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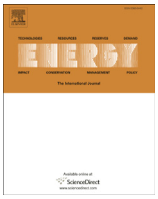

New formulations of the ‘energy hub’ model to address operational constraints

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ABSTRACT

We present new formulations of the ‘energy hub’ model and evaluate their performance. The energy hub model consists of a mixed-integer linear programming problem that balances energy demand and supply between multiple energy carriers by determining the optimal conversion and storage schedule within certain constraints. The new formulations extend the model to account for performance constraints concerning system efficiencies, storage losses and operating limits. Each formulation allows a more accurate representation of real plant performance to be included in the optimisation, giving more accurate optimised schedules and carbon emissions totals.

The first major innovation is a means of limiting the number of state changes (startups or shutdowns). This is achieved by specifying a minimum time for which the plant must operate once it is running. The second innovation is the use of stepwise approximations of efficiency curves, thus allowing part-load behaviour to be accurately simulated using a linear model. The third innovation adds a storage loss term that is a percentage of the current amount stored, rather than a fixed value.

The new formulations are demonstrated in an example case, where the impact on the optimal schedule is observed. They are also analysed for each week of the heating season, and their impact on the time taken to find the optimal solution is also discussed. Overall changes in the predicted carbon emissions of up to 22% were found, highlighting the importance of accurate plant representation in energy hub models.

1. Introduction

1.1. *Background*

The energy hub concept was introduced by Geidl and Andersson [11–13]. It is a powerful conceptual model that can be used to represent the interactions of many energy conversion and storage technologies. The original aim was to develop a model that was “sufficiently general to cover all types of energy flows, but concrete enough to make statements about actual systems” [11]. Possible energy streams include electrical (AC and DC; different voltages), thermal (different temperatures), and chemical (natural gas, hydrogen). Examples of application areas of the energy hub concept include power plants, industrial facilities and urban areas.

One of the benefits of the energy hub model is that is can be combined with fast, reliable optimisation approaches like linear programming. Depending on the model formulation, more advanced optimisation approaches may be needed that can include integer constraints or nonlinearities. There are algorithms that address these issues (for example nonlinear programming), but these introduce problems of reliability and computational cost. Alternatively, formulations may be used such as those developed here that avoid the need for advanced optimisation approaches but increase the difficulty of the core problem by adding many constraints. It is very difficult (and often impossible) to predict how ‘hard’ an optimisation problem is, and thus how long it will take to solve. Relatively small changes can increase the time needed by orders of magnitude. This is particularly problematic if the energy hub solver is embedded in a wider optimisation process and must be solved many times over.

It is not possible to determine from first principles whether it is better to use an advanced algorithm or a complicated model formulation. This work addresses this issue experimentally by introducing new formulations of the energy hub model and assessing their performance and run time.

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Nomenclature

β	Percentage loss from store per timestep
$\delta^i_+(t)$	Binary variable controlling charging of store i
$\delta^i_-(t)$	Binary variable controlling discharging of store i
η_σ	Plant efficiency at part load σ
$\gamma^i(t)$	Binary variable controlling stepwise plant
σ	Part-load ratio
Θ	Energy conversion matrix C in sparse form
A_+	Charging efficiency matrix
A_-	Discharging efficiency matrix
C	Conversion matrix between input and output energy streams
$E(t)$	Contents of stores at time t
E_0	Initial contents of stores
$E_{\max}$	Maximum storage level (capacity)
$E_{\min}$	Minimum storage level
F	Coefficients of energy inputs in objective function
I	Input energy streams
I_i	Input of energy stream i
$I_{\max}$	Maximum energy input for each stream
L	Output energy streams
L_i	Output of energy stream i
N	Total number of timesteps
n	Number of timesteps up to time t
n_{steps}	Number of steps in stepwise approximation
P	Conversion for each input–output pair
P^{b}_{a}	Decision variable determining conversion of input a to output b
$P_{\max}$	Capacity of plant for each conversion
$P_{\min}$	Minimum plant output for each conversion
Q_+	Energy used to charge stores
$Q^{\max}_+$	Maximum charging per timestep
Q_-	Energy discharged from stores
$Q^{\max}_-$	Maximum discharging per timestep
t	Current timestep
t_{m}	Minimum operational time
$z(t)$	Discriminant between successive decision variables

1.2. Previous research

Many works have applied the energy hub concept to different problems. Others have used conceptually similar formulations of linear programming problems to address the same issues. This section presents an overview of key past research in this area.

