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The ambivalence of personal control over indoor climate - how much personal control is adequate?

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Abstract. Literature sets personal control over indoor environmental conditions in relation to the gap between predicted and actual energy use, the gap between predicted and observed user satisfaction, and health aspects. A focus on building energy performance often leads to the proposal of more automated and less occupant control of the indoor environment. However, a high degree of personal control is desirable because research shows that a low degree (or no) personal control highly correlates with indoor environmental dissatisfaction and sick building syndrome symptoms. These two tendencies seem contradictory and optimisation almost impossible. Based on current efficiency classes describing the effect of room automation systems on building energy use during operation, fundamental thoughts related to thermophysiology and control, recent laboratory experiments, important lessons learnt from post-occupancy studies, and documented conceptual frameworks on the level of control perceived, we discuss the ambivalence of personal control and how much personal control is adequate. Often-proposed solutions ranging from fully automated controls, over manual controls to dummy controls are discussed according to their effect on a) building energy use during operation and b) occupants perceived control. The discussion points to the importance of *adequate* personal control. In order to meet the goals for nearly zero energy buildings *and* for a human-centric design, there is the need to establish design procedures for adequate personal control as part of the design process.

1 Introduction

The EU Energy performance of Buildings Directive EPBD, amendment 2018 (2018/844/EU) states the energy efficiency goal that all new buildings must be nearly zero energy buildings (NZEB) from 31 December 2020. In order to reach these goals not only the share of renewable energy in the grid will increase, also the big role consumers of energy play needs to be considered. Building occupants are the end-users of the energy consumed in buildings. The European commission (EC) states, that energy efficiency in buildings shall be enhanced with smart technologies, especially that i) ICT-based solutions in buildings can contribute to saving energy and ii) introducing the concept of Smartness Indicator for buildings that will characterize the ability of a building to manage itself, interact with occupants and take part in demand response and contribute to smooth, safe and optimal operation of connected energy assets. Therefore it can be expected that automated solutions in all energy related processes in buildings will become more prevalent in the future.

Indoor climate conditions in buildings are aimed to be set to comfortable conditions for their occupants and lead to energy use in certain periods of the year. Observed gaps between predicted and actual energy use in low energy buildings in many countries have directed the focus on the role occupants play in the energy use of buildings [1-6].

Occupant behaviour in buildings has often been summarised as being random, being too late (occupants do not act in advance, wait with acting until discomfort has been perceived for a while), tending to overcompensate minor discomfort, or tending to use the easiest to apply control means not necessarily the most appropriate [7]. This knowledge gained mainly in office buildings was confirmed for residential buildings, [e.g. 8, 9]. Therefore, it is often assumed and proposed by engineers and legislation [10, 11] that *more room automation* using advanced sensor and control technologies and *less occupant control* could solve the problem of the energy performance gap and reduce energy use during operation.

Complaints about indoor climate from real building operation practice leading to a large number of post-occupancy evaluation studies have shown that there is also a performance gap in expected and real proportion of satisfied occupants regarding the indoor climate. Furthermore, some occupants even suffer from symptoms summarised under the sick building syndrome. A

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variable, which is related to all three effects: i.e. energy performance gap, satisfaction gap, and health effects e.g. sick building syndrome, as aforementioned, is personal (or individual) control of occupants over their indoor climate. Research shows that occupants wish to have control over their indoor climate, especially when it is their home, and that they have difficulties to accept too much automatic control, followed among others by the above mentioned dissatisfaction with the indoor climate and health effects. If the most direct ways of alleviating discomfort (those control means most occupants like to use: adjustable thermostats, openable windows) are not offered to occupants, people find other way to satisfy their needs [e.g. 12, 13].

Following research showing that a low degree (or no) personal control is highly correlated with indoor environmental dissatisfaction [14-18] and sick building syndrome symptoms [18, 19-22], a *high degree of personal control over the indoor climate seems to be desirable*. As mentioned above, *more room automation* and *less occupant control* is assumed to reduce energy use during operation These two tendencies, *room automation's potential for operational energy conservation* and the *occupants' need for control*, appear to be contradictory and an optimisation appears almost impossible.

