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The value(s) of flexible heat pumps – Assessment of technical and economic conditions

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HIGHLIGHTS

- Modeling flexible heat pump operation based on first principles.
- Assessing the value of flexible heat pumps under real-time pricing.
- Drivers for the economic viability are explained.
- Analyses of manifold sensitivities provide highly robust conclusions.
- For very few set-ups/conditions, flexibility measures are economically viable.

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ABSTRACT

Residential heat pumps are one of the most resource-efficient means for space heating, and their market shares are expected to rise substantially over the next few decades. Through installation of a thermal energy storage, the operation of a heat pump is – to a certain extent – decoupled from heat demand. Such flexibility is frequently claimed to bear a high potential for demand-side management. This study investigates the operational cost savings achievable through the use of such a flexibility option. To this end, a dynamic model of a coupled building and heating system is developed, and several economic model-predictive control strategies for heat-pump operation are derived. These strategies exploit real-time prices and the flexibility of the thermal capacity of the building and/or heat storage. The proposed algorithms are applied using perfect and imperfect foresight. Furthermore, different variations of real-time prices along with several building and storage configurations are investigated. The resulting operational cost savings are contrasted with different paths of investment-cost developments. Results of this investigation demonstrate that investments in flexibility measures (smart-home equipment, thermal storage capacity, etc.) are, for the most part, economically unviable. However, it is also realized that economic feasibility depends greatly on the technical set-up and economic conditions. This study demonstrates that the potential of flexible heat-pump operation is frequently overstated. On the other hand, configurations for which overall system-cost savings could be deemed achievable are also identified.

1. Introduction

1.1. Motivation

Integration of large amounts of decentralized and nondispatchable renewables-based electricity generation (RES) poses great challenges to electricity systems. The location of variable electricity supply frequently does not coincide with that of its consumption, and network capacities are scarce because network expansion, in countries like Germany and others, has not been undertaken in sync with rising RES volumes. These circumstances have increased the need for preventive and curative congestion management measures.[1] Further (envisaged) effects include increase in short-term reserve requirements along with costs incurred for balancing (cf. [3]) and network extension (cf. [4]). The said challenges can be tackled in several ways. In addition to the classical approach of reinforcing transmission and distribution networks, an alternate means involves the use of demand-side management (DSM).

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[1] For instance, Lew et al. [1] describe an increase in curtailment of RES at an international level, whereas BNetzA et al. [2] summarize curtailment and redispatch quantities and corresponding costs for Germany alone.

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Nomenclature

Abbreviations and Definitions

COP	coefficient of performance
DSM	demand-side management
ECC	end-consumer charge
Efficient House	building as defined in Section 5.2
Excl-TES-Loss	method of not accounting for TES losses
HE	(electrical auxiliary) heat element
HP	heat pump
HVAC	heating, ventilation and air conditioning
Incl-TES-Loss	method of accounting for TES losses
KKT	Karush-Kuhn-Tucker
LP	linear program
MAE	mean absolute error
MPC	model-predictive control
NEP	(German) grid development plan (derived from the German abbreviation “**N**etz**e**ntwicklungs**p**lan”)
PV	photovoltaics
REL	renewable energy levy (as e.g. applicable according to the German Renewable Energy Act)
RES	renewable energy sources
RMSE	root mean square error
SC-MPC	single-constraint model-predictive control
Standard House	building as defined in Section 4.1
T-lift	TC-MPC with the additional and combined optimization of the set temperature of the heating zone
TC-MPC	temperature-constrained model-predictive control
TES	thermal energy storage
ToU	time-of-use
VARMA	vector autoregressive moving average
VAT	value added tax

