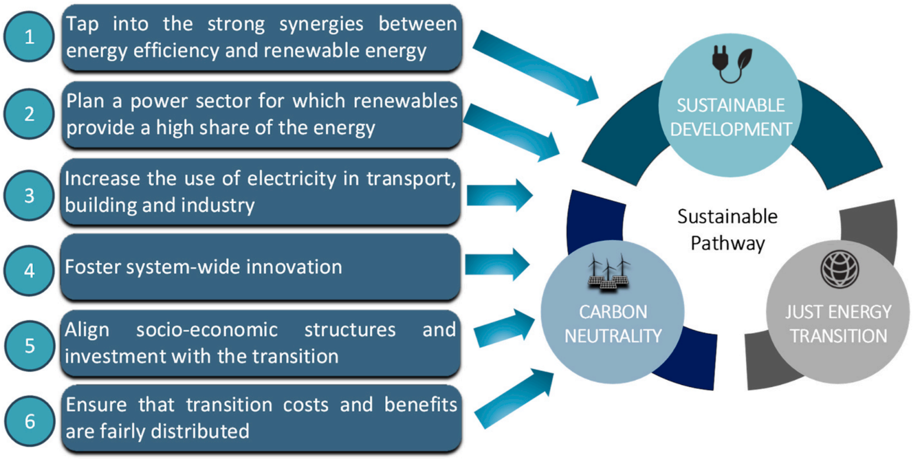

Fig. 1. Focus areas where policy and decision-makers should act towards a sustainable future (Adapted from Ref. [2]).

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[1] Several studies have begun to examine the concept of a “*just transition*” which can be split up into energy, climate and environmental “*justice*” [4]. Ref. [4] highlights the importance of this ‘*justice*’ approach in the transition towards a low-carbon economy although governments and institutions, in general, have neglected to mention this concept in their current plans.

[2] A systematic literature review of the role of energy systems for climate change mitigation is addressed by Ref. [47] highlighting the emergence of both energy-water-land nexus and energy storage areas and the growing interest in waste-to-energy and hydrogen energy production which have been also in the centre focus of much recent research.

[3] Examples of DER include Distributed Generation (DG), Demand Response (DR), Energy Efficiency (EE), Electric Vehicles (EVs) and storage systems.

[4] DSM can be broadly divided into Energy Efficiency Measures (EEMs) and Demand Response (DR) strategies.

Ref. [18] investigated the analytical frameworks traditionally employed to incorporate DR into long-term resource planning. To maximise the combined benefits of both EE and DR, the interactions between long-term EE and daily DR at an industrial firm were addressed by Ref. [19]. Ref. [20] assessed the effects of DR measures on EE, concluding that - in general - DR yields energy savings. Ref. [21] found that EE is much more prevalent than DR strategies, but synergies in policies and technologies might be considered to promote both approaches. Furthermore, strong complementary between EE and DR has been found in Ref. [22].

Bottom-up modelling is performed in Ref. [22], evaluating the interactive effects between EE and DR with a particular focus on buildings in regions of the United States. The impact of EE on electricity demand profiles is evaluated in Ref. [23], which estimated that peak demand could be reduced by 38% when appliances are replaced by more efficient equipment. A two-stage short-term model has been developed in Ref. [24], which coordinates both EE programs and DR strategies considering technical constraints. The model determines the participation level of customers in DR programs as well as the EE levels invested by the government. The integration between supply-side and demand-side options for long-term power system planning using the Long-Range Energy Alternative Planning (LEAP) system was investigated in the work of [25] for a system with high RES penetration (i.e., India) and considering different types and levels of DSM strategies, including both EE and peak load shifting. The authors of Ref. [25] argued that cost savings would occur to up to 18% due to the simultaneous implementation of both supply-side and demand-side measures and it would also imply a reduction for both the total installed capacity and CO_2 emissions of as much as 10% and 23%, respectively.

Notwithstanding, relatively few studies attempt to develop a full picture and a comprehensive examination of the role of DSM strategies in the long-term for the specific case of developing countries, particularly for systems that deeply rely on RES. The contribution of the current literature - particularly for high renewable-based systems – is, therefore, limited since few studies have investigated whether investing together in EE and DR might be economically feasible for the long-term and a synergistic and well-thought-out approach is highly recommended. The relevance and innovative aspects of this study are then strongly related to a comprehensive assessment of the co-benefits between different DSM mechanisms (EE and DR) on renewable-based energy systems following a long-term co-optimization[5] approach. The integrated DSM assessment focuses on the Brazilian power sector case study due to its high level of RES and continental dimensions avoinding the use of theoretical test cases [26]. Therefore, this research study attempts to address this gap by answering the following question: *To what extent can DSM implementation technical and economically compete with other supply-side options?* A set of code enhancements is proposed for the Integrated Brazilian Electricity System Model (IBESM), developed first by Ref. [15], which is used along with this research to evaluate the long-term impacts of implementing DSM in high-RES systems under a co-optimization approach. IBESM is enhanced by including a set of code additions to account for the inclusion of EE within the long-term model using the proposed concept of the Long-term Average Cost of Saved Electricity (LACoSE) [14]. This allows to recognise and account for energy efficiency reinvestment from a long-term perspective.

This paper is organised into six main sections. The contextualisation of the research is highlighted in this first section, followed by a theoretical background of DSM in Section 2. Section 3 introduces the proposed methodology, including a framework proposal to include EE in the long-term power planning model. An in-depth critical discussion and assessment of the research findings are addressed in Section 4. Section 5 draws upon some concluding remarks and provides a lively discussion highlighting the main policy implications of this study. Section 6 attempts to identify the study limitations and the main possible avenues for further research.

2. Theoretical background on demand-side management (DSM)

Driven by the recent trends toward a smart power system configuration [27], a major trend has been seen over the past years towards exploring not only the potential from supply-side options but also a strong growth has been at the centre of much attention exploring the flexibility potential from the demand-side, which has also been disrupting traditional energy planning models. For instance, technological advancements on the demand side have contributed to an increasingly active behaviour of consumers [28]. Ref. [25] argues that integrating Supply Side Management (SSM) and DSM resources is essential to achieve a more accurate model for power system planning purposes and support energy management in future smart grid models. DSM[6] measures have also been considered a powerful resource to contribute to the future challenges of integrating VRE resources into the power grid. Researchers have also dedicated valuable efforts to model and assess the impact of DSM measures not only in the short-term but also in long-term power planning studies.

Demand-side techniques might provide many benefits for power systems in general, including the need for reduced thermal capacity and deferring investments in distribution and transmission systems. It can also reduce GHG emissions and increase grid sustainability [11]. Hence, DSM has been considered a major driver to achieving the ambitious goal of the Paris agreement once the power sector has a central role in the transition toward carbon neutrality. This also means that the environmental impacts brought about by implementing both EE and DR programs are essential to account for climate change mitigation issues. There is extensive evidence that EE play a crucial role in benefiting the environment since it reduces the overall electricity generated and consequently have the potential to decrease the overall level of carbon emissions, water and land use, for example. However, according to Ref. [29], the environmental benefits brought about by DR implementation are not well-recognised primarily because of two factors: *"(1) the effects are specific to the time and place where energy use was avoided and (2) the effects depend on whether the electricity use was offset to another time - and if so, what power sources were used to generate that electricity"*.