Above mentioned summarised research point towards a high importance of personal control as a key factor to rethink our common understanding of indoor environmental design and the interaction of humans with their indoor built environment. The aim of this paper is to jointly discuss the two tendencies: more automated control (for lower building operational energy use) and more occupant control (for more satisfied users) and to find out how contradictory they are. We also discuss other ways than room automation to mitigate discomfort and their impact on energy use during building operation and occupant perception.

We base our discussion on considerations of control of building energy use during operation in EN 15232 [11] (section 2) and on recent research findings related to the meaning of personal control to humans, i.e.: i) human thermophysiology (section 3), ii) recent experiments on personal control (section 4), iii) important lessons learnt from post-occupancy studies (section 5), and iv) conceptual frameworks on perceived personal control (section 6). Our discussion on the ambivalence of personal control in this paper starts with reviewing often used and proposed solutions for occupant control after which we elaborate on the meaning of adequate personal control based on items summarised in the previous sections (section 6).The discussion points to the importance of *adequate* personal control. Finally, we conclude with some basic criteria for strategies in real buildings supporting better design for adequate personal control (section 7).

2 Control of building energy use during operation on room level

Building automation systems have been established many years ago and systems as for example outdoor-temperature controlled supply temperature in heating systems have been successfully used for many years. Such solutions are *centrally applied* building automation control systems (BACS). Room automation (RA) refers to automated control at the interface of rooms with the occupants and have been used more extensively in recent years. EN 15232 [11] defines BACS efficiency classes: Class D (not energy efficient), Class C (standard, no particular energy efficiency functions), Class B (RA functions are able to communicate with BACS), and Class A (RA system are fully integrated demand-controlled). EN 15232 assigns *functional minimum standards* for control and monitoring of heat and cold output, distribution and generation, for ventilation, lighting and sun shading. Only few of the huge variety of control functions impact the room level (room automation RA), hence the interface to the occupants [10]. Table 1 shows some of these RA functions and their assignment to efficiency classes.

BACS *efficiency classes factors* have been established in order to evaluate the energetical effect of such systems in the early design phase. An example for the efficiency regarding thermal energy used for room conditioning (heating, cooling) is shown in Figure 1 for several building use types. Class D refers to an energy use during operation which is 10 to 50% higher than the standard solutions of class C (reference). Classes A and B refer to solutions which control the energy for room conditioning in such a way that there is 10 to 30% less energy used.

Post-occupancy studies report on how room automation is received in practice. Opening of windows and thermostat settings in energy efficient buildings contribute to an increased use of energy while mechanical ventilation systems are present [e.g. summary of studies in 3], or when occupants have left but did not disable the control device (closing windows or set-back of thermostats). On the other hand, it has been shown that window opening behaviour is lower when the outdoor temperature is extremer, hence the expected energy effect is lower [e.g. 3]. It was even shown that opening the window may not considerably change the energy consumption of the house [23].Thermostat set-points seem to have increased over time in temperate and cold climates [6] and in energy-efficient buildings [3,24]. Furthermore, it was found that occupants block lighting or occupancy sensors [13]. However, research also shows that energy use can be reduced by applying manual-on/ vacancy-off control compared to occupancy-on/ vacancy-off control, which means that the "simpler" partly occupant controlled variant saved 60% energy [25].

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Table 1. Room automation (RA) functions and the building automation control system (BACS) classes they belong to [11], three classic examples shown, classes: D-not energy efficient, C-standard, no particular energy efficiency functions, B-RA functions are able to communicate with BACS, A-RA system are fully integrated demand-controlled.

		residential buildings				non-residential buildings			
		D	C	B	A	D	C	B	A
control & emission, heating/cooling	no automatic control (e.g. furnace)	■				■			
	central automatic control	■				■			
	room-wise control (e.g. thermostat)	■	■			■	■		
	room-wise control with communication	■	■	■		■	■	■	
	room-wise presence-dependent control with communication	■	■	■	■	■	■	■	■
control of air volume flow	no automatic control (window)	■				■			
	time function	■	■			■	■		
	presence-dependent	■	■	■		■	■	■	
	demand controlled	■	■	■	■	■	■	■	■
light control (occupancy)	manual on/off switch (classic switch)	■	■			■			
	manual on/off and automatic shutoff-signal	■	■	■		■	■		
	automatic demand detection	■	■	■	■	■	■	■	■

