Optimisation approaches for energy systems

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The Insights Series has been developed to highlight key findings arising from Energy Systems Integration Partnership Programme (ESIPP) research in decarbonised energy systems. These publications share new insights into various aspects of energy decarbonisation that have been gained from a multidisciplinary team of researchers in ESIPP from institutions across Ireland.

The aim of this Insight paper is to summarize key findings from six research papers on the optimisation of energy systems. The authors illustrate differences and commonalities on the spatial scope, algorithms used, research methods and highlight key findings and insights. These six research papers show that optimization is a powerful tool to investigate engineering problems and identify more optimal solutions. Assessing multiple objectives and pushing system boundaries will lead to more efficient and more sustainable solutions, which are necessary on the path to carbon neutral societies.

Context

Over the duration of the Energy Systems Integration Partnership Programme (ESIPP), researchers have published several papers on the optimisation of energy systems over a wide range of applications, optimisation algorithms, and spatial scales. Analysis of some of these publications highlights related key insights for research focused on the optimisation of energy systems which are outlined in this paper.

ESIPP is a major Science Foundation Ireland-funded research programme that is coordinated by the University College Dublin (UCD) Energy Institute and delivered in partnership with industry and a multidisciplinary team of researchers from UCD, Trinity College Dublin, NUI Galway, the Economic and Social Research Institute (ESRI) and Dublin City University. The research programme has three strands: (i) addressing operational and technical aspects of the network, (ii) identifying energy solutions for people in their homes and businesses, and (iii) informing energy policy and infrastructure investment to enable energy decarbonisation. One focus of research in ESIPP is the different methodologies used to better understand the optimisation of energy systems. The Insights Series aims to provide insights into key research areas which may be of interest to policymakers and industry stakeholders and provide unique perspectives gained through a multidisciplinary research approach.

For decades, researchers and practitioners have created simulation models in the context of buildings and energy systems. Traditionally, based on an initial simulation model, various scenarios are compared to answer specific design or operational questions. In the context of zero energy buildings and carbon neutral societies, the boundaries of simulations need to be pushed. Therefore, a trend in simulation is to use optimisation techniques to find an optimal solution given one or many objectives considering system boundaries. For further background, Baños *et al.* (2011) give a review and introduction of optimisation methods in the context of energy systems.

In this Insights paper, we summarise the findings of research on optimisation applied to energy systems from the ESIPP research programme based on the following papers:

- Study 1: Aghamolaei, Shamsi, and O'Donnell (2020): "Feasibility Analysis of Community-Based PV Systems for Residential Districts: A Comparison of on-Site Centralized and Distributed PV Installations."
- Study 2: Soroudi and Jafari (2020): "Power to Air-transportation via Hydrogen."
- Study 3: Piselli et al. (2019): "Cool Roof Impact on Building Energy Need: The Role of Thermal Insulation with Varying Climate Conditions."
- Study 4: Andrade-Cabrera, Turner, and Finn (2019): "Augmented Ensemble Calibration of Lumped-Parameter Building Models."
- Study 5: Carragher et al. (2019): "Investment Analysis of Gas-Turbine Combined Heat and Power Systems for Commercial Buildings under Different Climatic and Market Scenarios."
- Study 6: Beiranvand and Cuffe (2020): "A Topological Sorting Approach to Identify Coherent Cut-Sets within Power Grids."

We first highlight the spatial scale to discuss various applications of optimisation. Furthermore, we identify the similar aspects of the research methods used in the studies above. The optimisation field provides a wide range of available algorithms and approaches; thus, we place the algorithms used in the six papers in context of general optimisation approaches. Finally, we discuss key findings, insights, and applications of the papers.

Research Description

A summary description of each of the six individual papers is provided in this section. The applications range from component level optimisation of cool roofs (Study 3) to optimisation of neighbourhoods (Study 4) or the electrical grid (Study 6). Two studies look across different scale boundaries. Study 4 developed a technique to improve calibrated building models at the building level so they can be used at the district level for retrofit analysis. Study 1 looked at optimisation across scale boundaries from the component to the neighbourhood level to answer the question if PV systems with storage are more efficient at the building or neighbourhood level.

These six papers show that optimisation can be performed for a wide range of applications at different or even across spatial scales. **Figure 1** illustrates the six papers along the spatial scale axis.