DSM techniques can be broadly divided into Energy Efficiency Measures (EEMs) and Demand Response (DR) strategies and it may provide an increase in the level of flexibility of power systems in general by reshaping the load profile [30] and reducing the peak load [31]. Fig. 2 summarises the main categories of DSM strategies, which can be broadly divided into the use of DR strategies[7] (e.g., valley filling, load shifting, peak clipping and flexible load shaping) and EEMs (also known as strategic energy conservation).

DSM techniques may also help to release the energy network stress. Peak clipping, for instance, might greatly assist the power system, particularly during peak times [32]. Load shifting is considered one of the most prominent DSM strategies since this technique may shift the load from peak to off-peak times [31]. DSM may also play a central role in integrating renewables, poverty alleviation, and employment issues [33]. A systematic review of DSM architecture, approaches,

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[5] According to the definition proposed by Ref. [48], "*co-optimization is the optimization of two or more different yet related resources within one planning framework*". A review of co-optimization approaches for energy planning problems may be found in Ref. [26].

[6] Literature has been using different terms to refer to "DSM measures" [49,50], which includes: (1) DSM techniques [51,52], (2) DSM strategies [14,40], (3) DSM initiatives [53,54], (4) DSM schemes [55,56], (5) DSM programs [54,57], (6) DSM approaches [31,58] and (7) DSM procedures [53]). Thus, these different terms have been employed interchangeably across different research papers within the literature.

[7] The strategic load growth can be classified as a particular DSM strategy.

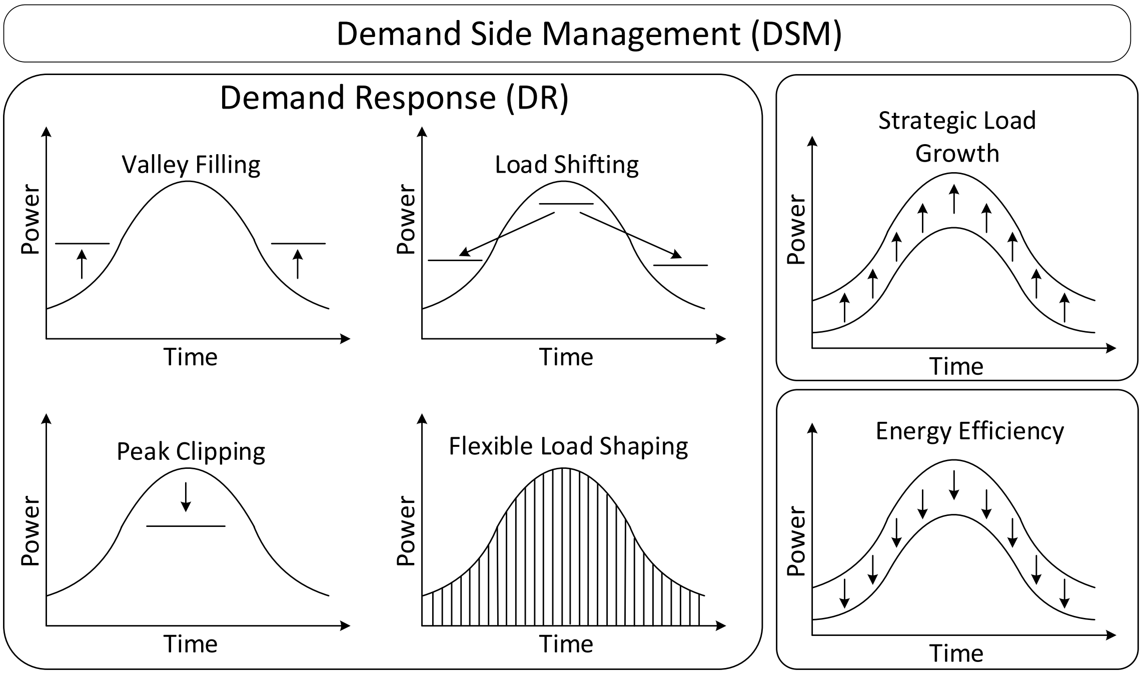

Fig. 2. Key Demand-Side Management (DSM) techniques for load management.

optimization models, and methods was addressed by Ref. [31]. The authors of [31] classified DSM measures regarding the optimization approach (deterministic *versus* stochastic), the time-scale (day-ahead *versus* real-time), and user interactions (individual users *versus* cooperative users).

The co-benefits from investing in EE have also become increasingly important in the past years. Ref. [33], for instance, demonstrated the contribution of EE to economic and social development, environmental sustainability as well as increasing prosperity. Although EE and DR are considered strictly related concepts and present strong synergy, in general, each approach has been traditionally designed and evaluated independently [34]. However, with only a few exceptions, what is not yet clear and research has not extensively addressed is related to the interactions and co-benefits (also called multiple benefits) between DR and EE. Although DR primarily aims to promote reductions in demand (i.e., kW) during the most expensive times and EE yields energy savings (i.e., kWh) at all times, overlapping effects of DR and EE can also be observed since DR may indirectly promote the reduction of the total electricity consumption while EE would reduce the demand permanently. Therefore, both EE and DR might deliver benefits across the electricity system, reducing the overall generation costs and the peak demand [19]. It is worth mentioning that implementing DR does not necessarily reduce the overall electricity consumption [35].

The co-benefits of using both EE and DR also include applying the revenue stream obtained by the consumer due to energy savings from implementing DR strategies in more efficient appliances. Consequently, deeper electricity savings would occur, which in turn would represent a new revenue stream. On the other hand, the outcome related to the presence of multiple rebound effects linked to EE would partially break down this so-called “Virtuous Cycle” since energy efficiency improvements might save less energy than expected. The rebound effect (also known as load kickback effect) *“can be described as the sudden rise in demand during the non-peak hours that is caused by the overuse of power by the consumers after their reduction of power during peak hours* [36]”. Researchers have also investigated the interactions between the load kickback effect with DR (see, e.g., Refs. [36,37]). The load kickback effect is a key issue to address when implementing DR measures, because it can also jeopardise the power system operation by causing congestion problems [37]. Traditionally, the load kickback effect has been controlled using direct load control of electronic devices or incentive reward systems that pay for consumers to minimise their consumption during specific periods [36].

3. Research methodology

The general methodology approach proposed in this research for the long-term assessment of the co-benefits between EE and DR on renewable-based energy systems is summarised in Fig. 3.

The methodology can be split into four main stages (see Fig. 3). **Stage 1** comprises the main input assumptions of the long-term co-optimization model, including using a set of input parameters and technologies and the definition of relevant scenarios. The co-optimization model is based on the Open-Source Energy Modelling System (OSeMOSYS), implemented in GAMS language. Further information about the modelling assumptions can be found at www.osemosys.org. Other information related to the particular power system evaluated in this research and the enhanced developed model (i.e., IBESM) can be found in Ref. [14] and Ref. [15]. The emissions factor ($MtCO_2/TWh$) was established based on historical average values for the power system [38] and the projected CO_2 emissions allowances prices (US\$/tons of CO_2) were established considering average prices extracted from Ref. [39] (see Appendix A – Table A.1). Table A.1 also presents additional techno-economic parameters.