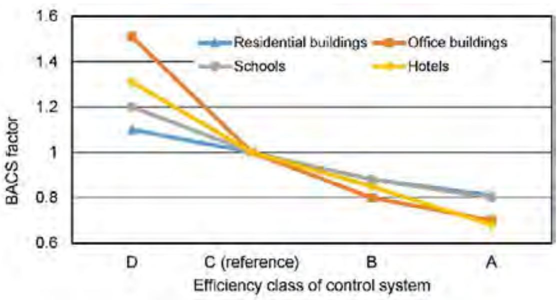

Fig. 1. BACS factor (reduction ratio) for efficiency classes effect on energy use for room conditioning (heating or cooling) for residential buildings, office buildings, hotels and schools, class C is defined as the reference configuration, data from EN 15232 [11].

3 Human thermophysiology and control

Our environment changes dynamically and similar do so the needs of the human body. Among other factors, human needs depend on the activities recently carried out. Responses to these changing environmental conditions or needs of the body comprise several strategies such as: i) vasomotor adjustment (vasodilation and vasoconstriction) which is activated autonomously, ii) behavioural adjustment (e.g. adjusting clothing, going to a different location, opening/closing a window, using a thermostat), and iii) sweating or shivering. The latter are activated only *after* behavioural thermoregulation [26]. The initiator for behavioural thermoregulation is the feeling or anticipation of upcoming thermal discomfort, which is sensed by the human skin [27]. Humans learn from their daily practice in e.g. buildings, which behavioural thermoregulatory actions (control actions) are successful to cause a certain change of the indoor environment. The psycho-physiological feedback signal for the recognition of success/failure of these actions is received via the skin at the point in time when a change in the desired direction is detected [27,28]. This causes a pleasurable feeling that supports learning this behaviour and "bridges" the time needed until comfort is reached again [29].

Another effect originating from the nature of human thermophysiology is that the human body gets used to the environment that it experiences every day including experiences within the indoor, and as well as the outdoor environments. Acclimatisation is an important mechanism in this adaptation process, which occurs seemingly with seasonal change or if one moves to a new climate zone [30].

4 Experimental findings on personal control

In this section, we focus on three key experiments demonstrating relevant factors influencing personal control. Schweiker and Wagner [31] conducted an experimental study in *summer season* manipulating solely the number of occupants in an office-like test facility. The objectively available control opportunities were the same. The participants controlled them individually through a web interface. However, with a *higher number of occupants* in the test-room, participants were comfortable only at a *lower room temperature.* This effect can be explained by a decreased level of personal control perceived, which is also expressed in a lowered number of exercised controls when more people were in the test room. The need to negotiate with the other persons in the room upon whether a blind or fan can be used is the reason for this effect.

In another experiment, Schweiker et al. [32] tested the effect of a placebo controlled ceiling fan by comparison of three conditions: 1) no ceiling fan control, 2) ceiling fan control, and 3) ceiling fan control with largely reduced effect on the workplace due to a manipulated direction of rotation, hence *pretending* control. Condition 2) with effective control was evaluated best. Interestingly, condition 1) without control and condition 3) with non-effective control were evaluated similar, with a tendency of non-effective control to be evaluated even worse. Hence, occupants get a sense of the low or non-effectiveness of control in condition 3) and it is as dissatisfying as having no control or even worse.

In another context, *extensive choices* led to a decreased satisfaction. Iyengar and Lepper [33] investigated people's choice when buying jam and when offered extensive choice or a lower amount of choice. In general, the people in this experiment enjoyed having extensive choice. However, they bought fewer jam and were less satisfied with their choice as compared to the case with lower amount of choice. It turned out to be stressful and demotivating to decide for which marmalade to go as of the sheer number of distinctive features that led to an information overload. Choice overload can also happen in buildings.

5 Lessons learnt from post-occupancy studies

Numerous field studies have found that the vast majority of occupants wish to have control over their indoor climate [e.g. 19] or the studies documented low satisfaction rates with low amount of control available [e.g. 18]. There is a number of post-occupancy or field studies presenting results in line with the experimental studies introduced in section 4. Post-occupancy studies show that with increasing number of people in a room the degree of personal control on temperature, ventilation and lighting decreases [14, 34]. From Dutch offices, Boerstra and Beuker [35] report that *effective* personal control options result in a decreased amount of complaints compared to those cases with *none* or *ineffective* personal control. A group of people having ineffective control had even a higher complaint rate than those with not control.