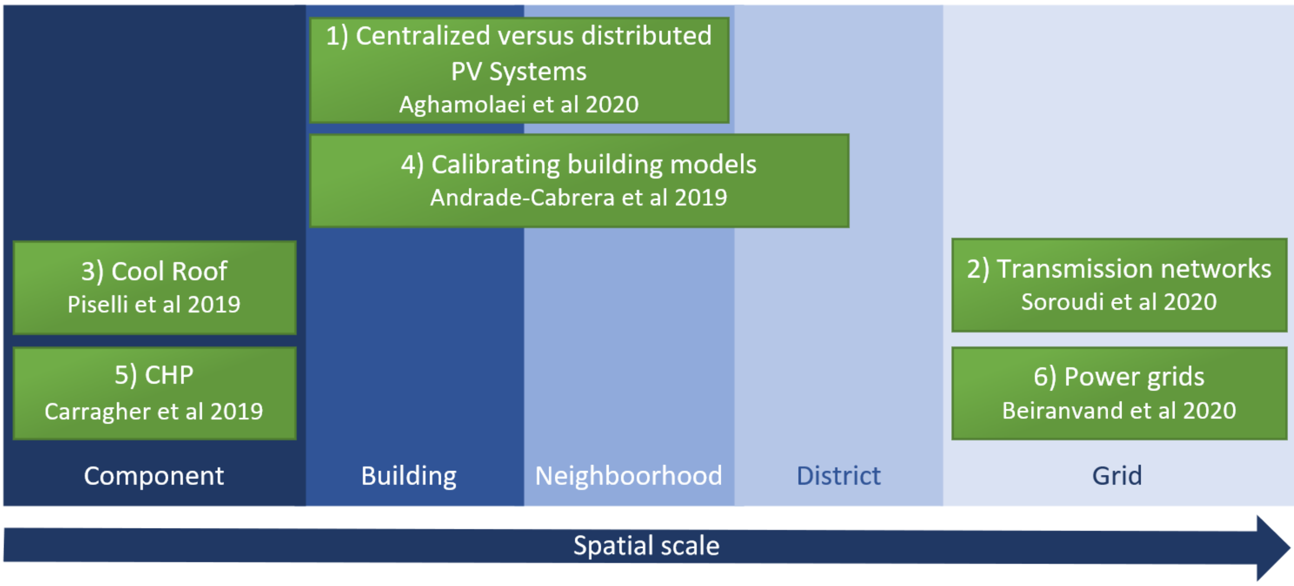

Figure 1: Spatial scale of optimisation applications

Research methods

The overarching research methodology of the six papers is following the traditional approach to develop a hypothesis and then test it with valid data. Here either a new approach is developed, or a new question is raised and a simulation with optimisation is performed. Study 6, focused on the electrical grid, uses a standard test system with two different test cases to validate their model while all others use either a reference building or representative transmission network to validate and test their model. This case study-based approach is very common in this research area, but also has some limitations due to the limited number of cases.

Types of algorithms

The summarised papers use different types of algorithms for optimisation. One key aspect when using optimisation is the objective. Commonly we differentiate between a single and multi-objective problem. A typical single objective could be to minimize costs (e.g., Study 3), whereas an example for multi-objectives is technical and economic optimisation (e.g., Study 5). Two papers (e.g., Studies 2 and 4) use optimisation algorithms with a single objective within the population-based meta-heuristic algorithm category. Population-based optimisation algorithms are based on a "population of solutions which evolve during a given number of iterations" (Baños et al. 2011) and result in a reduced number of possible solutions. One paper (3) uses a trajectory optimisation strategy with a single objective. Trajectory optimisation algorithms "use a single solution during the search process and the outcome is also a single optimized solution" (Baños et al. 2011).

The remaining three studies (1, 5 and 6) use hybrid optimisation approaches, either using existing optimisation applications with a single objective (e.g., HOMER) or with two objectives (techno and economic). **Figure 2** illustrates optimisation strategies of all six papers in the context of generic optimisation categories. It highlights the six papers on two different scales, single versus multi-objective as well as differentiates between population-based and trajectory-based optimisation methods. In addition, some papers use a combination of approaches and can be placed in the hybrid category.

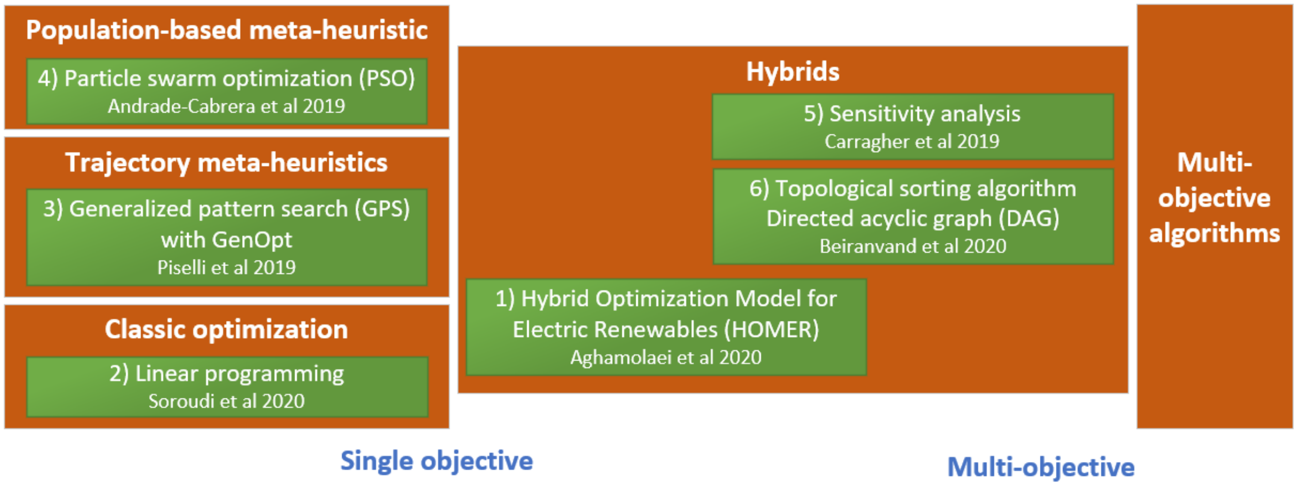

Figure 2: Optimisation algorithms

We summarise a description of all applied algorithms of each paper here:

- Study 1 uses HOMER (Hybrid Optimization Model for Electric Renewables) to assess centralized and distributed community-based PV-systems. They use a single objective cost function.
- Study 2 uses a commercial solver called CPLEX for solving the proposed linear formulation. They use a single objective function.
- Study 3 uses Ganot to execute a generalized pattern search (GPS) based on a thermal simulation with EnergyPlus. They use a single objective cost function.
- Study 4 uses a particle swarm optimisation (PSO) to minimize the calibration error of simulated models compared to measured data. They use a single objective function.
- Study 5 generates energy consumption profiles with EnergyPlus that feed into a steady state regime simulated in Matlab. In this context they perform a sensitivity analysis to investigate gas-turbine combined heat and power (CHP) systems. They use a two-objective function for techno and economic optimisation.
- Study 6 uses a novel topological sorting algorithm in combination with a directed acyclic graph (DAG) to find bottlenecks in an electrical grid. They use a two-objective function.

Findings/Discussion

A society thriving towards sustainability and decarbonisation needs to optimize existing technical systems as well as develop new concepts. The papers summarised here use current optimisation techniques to increase the performance of a specific technical system, either at a component, building, neighbourhood, district, or network scale. The trend in these papers is to use sophisticated optimisation algorithms to find better solutions to today's design and operational challenges.

All summarised research papers use one or two test cases to test the developed hypothesis or model. These studies highlight that for more robust results, a key limitation to ground these methods would be to increase test cases and further utilise real data from buildings or other scales.

The key findings of these papers are:

- The key parameters for building annual energy efficiency of cool roofs are layer thickness of thermal insulation and solar reflectance of the roof (Study 3).
- Specific seasonal variation of thermal energy demand is strongly affecting the performance of a CHP unit (Study 5).
- Neighbourhood scale PV systems with electrical storage are generally more efficient than single house installations due to the reproduction in overall system size and associated costs. (Study 1).
- Developed a novel topological sorting approach for Directed Acyclic Graphs (DAG) to identify distinctive topological sorts. The resulting topological sorts enable the detection of bottlenecks within power grids and the identification of heavily congested flowgates (Study 6).
- Minimizing calibration errors of building models by enhancing the Ensemble model by adding glazing and infiltration parameters in a retrofit scenario (Study 4).
- The development of a framework to assess the capability of Irish transmission network to use the excess amount of available wind resources and convert it to the green hydrogen for future aviation transport systems (Study 2).

Through the findings in the papers, guidelines for different design challenges can be established considering the system boundaries such as different climate conditions or different market price scenarios.

Key Insights and Application

As indicated above these papers include guidelines for designing energy systems based on an optimisation study. These guidelines can influence design practise but are limited by the optimisation system boundaries. Therefore, providing easier access to optimisation tools and techniques to practitioners would greatly enhance the optimisation possibilities especially across system boundaries. A CHP that is highly dependent on the thermal energy demand could be integrated into a district heating system at the neighbourhood level to use excessive thermal energy and increase the overall system performance. The district level PV system may be more efficient compared to single house systems but could cause more challenges to the reliability of the electrical grid than distributed systems or vice versa.

Going forward, multi-objective optimisation that improves environmental and economic aspects should be applied to many technical challenges to identify the most feasible solutions. While for a given application a single objective optimisation is useful, to assess and improve technical systems in the future, we should use optimisation on multi-objectives, such as environmental and economic aspects. Finding optimized solutions for both environmental and economic objectives will underline that technical solutions that combine both aspects are technically possible and economically meaningful.

Optimisation techniques are a useful tool to help us improve energy systems that are needed now and in the future that cross scale boundaries, have multi-objectives and consider multiple systems. Enhancing those techniques even further and pushing them to make their use more commonplace will be a key aspect of improving our overall systems performance. Thus, using multi-dimensional performance analysis should become a standard tool in the design process of energy systems and could be supported or even required by future energy codes. While a standardization of tools is very difficult due to the large number of different simulation and optimisation tools available, it may be useful to require a standard result data set to easily evaluate key characteristics and insights of the optimisation study. A first step could be to require the analysis of key objectives and a meaningful number of different alternatives to be considered, so that practitioners are pushed to use optimisation tools which make this analysis much easier and quicker. In addition, considering multi-objectives across system boundaries could greatly enhance overall system performance and should be supported in future energy codes.

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