Stage 2 comprises the estimation of the so-called Long-term Average Cost of Saved Electricity (LACoSE) such as described in Equation (1), where k represents the interest rate (%), E_i is the estimated saved electricity for each EEM (i) in MWh/year, C_i is the estimated total cost of implementing each EEM (i) (US\$), ΔT is the planning period of the long-term model (years), N_P is the last EEM (i) included in the analysis and T_i is the life-time of each EEM (i). The LACoSE estimation also takes into account the average life-time of all EEMs (T_A in years) calculated according to Eq. (2) [14]. The LACoSE has been proposed by Ref. [14] and accounts for reinvestment in energy efficiency from a long-term perspective.

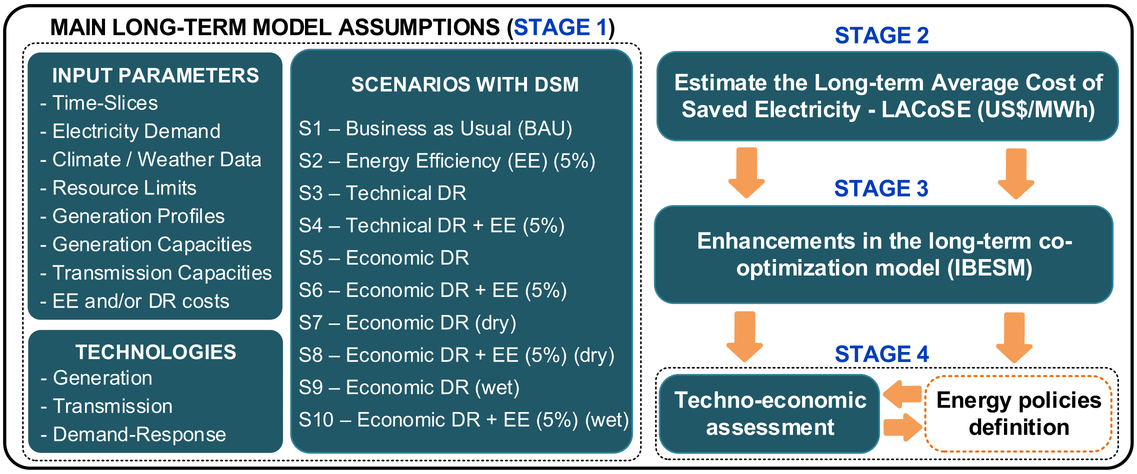

Fig. 3. The general framework for the technical and economic assessment of investing in DSM strategies under a long-term perspective.

Table 1
Scenarios description.

Scenarios	Description
Scenario 1	Business as Usual (BaU)
Scenario 2	5% of Energy Efficiency Measures
Scenario 3	Technical DR potential
Scenario 4	Technical DR potential + 5% of Energy Efficiency Measures
Scenario 5	Economic DR potential
Scenario 6	Economic DR potential + 5% of Energy Efficiency Measures
Scenario 7	Economic DR potential (drought year – 2015)
Scenario 8	Economic DR potential + 5% of Energy Efficiency Measures (drought year - 2015)
Scenario 9	Economic DR potential (wet year – 2011)
Scenario 10	Economic DR potential + 5% of Energy Efficiency Measures (wet year - 2011)

$$LACoSE = \left(\left[\frac{k \cdot (1+k)^{T_A}}{(1+k)^{T_A} - 1} \right] \cdot \frac{\sum_{i=1}^{N_p} C_i}{\sum_{i=1}^{N_p} E_i} \right) \cdot \frac{\Delta T}{T_A} \tag{1}$$

$$T_A = \frac{\sum_{i=1}^{N_p} T_i \cdot E_i}{\sum_{i=1}^{N_p} E_i} \tag{2}$$

A set of code enhancements has also been defined within the original long-term planning model to account for the inclusion of different levels of EE (**Stage 3**). These improvements allow simulating the effects of investing in EE and comparing them with scenarios without such energy efficiency improvements. It is worth mentioning that the inclusion of EE within the model is performed by reducing the final electricity demand projected for each year (see Ref. [14]). Therefore, a five-step methodological approach is proposed (Fig. 4), enclosing the main required changes in the original model.[8]

The standard annual electricity demand 'SpecifiedAnnualStandardDemand(r,f,y)' and the total yearly electricity demand 'SpecifiedAnnualTotalDemand(r,f,y)' should be exogenously estimated and included within the long-term co-optimization model (**Step 1**). The 'SpecifiedAnnualTotalDemand(r,f,y)'[9] comprises both the flexible and inflexible demands, whereas the 'SpecifiedAnnualStandardDemand(r,f,y)' discounts the estimated power system's flexible demand.

The original energy efficiency ratio 'TEE' corresponds to the level of reduction in the final electricity consumption (expressed in decimals). This parameter is used to calculate the modified energy efficiency ratio 'TEE_new(f,y)' according to Equation (3) - **Step 2**. The modified energy efficiency ratio is included within the co-optimization model to fairly account for the reductions in the final electricity demand for each year of the planning period when considering both EEMs and DR strategies. It is worth mentioning that in the case the model takes into account only the inclusion of EEMs (i.e., DR strategies are not considered), 'TEE_new(f,y)' assumes a value equal to TEE since the 'SpecifiedAnnualTotalDemand(r,f,y)' is equal to the 'SpecifiedAnnualStandardDemand(r,f,y)' in this particular case. However, if both EEMs and DR strategies are considered in the long-term model, 'TEE_new(f,y)' assumes an adjusted value, as represented in Equation (3).

$$\text{TEE\_new}(f,y) = \frac{\sum_r \text{SpecifiedAnnualTotalDemand}(r,f,y)}{\sum_r \text{SpecifiedAnnualStandardDemand}(r,f,y)} \cdot TEE \tag{3}$$

The 'NewSpecifiedAnnualStandardDemand(r,f,y)' (**Step 3**) can be further estimated by applying Equation (4), which takes into account the contribution of the estimated ratio of energy efficiency 'TEE_new(f,y)'.

$$\text{NewSpecifiedAnnualStandardDemand}\ (r,f,y) = \text{SpecifiedAnnualStandardDemand}(r,f,y) \cdot [1 - \text{TEE\_new}(f,y)] \tag{4}$$

The value of the LACoSE estimated in **Stage 2** (see Fig. 3) is then used to calculate the total yearly cost of investing in energy efficiency 'TotalCost_EE(r,y)' as illustrated in Equation (5) - **Step 4**.

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[8] In Fig. 4, r represents the region; f the fuel and y the year (details can be found in Refs. [14,59]).

[9] This parameter is included exclusively to consider issues related to the inclusion of energy efficiency measures within the model.