In a naturally ventilated building, Brager et al. [36] showed that participants stating a high level of perceived control are in average comfortable at a 1.5 K higher temperature in *summer* compared to those with a low level of perceived control, indicating that the energy use for air-conditioning in the offices with control would be lower or even air-conditioning not necessary.

Research shows that technological opportunities and material arrangements (e.g. floor plans, level of insulation, ventilation type, control devices) shape the occupants' thermal comfort attitudes [24, 37]. *Clear and simple settings* can result in high degrees of occupant control and satisfaction: e.g. openable windows and reasonably low window to wall ratio, light switches, radiators with thermostats in office units with one to few people. A contrary tendency is to be found in buildings with sealed highly glazed facades, air-conditioning systems (heating and/or cooling), open-plan offices and only zonal temperature and light control [15, 38]. However, in a field study in Jordanian offices, occupants showed a high degree of control and satisfaction in offices with mainly openable windows and decentralised occupant controlled split unit resulting in a diversity of temperatures in the different offices [39].

6 Frameworks on personal control

Based on findings from experiments and fieldwork conceptual frameworks were developed in order to better explain the perceived level of personal control and its impact on comfort and well-being of humans. Personal control has been defined as (objectively) available control, exercised control, and perceived control (degree of personal control perceived) [40]. Boerstra [18] showed that the degree of personal control modifies how the indoor environment affects comfort, health and performance.

Hellwig [29] defines personal control as having the opportunity to adjust the indoor environment according to ones needs and preferences, in the case of discomfort. The access to controls and effectivity of these controls is hereby driven by the built and social environment. An occupant's actual physiological state, expectations, and actual preferences have an impact as well as personality and experiences of an occupant have. Furthermore, the beliefs in how successful he/she can cause changes, the competences or skills, knowledge of the building and its technical systems as well as success or failure in previous behavioural control actions influence the degree of control [29].

Al-Atrash et al. [34] developed a framework to investigate the relation of objective availability of controls, perceived availability of controls and desired controls on the level of perceived control. They introduced two new variables: 1) consistency between objective availability and perceived availability of controls and 2) conformity to expectations, which describes the degree of conformity between desired and perceived availability of controls. For the latter variable the median perceived control score is lower if expectations of the occupants regarding control (here: windows and blinds) are not met. Whereas a correct identification of control options a room offers does not directly affect the level of personal control.

Based on the background of numerous post-occupancy studies, Bordass et al. [41] developed criteria for usability of controls in buildings: a) clarity of purpose, b) intuitive switching, c) labelling and annotation, d) ease of use, e) indication of system response or feedback, and f) fine-tuning capability. They recommend a placement of controls close to desks or close to the place of usage. When leaving a room, occupants should be supported in switching off equipment which would be best realised in placements close to the door.

7 Ambivalence of personal control – results and discussion

Often proposed solutions. We compare and discuss examples of often applied and proposed solutions in light of above summarised findings on control of building energy use during operation and on the importance of personal control including usability. Table 2 shows the comparison of different control options on room level from Table 1 and additional control options, comprising control on person level (personalised control and clothing), indirect control (by request to the facility manager), dummy control and building design (here: floor plan/zoning). Means of personal control can be non-energy using or energy using. Additional evaluation criteria could be related to costs and other side effects, but such evaluation would be beyond the scope of this paper and e.g. reliable and holistic cost estimations are scarce.

The evaluation of the effect of a control option on the building energy use during operation in Table 2 is based on the efficiency classes in EN 15232 [11] were available. Control options not mentioned in EN 15232 were evaluated with the same scheme based on literature and based on the authors' own knowledge. The evaluation of the effect of control options on the level of personal control is based on the authors' own previous work [5,15, 18,21,31,32,34,35,39], literature [3,9,13,17,19,25,36,39, 40] and last but not least the tremendous experience from post-occupancy studies documented by the Usable Building Trust [7,14,41].

Classic control systems. Openable windows and thermostats on individual/small group level are the most appreciated controls because occupants perceive high control with these systems (section 5). Although occupants may not always understand the intended use of thermostats or they lack knowledge of how to use controls in the intended way, they may use them in their own way in a sufficient manner [8].