Symbols

$\mathbf{A}$	coefficient matrix of state-space representation [1/h] (unit of each element)
α	parameter for the price forecast [–]
A_{f-z}	surface of heated floor subject to heat transfer to the heating zone [m^2]
a_j	parameters for the polynomial approximating $\dot{Q}_{hp,nom}$ [kW], [kW/K], [kW/K^2] (unit depending on j)
A_p	cross section of piping of the floor heating [m^2]
$A_{tes-sur}$	surface of TES subject to heat transfer to its surroundings [m^2]
A_{w-f}	inner surface of pipes of the floor heating subject to heat transfer to the heated floor [m^2]
A_{z-amb}	surface relevant for heat transfer from the heating zone to the environment [m^2]
$\mathbf{B_1}$	coefficient matrix for the control vector [K/kWh]
$\mathbf{B_2}$	coefficient matrix for the excitation vector [K/kWh], [1/h] (unit depending on column/row)
β_i	error weight for price forecast [–]
b_j	parameters for the polynomial approximating $P_{hp,nom}$ [kW], [kW/K], [kW/K^2] (unit depending on j)
$\widetilde{C}_t^{24}$	total expected operational costs for the next 24 h [€]
c_c	specific heat capacity of concrete screed [kWh/(kg K)]
COP	integrated cyclic coefficient of performance [–]
COP_{nom}	nominal coefficient of performance [–]
c_w	specific heat capacity of water [kWh/(kg K)]
C_z	absolute heat capacity of heating zone [kWh/K]
$\Delta E_{sys,t}$	term for heat demand forecast taking into account a deficit/surplus of sensible heat of the system [kWh]
$\Delta\dot{Q}_{lift,t}$	difference in heat demand due to a change of the set temperature (ΔT_z) [kW]
Δt	time increment of control algorithm (1 h)
ΔT_z	temperature increase (above T_{comf}) [K]
$\Delta T_{z,max}$	maximum allowable temperature increase (above T_{comf}) [K]
$\mathbf{e}$	vector of all 1s [–] (unit of each element)
$\mathbf{E}$	identity matrix [–] (unit of each element)
$\dot{E}_z$	term for mass flow control of the circulation pump taking into account the deficit/surplus of sensible heat of the building [kW]
ε	forecast error of the ambient temperature forecast (index T) [K]/electricity price forecast (index p) [€/kWh]
i	superscript indicating the look-ahead hour
I	set of hours of the look-ahead horizon (including $i = 0$)
I'	set of hours of the look-ahead horizon reduced by $i = 24$
η_{he}	efficiency of the heating element [–]
$\mathbf{\Theta}$	abbreviation as defined in Eq. (30) [–] (unit of each element)
$\widetilde{\mathbf{f}}$	free response of T_{tes} [K] (unit of each element)
f_{num}	numerical constant (= 1.2) [–]
$\boldsymbol{\kappa}$	abbreviation as defined in Eq. (30) [–] (unit of each element)
$\mathscr{L}$	Lagrange function
$\widetilde{\lambda}_{d,t}^{i,*}$	Lagrange multiplier of the demand constraint
$\widetilde{\lambda}_{he,t}^{i,*}$	Lagrange multiplier of the capacity constraints of the HE [€/KWh]
$\widetilde{\lambda}_{hp,t}^{i,*}$	Lagrange multiplier of the capacity constraints of the HP [€/KW]
l_p	length of the pipes of the floor-heating system [m]
μ	abbreviation as defined in Eq. (29) [–]
$\dot{m}_w$	mass flow of water through the pipes of the floor-heating system [kg/h]
$\dot{m}_{w,max}$	nominal mass flow of the circulation pump [kg/h]
ν	abbreviation as defined in Eq. (29) [–]
p_{el}	electricity price [€/kWh]
P_{he}	electric power of the heating element [kW]
	electric capacity of the heating element [kW]
P_{hp}	electric power of the heating element [kW]
$P_{hp,nom}$	electric capacity of the heating element [kW]
$p_{th,24h-realized,t}$	supply-weighted heat price over the last 24 h [€/kWh]
$\dot{Q}_{he}$	usable heat flux from the HE to the TES [kW]
$\dot{Q}_{hp}$	usable heat flux from the HP to the TES [kW]
$\dot{Q}_{hp,nom}$	nominal heating capacity of the HP [kW]
$\dot{Q}_{int}$	internal heat gains of the building [kW]
$\dot{Q}_{sol}$	solar heat gains of the building [kW]
$\widetilde{Q}_{sys,dem,t}^{24}$	forecast heat demand of the system for the next 24 h [kWh]
$\dot{Q}_{tes-sur}$	heat flux from the TES to its surroundings [kW]
$\dot{Q}_{z,dem}$	instantaneous heat demand of the building [kW]
$\dot{Q}_{z-amb}$	heat flux from the heating zone to the ambient air [kW]
$\dot{Q}_{z-env,t}$	heat flux from the building to the environment [kW]
$\dot{Q}_{z-amb,t}$	heat flux from the building (heating zone) to the ambient air [kW]
$\dot{Q}_{he,nom}$	nominal heating capacity of the HE [kW]
ρ_c	density of concrete screed [kg/m^3]
ρ_w	density of water [kg/m^3]
t	index for time step of control algorithm
$\mathbf{T}$	vector of state variables [K] (unit of each element)
T_{amb}	ambient temperature [K]
T_{comf}	comfort temperature (= set value of the zone temperature) [K]
T_f	temperature of heated floor (concrete screed) [K]
T_f^{ref}	reference temperature of heated floor (concrete screed) [K]