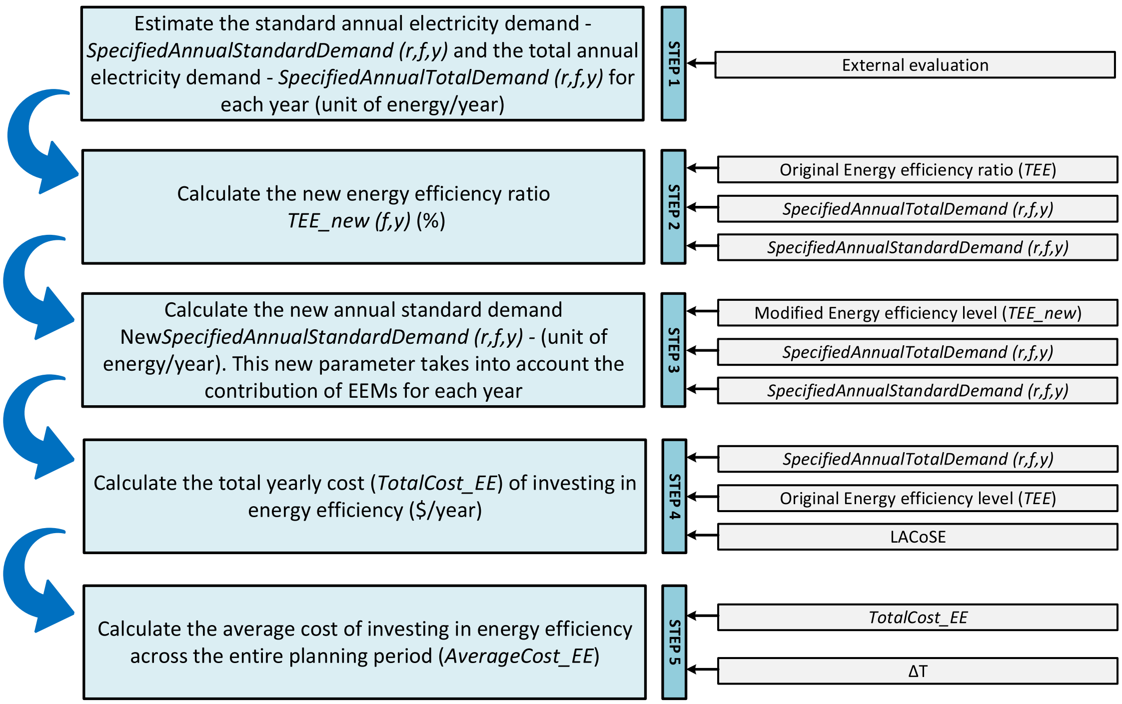

Fig. 4. A five-step methodological approach to account for the inclusion of EEMs into the long-term power planning model (**Stage 3** in Fig. 3).

$$\mathrm{TotalCost\_EE}(r,y)=\sum_{f}[\mathrm{SpecifiedAnnualTotalDemand}(r,f,y)\cdot TEE\cdot LACoSE] \tag{5}$$

Finally, Equation (6) accounts for estimating the average cost of investing in energy efficiency 'AverageCost_EE(r)' across the entire planning period (**Step 5**).

$$\mathrm{AverageCost\_EE}\ (r)=\frac{\sum_{y}\mathrm{TotalCost\_EE}\ (r,y)}{\Delta T} \tag{6}$$

The last stage of the proposed framework (**Stage 4- Fig. 3**) addresses the external technical and economic evaluation (see Section 4). Last but not least, the definition of energy policies can be further established for each scenario, as suggested in **Stage 4**.

4. Results and discussion

This section assesses the long-term effects of combining both EEMs and DR strategies on a high RES system. Table 1 describes the scenarios that will be evaluated, representing different levels of energy efficiency investments with different categories of DR strategies whose details and full description will be further presented. As stated previously, the Brazilian power system is considered as the case-study, justified by the following factors: (i) high-RES share; (ii) continental dimensions; (iii) access to data and (iv) vulnerability to climate change. For the technical DR potential estimation, no costs are associated with both load shedding and load shifting strategies and only technical restrictions are considered. However, for estimating the economic DR potential, in addition to the use of technical constraints, the variable costs to implement DR are also considered (see Ref. [40] and Ref. [15] for details). The main technical and economic scenario assumptions for DR implementation are presented in Table A.2 (Appendix A).

The modelling approach relies on theoretical, technical and economic assumptions[10]. For the sake of promoting a fairly comparison among the results, particular useful scenarios were selected from previous research, which accounted for evaluating the use of these particular DSM strategies separately for the assessed power system, i.e., the use of EEMs only (Scenario 2 - [14]) or DR strategies only (Scenarios 3, 5, 7 and 9 – Ref. [15]).

The following subsections move on to address the main findings of this research. Section 4.1 illustrates the Business as Usual (BaU) scenario (without DSM), which will be further compared to scenarios with DSM in Section 4.2. Section 4.2 also carries out a sensitivity analysis over the LACoSE variable (i.e., −50%, +50%, and +100% over the base value), focusing on verifying the extent to which the LACoSE might have over the general research findings.

4.1. Business as usual (BaU) scenario (without DSM)

This section attempts to describe the Business as Usual (BaU) scenario (Scenario 1) projected for 2040, which will be further used to compare with DSM scenarios. Fig. 5 illustrates the installed capacity for each power source across the entire planning period for scenario BaU (in percentage). Clearly, the overall percentage share of hydropower plants is projected to decrease steadily along with the planning period. The contribution share of solar PV[11] systems seems to have the highest growth, following the government projections. A flat contribution from thermoelectric power plants is also forecasted throughout the planning period. Together, these results provide important insights into the future role of each power source in the power system. The growth of VRE (especially from solar PV systems) can be particularly outlined.

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[10] The theoretical, technical and economic assumptions used along of this research within the modelling approach can be found on Ref. [14] and Ref. [15].

[11] It is worth mentioning that Solar PV has been exogenously included in the co-optimization model according to future government projections (see Ref. [43]).

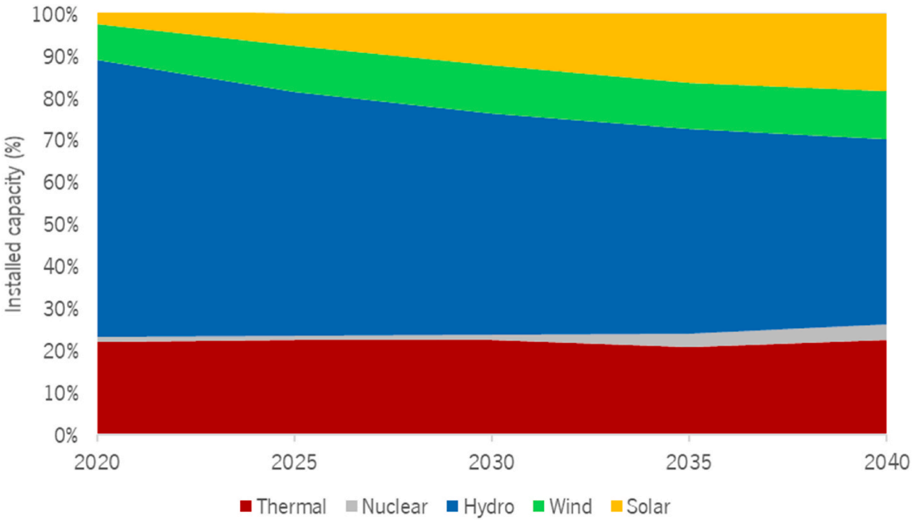


Fig. 5. Installed capacity for scenario BaU (%).