Automatic control. Fully automated control is suggested to reduce the influence of occupants' interaction on indoor thermal conditions and energy use. In light of above described findings and frameworks, it is clear that occupant satisfaction will decrease with such systems as it largely reduces perceived control. Potential energy savings may counterbalance increased costs due to occupants trying to jeopardising the system as shown in previous field studies, where user block lighting or occupancy sensors [13]. On the other hand in experimental observations [25], a reduction of 62% of the time when light was on during occupancy was found through using the manual-on/vacancy-off control system compared to the occupancy-on/vacancy-off control system. Systems meant for user interaction should therefore be *switched on manually. Switching off* can be manual or automatic. Standby settings should be low-energy defaults [41]. A minimum requirement to improve the situation of fully automated controls is the addition of override options for the users. Such functionality will likely increase perceived control. However, there is a lack of studies assessing the optimal extent of such override functions, e.g. related to the length of the period after an override, the system is not switching back to the automation (15 minutes, 1 hour, until the end of a working day?). As for example for demand controlled ventilation, depending on the context it might work well if combined with openable windows [15,39].

Table 1. Comparison of the effect of control options on building energy use during operation and on personal control/usability. Scale used: operation energy use based on efficiency classes of EN 15232: "-" non-energy efficient (class D), "0" reference, (class C), "+" energy efficient, (class A and B). Evaluation of personal control/usability based on literature (see text): "-" no personal control/usability; "0" low personal control/usability; "+" high personal control/usability

Control option	operation energy use	personal control/ usability
Window, manually openable (classic)	- [11] / 0 [3,23]	+
Thermostat (classic radiator, decentralised air-con)	0	+ 4)
Light switch (classic)	0 1)	+
Automatic light control: manual ON, vacancy-OFF;	+	+
Automatic light control: ON, OFF, with override	+ / - 3)	- 5)
room-wise presence-dependent temperature control with communication	+	+ 6)
Demand controlled ventilation	+	+ 7)
floor plan/zoning: open plan office*	0	-
floor plan/zoning: small office units*	+	+
Clothing adjustment*	+**	+ 8)
Personalised comfort systems*	+**	+ 9)
Contact facility manager*	+**	0
Dummy control*	0**	-

1) dependent on occupant behaviour and building type
3) more energy use compared to manual ON, Factor 2.5 more!, [25]
4) although many occupants do not correctly understand how to use it, they get the desired response [8]
5) automatic ON not preferred by occupants [25],
6) Dependent on usability of interface [41]
7) Only if combined with an openable window [15]
8) Requires communication strategy
9) depending on product
* evaluation based on literature, see text and authors' experience

Personalised control and clothing. Another opportunity is to control comfort on the level of each individual person. Clothing adjustments have long been the measure of choice, are in principle well understood and work for a temperature compensation of 1 to 2 K for extra pieces of garments, hence can contribute to a 10 to 20% building energy conservation during operation. Automated systems with manual override functions may become so convenient that they may also lead to changes in behaviour: When the effort to use the system is so low that relying on classic control options like changing the clothing requires more effort for a person. Less clothing than previously (as described in standards) is worn in the cold season already today [24].

Personalised comfort systems provide locally additional heating or cooling [42]. Their corrective power

[43] ranges between 1-6 K for cooling and 2-10 K for heating, which means that the room temperature can be higher or lower by this amount accordingly. Personalised comfort systems can help mitigating low perceived control at special workplaces, e.g. open-plan offices or welcome desks in entrances halls. With personalised comfort systems, the difficulty is in limiting the amount of interaction between the user and the system. Leaman and Bordass et al. [41] found, that people also get dissatisfied in case they have to hassle too often with controls. The energy efficiency of personalised comfort systems depends highly on how energy efficient the decentralised systems are and what temperature difference they should compensate for and in which context. Compensation potential is from our point of view generally higher in settings like open-plan offices because a single office has already a highly occupancy linked energy use. Because of the much larger amount of adaptive opportunities/perceived control at homes in general, we argue that personalised comfort systems are not an issue for now at home due to people's freedom in choosing clothing level and other adjustments (moving to another room) for example.