Geidl and Andersson [11] originally proposed the energy hub conceptual model in a nonlinear formulation. They later [12,13] added the linear formulation. They also proposed the power flow model for interactions between a network of hubs, based on a set of nonlinear constraints that describe network connectivity and transmission losses. They applied the model to optimal dispatch and power flow problems, using examples that included combined heat and power (CHP) engines, gas furnaces and heat exchangers. They discussed the use of storage and it's inclusion in the model, but presented only the steady-state case, i.e. without time-dependent parameters.

Fabrizio et al. [9] developed a transient, nonlinear version of the energy hub that allowed for changes to efficiencies. This was used to account for changes due to plant capacity (bigger equipment is more efficient), partial loading of plant (efficiency is often highest at full load), changes in system temperatures and climatic parameters, and variable pricing tariffs. They also included changes in plant capacity as design variables to be optimised. They state that this formulation is more suited to application in later design stages, when more precise information is available. There is no information on the time taken to solve the optimisation problem, and no comparison is given to simpler formulations. The approach was developed specifically for problems in building design, and a case study is presented that includes a high degree of detail concerning the performance of equipment used in building energy systems. The same group [8] also developed a formulation of the energy hub model for optimising multi-energy systems in buildings at an earlier stage. They used the generalized reduced gradient approach to iteratively optimise the nonlinear problem.

Parisio et al. [18] implemented a robust optimisation approach to the control of an energy hub with uncertain plant efficiencies. They used a time-dependent formulation that used binary variables to control storage, and a mixed-integer linear programming optimisation approach. They applied this to a case study that included CHP, hydrogen production and a fuel cell. They used the robust optimisation technique of [2] to find solutions that are resilient to bounded uncertainties regarding equipment efficiency. The approach could be used for uncertainty in energy demands or costs, though the necessary assumption of independence among random variables is less realistic in that case.

Ashouri et al [1] developed a framework for applying mixed-integer linear programming to the selection, sizing and control of building energy systems. Though they do not refer to it as such, their approach could be regarded as a specific case of the energy hub model, adapted to building energy systems. Converters and storages were applied to three energy streams (electricity, heating, cooling).

Maréchal has undertaken substantial work applying optimisation techniques to very detailed energy system models. A paper with Kalitventzeff [17] applied mixed-integer linear programming techniques to the selection of utility systems in combination with effect modelling and expert systems. Subsequent work with Weber [20] on the optimisation of district energy systems applied a structuring process to divide the problem into nonlinear and mixed-integer parts. Fazlollahi and Maréchal [10] also explored an alternative approach that combined mixed-integer nonlinear programming with evolutionary approaches that also allows multi-objective optimisation.

1.3. This paper

In this work, we explore different energy hub formulations and different optimisation approaches. First, the energy hub concept is described in detail, following the formulations used by Geidl and Andersson [11] and Parisio et al. [18]. An example formulation is then given for a simple energy hub. Next, details are given of various optimisation approaches that can be used in conjunction with the energy hub model to solve energy dispatch problems. The following section presents a number of novel formulations that extend the energy hub optimisation to include new constraints, which are shown to be necessary if an accurate estimate of operational schedule or the resulting carbon emissions is required. Existing and new formulations are applied to a simple case study using various optimisation approaches. The results focus on the effectiveness of the optimisation and the impact of choices regarding the formulation of the energy hub model.

2. The energy hub concept

The energy hub relates a vector of energy inputs I to outputs L by means of a conversion matrix C, as shown in Eq. (1) (the original

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