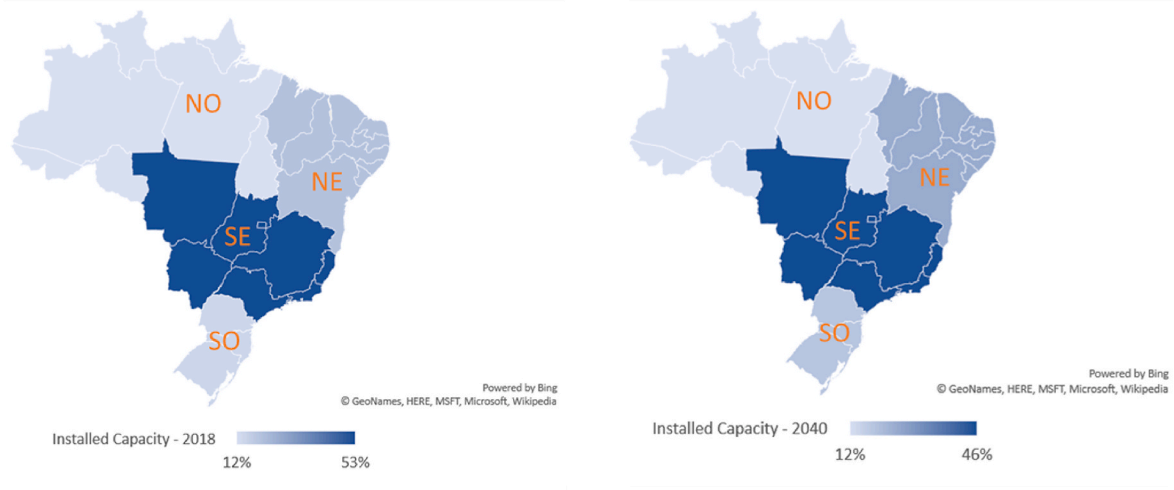


Fig. 6. Overall regional installed capacity for scenario BaU in 2018 and 2040 (%).

Fig. 6 illustrates the simulation results for the overall regional installed capacity for the first and last year of the planning period, respectively. It can be seen that although a decrease in the overall installed capacity seems to arise in the Southwest (SE) (reducing from 53% in 2018 to 46% in 2040), this region is projected to have the highest contribution share for the entire planning period. However, no significant differences in the overall installed capacity were found for the North (NO) (12% in 2018 and 12% in 2040). The single most striking observation to emerge from the data comparison comes from the overall installed capacity increase for both South (SO) (15% in 2018 and 18% in 2040) and Northwest (NE) (increasing from 20% in 2018 to 24% in 2040) regions.

Before examining the integrated role of DSM strategies in the power sector, the comparison between simulation results and government projections might be worthwhile. Fig. 7 illustrates this comparative analysis of the overall installed capacity between 2018 and 2027 (according to the government's available data [41]). In summary, the results illustrated in Fig. 7 reveal no significant differences between the simulation results and government projections for the period analysed.

4.2. Scenarios with demand-side management (DSM)

This section attempts to simulate a set of scenarios based on different categories of DSM strategies, including both EEMs and DR strategies. For the sake of clarity and to fairly compare scenarios that take into account the use of EEMs only, the same amount of investment in EE is considered for all scenarios (equal to 5%). This premise has been assumed for scenario 2 (which considers the implementation of EMMs only) and scenarios that take into account the use of both EEMs and DR strategies (i.e., scenarios 4, 6, 8 and 10). The detailed scenario description can be found in Table 1 and the simulation results for each scenario are presented in Table A.3 (Appendix A).

Fig. 8 illustrates the percentage changes for the new installed capacity, CO_2 emissions and total systems costs for all scenarios compared to scenario BaU (scenario 1). It can be seen from the data illustrated in Fig. 8 that compared to scenario 1 (BaU), there is a percentage reduction for the new installed capacity (varying from −1.0% to −20.6%), CO_2 emissions (−2.4% to −11.8%) and total system costs (−0.5% to −15.8%) for all scenarios.

Compared to scenario BaU, the highest decrease in the new installed capacity, CO_2 emissions, and total system costs were observed for scenario 4, whereas the smaller percentage reductions were observed for scenario 7. As presented in Table 1, scenario 4 represents the exploitation of the technical DR potential together with the implementation of 5% of EE (i.e., with a reduction in the final electricity demand of 5%). Compared to other scenarios, a possible explanation for the higher

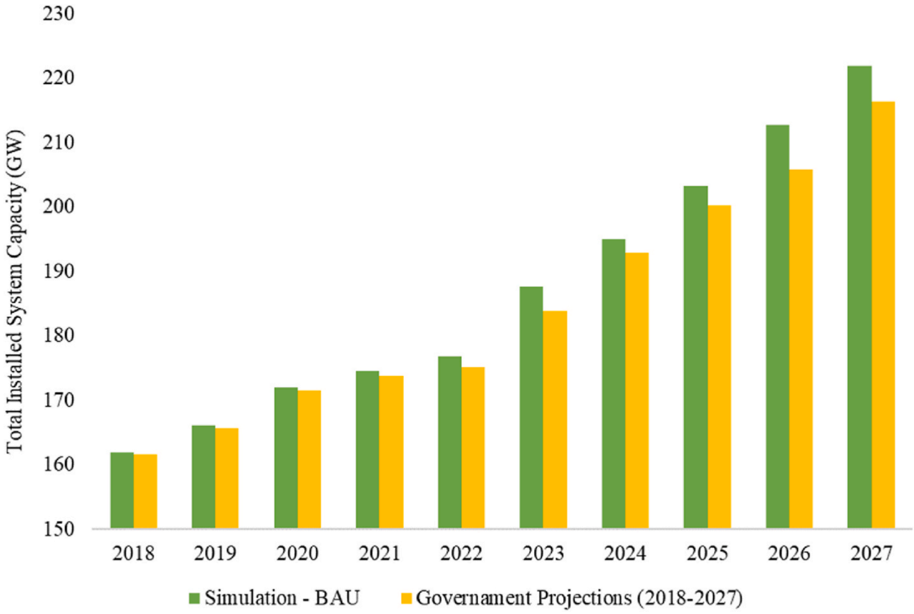
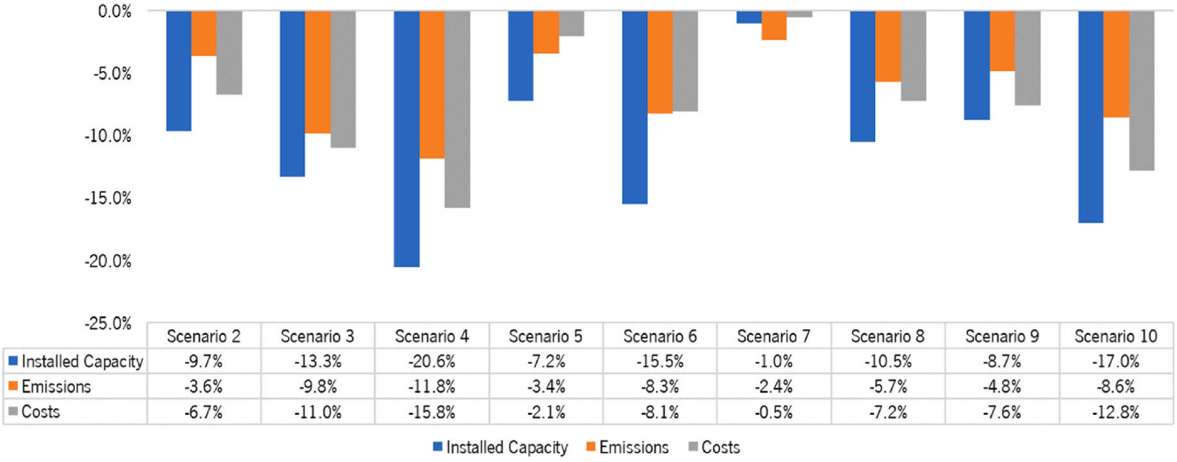


Fig. 7. Comparison between simulation results and government projections for scenario BaU (2018–2027).