Floor plan/ zoning: In open-plan offices, lighting and heating will have to remain running until the last person leaves the office, i.e. conditioning the complete open space. In single offices, only one office needs to be kept at the right lighting, temperature and indoor air quality level, while others can go already to set back values. However, more systematic research, including a consistent definition of benchmarks or cases to compare with have yet to be established.

Indirect control and dummy control: In open-plan offices and fully automated indoor environments, the occupants are left with very few opportunities to adapt (clothing) leading to a general low perception of control. However, it has been argued that individual control can be perceived rather high as long as there is sufficient control e.g. by calling facilities' management and having the request resolved quickly [14]. Dummy thermostats are often proposed to mitigate the conflict between user behaviour and energy-efficient or smooth building operation. In fact, they have no effect as they are not connected, they are fake temperature knobs that pretend some level of control over the indoor environment. On the long term, the introduction of dummy thermostats is one of the worst things to realise! The occupants will find out that their usage of the dummy control device does not have any effect. This can result firstly in a loss of confidence in their own capabilities or in a loss of trust in building systems or the facility manager. Occupants then may conclude that the building operates by chance or that the facility manager did not treat their complaints seriously. This will make them more critical of the functioning of the building [29]. As shown in experimental settings and in field studies: the potential for discomfort or complaints can be even higher compared to the case with no control at all [32; 35].

How much personal control is adequate? There is no simple answer to this. Too much personal control can result in stress or confusion, especially if usability aspects are not strictly followed. Control should match the context (location, task, time). Control options most familiar to the occupants, i.e. culturally rooted in a society, are advisable to be considered. When a building is retrofitted, it is advisable to keep the most liked (control) features in the old building [44]. Indication was found that replacing formerly openable windows partly with fixed glazing also affects the degree of control [45]. Providing the users with the controls they missed before the renovation or in their old building can add to an increased personal control in the renovated or new building. An appropriate amount of automation, predictability (conformity to expectation), information and responsiveness of the system or feedback are seen as core factors that users feel that they are in control [21]. The factors mentioned lead also to the answer of the question: *How to design for adequate control?* In [44], a procedure to develop a design portfolio for adequate personal control which meets the building use type, climate, task and cultural context is proposed.

Health aspects. A question discussed among the authors of this paper is, whether with a high degree of control and systems which always deliver the change requested, whether people adapt to narrower temperature ranges with lower variance [46] and get more sensitive towards temperature amplitudes. Hence, the question we raise is whether people having perfect control available that enables them removing temperature stimuli early and fast, would lose their ability to adapt with thermoregulatory adjustments [47]. Thermal comfort research implies this [e.g. 48] as well as health research [e.g. 49]. However, there is still a lack of knowledge in research clarifying important questions like this one.

8 Conclusion

The aim of this paper was to jointly discuss the two tendencies: more automated control (for lower building operational energy use) and more occupant control (for more satisfied users). Automation has been playing a great role in all kinds of conditioning applications in buildings for a long time and its potential in appropriate applications has to be appreciated. It was shown, that for some control options the evaluation of the impact on building energy use is contradictory to the occupants perception of the same control option, for other control options there is a good agreement between both evaluations. However, implementing automation, e.g. demand controlled ventilation does not mean that established and liked simple control options as openable window can be turned into sealed windows. In our discussion, we showed that the amount of control expected by people depends on the context: the task, the level of privacy, the climate etc. A fact building designers should pay careful attention to is that behavioural thermoregulation is activated by body signals and therefore it is in the building planners' and operators' responsibility to account for this natural and basic human need for control. High perceived control could be implemented with: a low number of persons sharing one office, accessibility of control devices for the occupants, and user-friendly interfaces, and with control over temperature, fresh air supply and lighting.

Our discussion of common control solutions and devices in buildings with regard to the level of occupant control, energy and usability highlights, that there is a need for systematic evaluation of control options with regard to their effect on building energy use and occupant perception. In order to meet the goals for nearly zero energy buildings and for a human-centric design, there is the need to establish design procedures for adequate personal control as part of the design process. Furthermore, there is a need to develop systematic ways to operate for appropriate personal control for occupants. Runa T. Hellwig would like to thank the Obelske Familiefond, Denmark for supporting this work. Marcel Schweiker's was funded by the German Federal Ministry of Economics and Technology (BMWi) with the project ID: 03EN1002A.

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