	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
Installed Capacity	-9.7%	-13.3%	-20.6%	-7.2%	-15.5%	-1.0%	-10.5%	-8.7%	-17.0%
Emissions	-3.6%	-9.8%	-11.8%	-3.4%	-8.3%	-2.4%	-5.7%	-4.8%	-8.6%
Costs	-6.7%	-11.0%	-15.8%	-2.1%	-8.1%	-0.5%	-7.2%	-7.6%	-12.8%

Fig. 8. Percentage change for the new installed capacity, CO_2 emissions, and total system costs for each scenario compared to scenario 1 (BaU).

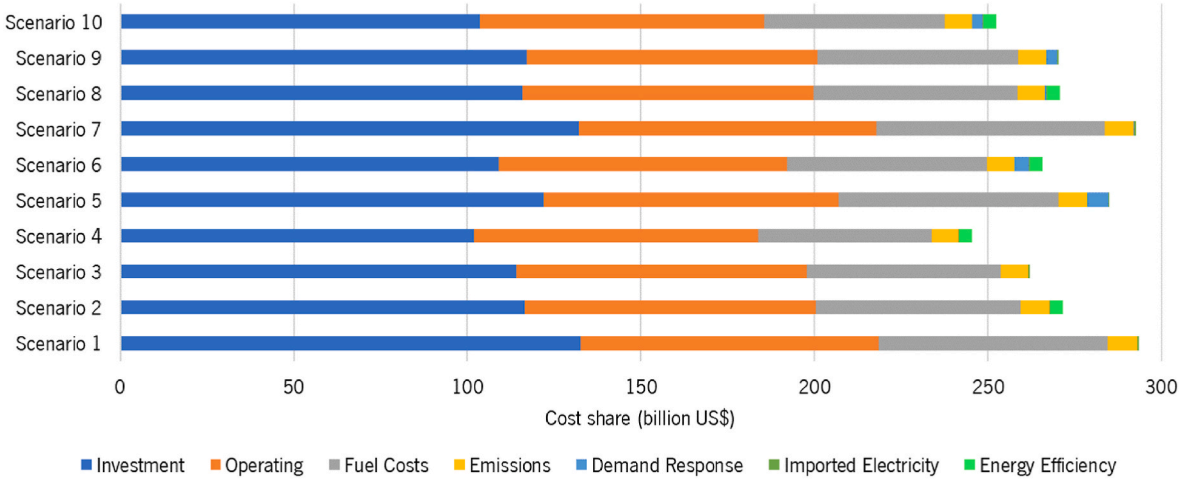


Fig. 9. Cost categories for each scenario.

reductions in the overall costs, newly installed capacity and CO_2 emissions for scenario 4 compared to scenario 1 seems to be related to the scenario assumptions, i.e., for the technical DR potential estimation, no variable costs are attributed to DR implementation. Thus, the reductions in the costs, installed capacity and CO_2 emissions are higher compared to other scenarios. However, for scenario 7 - which attempts to assess the economic DR potential for a typical drought year - the changes in the costs, newly installed capacity, and CO_2 emissions are relatively small compared to the other scenarios. The weakly associated benefits of implementing DR strategies for scenario 7 are interesting but not surprising since they can be partially explained by the higher shedding costs attributed to this drought scenario - which increased the need for new installed capacity and consequently, there was a significant increase in the fuel costs compared to other scenarios.

However, the single most striking observation from the data comparison comes from scenario 8 - which differs from scenario 7 by including 5% of EE (also for a drought year scenario). In this case, the reductions in the costs, installed capacity and CO_2 emissions are more insightful, indicating the great potential that the joint implementation of both DR and EE investments might play in the power system evaluated, particularly for drought years. Further analysis reveals that the economic benefits would be higher for a wet year case (scenario 10) than for a typical drought year scenario (scenario 8). A possible explanation for these results may be related to the costs attributed to load shedding, which are considerably lesser for the wet scenario than in the drought scenario. Hence, the need for additional installed capacity in the wet scenario is reduced from 189 GW (scenario 10) to 176 GW (scenario 8), whereas the fuel costs are reduced by 11%. It is worth mentioning that the reduced costs for implementing load shedding for typical wet years can be strictly associated with the good rainfall conditions associated with these years.

Fig. 9 breaks the costs for each scenario into seven categories (investment, operating, fuel, CO_2 emissions, demand-response, imported electricity, and energy efficiency costs). The findings reported in Fig. 9 clearly reveal that the investment costs represent the highest share for all scenarios, followed by operating and fuel costs. The costs for importing electricity, CO_2 emissions, energy efficiency, and the ones related to DR seem to be much lower compared to the investment, operating, and fuel costs for all scenarios.

The interpretation of research results may be better supported if scenarios would be compared in pairs (i.e., scenario 1 with scenario 2, scenario 3 with scenario 4, and so forth) since the second scenario of each pair represents the conditions of the previous scenario by also adding up a level of 5% of EE. This means that this comparison allows us to verify the impacts of using EE for each scenario together with the implementation of the different categories of DR.

Fig. 10 illustrates the percentage variation for the new installed capacity, CO_2 emissions, and costs for each pair of scenarios. It is also possible to hypothesise that among scenarios that assess the economic DR potential (i.e., scenarios 5, 6, 7, 8, 9 and 10); scenarios 7, 8, 9 and 10 are less likely to occur in reality compared to scenarios 5 and 6 since they represent extreme rainfall conditions. Therefore, the following analysis will evaluate scenario 6 (compared to scenario 5), since these scenarios would represent a typical year with average weather conditions and, therefore, may more accurately represent the future real power system conditions. As shown in Fig. 10, a reduction in the total system costs of about −6.2% is projected for scenario 6 compared to scenario 5. This would decrease CO_2 emissions and the new installed capacity by about −5.0% and −8.9%, respectively, for the entire planning period.

Moving on to analyse the long-term impact of using (i) only EE; (ii) DR only or (iii) both EE and DR strategies for the most likely to occur scenarios, i.e., scenario 2 (only EE), scenario 5 (economic DR potential) and scenario 6 (EE with the economic DR potential), a set of significant conclusions can be drawn. Compared to scenario 1 (BaU), the economic advantages for scenarios 2, 5 and 6 can be clearly identified since there is a cost reduction for all scenarios (see Fig. 9). In summary, these results also reveal a decrease slightly higher than −1.4% for scenario 6 compared to scenario 2 regarding the total system costs over the entire planning period. This would also promote a reduction of −4.8% and −6.4% in CO_2 emissions and new installed capacity, respectively.

The overall system costs for scenarios 2, 5, and 6 are estimated to be about US$ 225.4 billion, US$ 236.7 billion, and US$ 222.2 billion, respectively. What emerges from these results is the higher estimated costs for scenario 5 compared to scenario 2. However, the single most striking observation to emerge from the data comparison relates to the higher but limited economic benefits for scenario 6 compared to scenario 2. This suggests that the integration between EE and DR investments seems to represent the most cost-effective strategy, although the minor differences in the overall system costs for scenario 6) compared to scenario 2 . These results also underline the projected higher economic benefits of investments in EE compared to investments in DR only, supporting the hypothesis that the potential of investing only in DR is somewhat limited for the power system evaluated in this research. This rather interesting finding might be explained because the evaluated power system relies mostly on hydropower with low operating costs, which competes against the variable costs for implementing DR.

Our results also revealed that the new natural gas installed capacity would decrease from 32.9 GW (scenario 2) to 26.4 GW (scenario 6), which corresponds to a reduction of nearly −20%. This decrease is even higher when comparing scenario 6 with scenario 1, reaching a reduction of almost −37%, which comes with a decrease of −8.3% in the overall level of CO_2 emissions. However, as expected, the new installed capacity for natural gas for scenario 5 is substantially higher than for scenario 6 (+25%). No significant differences were found for the new natural gas installed capacity comparing scenario 5 with scenario 2 (+0.07%). The higher reduction in the natural gas installed capacity for the scenario with both EE and DR (scenario 6) compared to other scenarios suggests that the synergies brought about by this combination of DSM strategies may empower the benefits for the power system evaluated in this research. A further interesting outcome that emerged from the simulation results is the projected decrease for the new capacity of run-of-river hydropower plants, which accounted for a reduction of 14%, comparing scenario 6 with scenario 1. The carbon emissions for two selected scenarios (i.e., scenario 1 and scenario 6) are highlighted in Fig. 11. The increasing production from intermittent RES can explain the reduced emissions for the last ten years of the planning period, which reduced the thermal needs (especially from natural gas and coal power sources) for both scenarios analysed.

Fig. 12 illustrates the delay in investments in new installed capacity for the most relevant pair of scenarios. Fig. 12 is quite revealing in several ways and what can be clearly seen is the extent to which DSM might delay the investments in new installed capacity. Scenario 6 compared to scenario 1 (i.e., scenario 6/1) seems to have the highest potential to delay investments, particularly between 2020 and 2030, decreasing almost −26%. This finding might be partially explained by the combined benefits of implementing EE and DR in scenario 6 compared to scenario 1. Strong evidence for a higher potential to delay investments was found for 2020–2030 compared with the last planning period (2030–2040) for all scenarios. Together, these results provide important insights into the potential of delaying investments in the long-term, allowing at the same time the decision-makers to identify possible synergies between these different DSM strategies but also supporting the establishment of future energy policies in the country.

A sensitivity analysis has also been performed, adjusting the LACoSE by −50%, +50% and +100% over the base value to analyse how this variable may affect the evaluated scenarios. Fig. 13 shows the

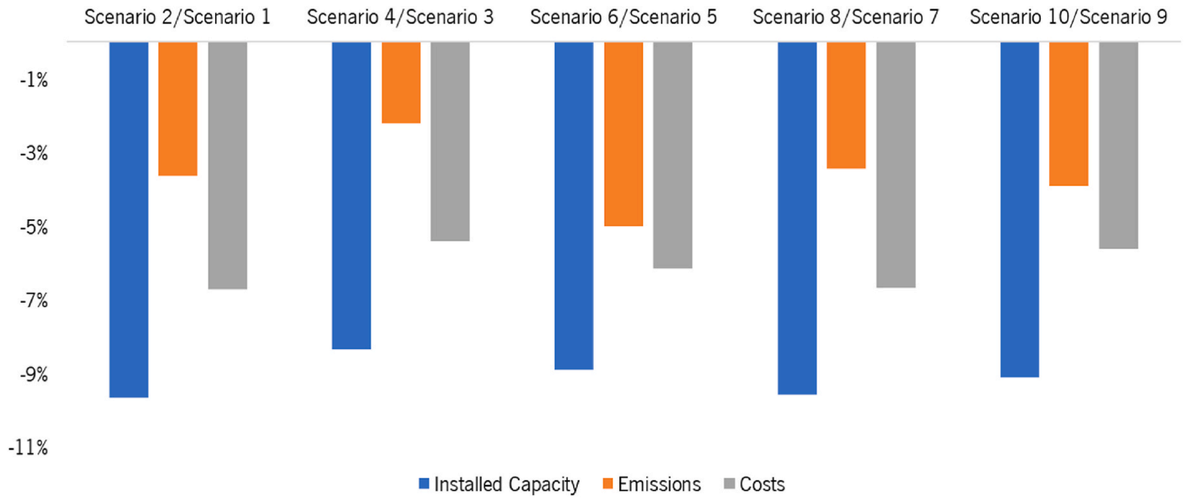


Fig. 10. Percentage variation for the new installed capacity, CO_2 emissions and costs.

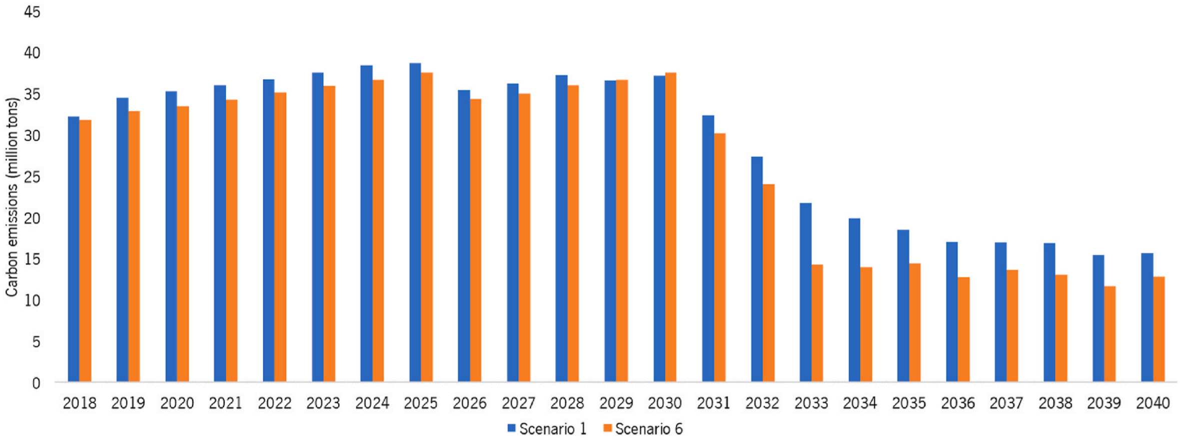


Fig. 11. Carbon emissions for scenarios 1 and 6.

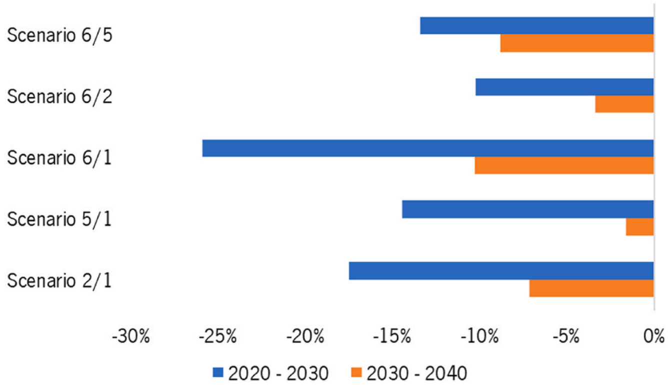


Fig. 12. Delay in investments for the new installed capacity for selected scenarios.

percentage cost variations for each pair of scenarios. Scenarios are compared in pairs to proper evaluate the impact of different prices for the LACoSE. Because of the small[12] costs related to the investments in EE compared to the total system costs for each scenario, no significant reductions were found between scenarios compared to the base LACoSE value. However, with successive increases in the LACoSE, it can be seen a substantial increase in the total system costs (see Fig. 13).

The following section discusses the main findings that emerged from our analysis, together with a summary of the main policy implications.

5. Conclusion and policy implications

Overall, this paper provides valuable insights into how integrating DSM resources and clean energy supply options might affect the long-term power planning strategies for renewable-based energy systems. The relevance and innovative aspects of this study are strongly related to a framework proposal for assessing the co-benefits between energy efficiency and demand-response on renewable-based energy systems from a long-term perspective. By incorporating energy efficiency concerns in the long-term model, this research also suggested methodological improvements in a previously developed co-optimization model.

The results of this study indicate that there would be a percentage reduction for the new installed capacity (ranging from −1.0% to −20.6%), CO_2 emissions (−2.4% to −11.8%), and overall system costs (−0.5% to −15.8%) for all scenarios when compared to scenario 1 (BaU). Investments in EE are projected to be more economically valuable than investing only in DR strategies. The second significant finding indicates that integrating EE and DR would empower the power system's overall benefits. The delay in supply-side investments was clearly identified for all scenarios. A clear advantage of implementing DR

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[12] The average value among scenarios that consider the use of 5% of EE was found to be only around 1.8% of the total system costs.

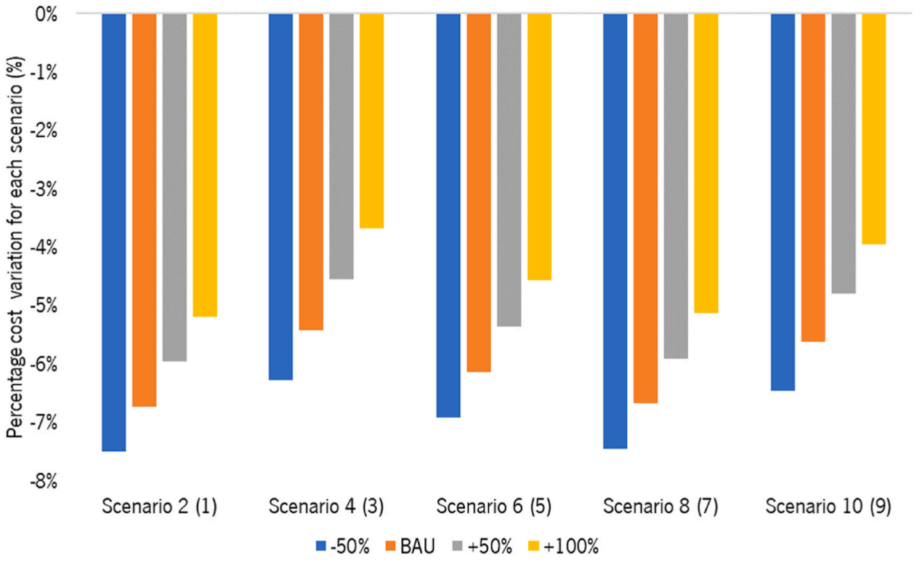

Fig. 13. Sensitivity analysis over the estimated LACoSE.

combined with EE, e.g., for scenario 6, is related to the synergies that might exist between these two categories of DSM strategies. Therefore, the economic impacts brought about by the use of EE and the economic DR potential exploitation (scenario 6) were more advantageous when compared to scenario 5. However, comparing scenario 5 with scenario 2, the advantages of investing in EE compared to DR investments only can be particularly outlined. This finding would also represent a limited contribution of investing only in DR, particularly for the Brazilian power system, which could be attributed to its high reliance on hydropower with low variable operating costs.

Therefore, these findings have significant implications and provide valuable insights into whether EE and DR strategies might be cost-effective. The insights gained from this study may assist both practitioners and policy-makers by empowering the development of more advanced DSM strategies and conceiving which technological innovation would have disruptive effects in the energy sector. This research might also support policy-makers in deciding whether the country's current policies and regulations are focused on achieving the required energy transition goals.

6. Limitations and future research

This section presents a lively discussion regarding the key advantages but also the limitations of this research. This study set out to provide a holistic assessment regarding the role of both EE and DR in a highly electrified hydropower-based energy system by evaluating how effective the implementation of a set of specific DSM strategies would be.

Although this research has successfully demonstrated the potential of integrating DSM within long-term power planning models, it has certain limitations in concentrating its efforts on technical and economic assessments. The study did not assess, for instance, the possible effects of biased consumer preferences or beliefs which might condition the overall findings since it assumed that end-users are rational and active economic agents. This also means that consumers' acceptance to load interventions would be a fruitful area for further work, which might take the non-rational behaviour of end-users into account. Ref. [42] addressed, for instance, the end user's psychological effects on DR actions, using behavioural economics for modelling DR.

It is worth mentioning that the long-term horizon carries out a set of uncertainties, such as the estimated future electricity demand. There are also many uncertainties related to urban mobility standards, technological and raw material competitiveness, the growth of the standard of living, consumer consumption patterns, and economic developments [43]. Because of both the lack of data regarding future EE projects and the possible future new technological developments, caution must be applied, as the findings might not be broadly generalisable.

Our assessment efforts focused on evaluating different percentage shares of EE in the long-term by reducing the electricity consumption in each year of the planning period. Future investigations could include the EEMs within the co-optimization model to compete against other supply-side options. This would bring another perspective on assessing whether EE would be cost-effective under a co-optimization approach.

For the sake of simplicity, the proposed methodology framework acknowledges that investments in EE are made in the first year of the planning period. This also means there is abundant room for further progress in determining the impact of making annual investments in EE projects. Research questions that could be asked include, for instance, what would be the economic effects in the case of distributing the EE investments along with the planning period. Therefore, additional studies are required to develop a complete picture of the impact of investing in EE projects under a long-term perspective. The Real Options Theory (ROA) could also be considered to account for management flexibility, such as the deferral of investing in DSM strategies.

Apart from economic aims, technical objectives may also be assessed in future research evaluating, for example, the extent to which DSM might have on reducing the peak demand but also the consequences of the rebound effect. A further study could assess the synergies between EE and the rebound effect, as better discussed in Refs. [44–46]. Using new methodologies to separate overlapping effects (i.e., between DR and EE) and analyse them individually also opens up new avenues for further research.

The long-term average cost of saved electricity (LACoSE) has been calculated based on administrative costs. However, future studies should also take into account the participant costs (i.e., related to the consumers), which would change the cost-effectiveness of future EE investments. The investment costs for DR implementation are not computed, mainly because there is currently little agreement on these values and further studies could focus on this direction. The assessment of the externalities associated with DSM also opens up new avenues for further research.

The combination of DR and EE into a well-thought-out integrated framework for both policy and implementation could be considered a further step to be developed by the government to increase the DSM potential in the country. The multiple benefits of using an integrated assessment for DSM strategies may bring a broad range of potential positive impacts compared to evaluating the strategies independently. The additional benefits from DSM implementation could also be assessed in further research using multicriteria decision analysis methods. Establishing the multiple and the range of synergies and benefits of implementing DSM strategies is beyond the scope of this study and future studies with more focus on these issues are therefore highly recommended.

Despite these limitations, this study certainly adds to our understanding and the results might support the current government pathways by providing a national and sectoral evaluation of the long-term impacts of investing in EE and DR measures.

Credit author statement

Géremi Gilson Dranka: Conceptualization, Formal Analysis, Methodology: Data curation, Writing - Original draft preparation. Paula Ferreira: Formal Analysis, Supervision, Visualization, Resources, Investigation, Writing - Review & Editing. Ismael F. Vaz: Supervision, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112936.

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