Article

The Human's Comfort Mystery—Supporting Energy Transition with Light-Color Dimmable Room Lighting

Simon Wenninger ^{1,2,*} and Christian Wiethe ¹

¹ Project Group Business and Information Systems Engineering of the Fraunhofer FIT, 86159 Augsburg, Germany; christian.wiethe@fit.fraunhofer.de

² FIM Research Center, University of Applied Sciences Augsburg, 86159 Augsburg, Germany

* Correspondence: simon.wenninger@fit.fraunhofer.de

Abstract: The constant increase of intermittent renewable energies in the electricity grid complicates balancing supply and demand. Thus, research focuses on solutions in demand-side management using energy flexibility to resolve this problem. However, the interface between demand-side management and human behavior is often insufficiently addressed, although further potential could be leveraged here. This paper elaborates on the effect of light color on humans' temperature and comfort perception in connection to energy flexibility. Researchers have found that people perceive blue light as colder and red light as warmer. To this end, we evaluate the effect of light color in a case study for a German industrial facility assuming sector-coupled electric heating. We simulate the entire heating period from October to April in an hourly granularity, using the well-established real options analysis and binomial trees as a decision support system to heuristically minimize energy expenditures by utilizing deferral options when energy prices are high. Our results show a 12.5% reduction in heating costs for sector-coupled electric heating, which extrapolated leads to CO₂-eq emission savings of over 34,000 tons per year for the entire German industry, thereby supporting the energy transition.

Keywords: demand-side management; humans' comfort perception; light color; energy transition

Citation: Wenninger, S.; Wiethe, C. The Human's Comfort Mystery—Supporting Energy Transition with Light-Color Dimmable Room Lighting. *Sustainability* **2022**, *14*, 2311. <https://doi.org/10.3390/su14042311>

Academic Editors: Ortzi Akizu-Gardoki, Jukka Heinonen and Sanna Ala-Mantila

Received: 15 January 2022

Accepted: 15 February 2022

Published: 17 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

To achieve ambitious climate targets and boost the energy transition, reducing energy consumption and CO₂-eq emissions is crucial [1]. To this end, energy research bears enormous potential by exploring and developing innovative and sustainable concepts in energy supply and demand [2]. Energy research is multifaceted and investigates technical, economic, social, and political aspects of energy-saving approaches [3,4]. Historically, there has been a strong focus on improving consumers' energy efficiency and energy conversion, for instance, the fuel consumption of cars. However, balancing supply and demand has recently become increasingly important due to the rapid incline in renewable energies and the associated intermittent energy supply [5]. A sole focus on energy efficiency no longer meets the requirements of non-fossil-based energy supply [6], as indicated by recent publications and research projects on demand-side management (DSM) and energy flexibility [7]. To this end, considering human behavior as a central element in the world's energy consumption bears potential for a well-targeted DSM. For example, almost 27% of Germany's total final energy consumption stems from space and water heating due to humans' temperature comfort [8]. Through integrated energy systems, commonly known as sector coupling, targeted linking and interaction of energy-consuming sectors is possible, e.g., using heat pumps or power-to-gas technologies [9]. Thus, a carefully nuanced nudging of the humans' thermal comfort offers great potential for balancing intermittent renewable energy supply with sector-coupled energy demand.

Recently, researchers have found that light color influences people's perception of temperature. More precisely, people perceive blue light as colder and red light as warmer,

with potential energy savings in heating and cooling buildings [10]. This phenomenon shows that adjusting light color and impacting humans' perception of comfort can support the management of energy supply and demand. However, the focus of the research has been on investigating the effect itself and potential energy savings through energy efficiency. The use of the phenomenon for energy flexibility in energy systems and interactions for controlling and managing energy supply and demand has not yet been considered. The idea is a short- to medium-term use of the effect when the consumption for heating or cooling must be adapted to the energy supply. Since cooling or heating is often electricity-based, i.e., generated with compression chillers or heat pumps, the connection of the cooling and heating sectors with the electricity sector is feasible seamlessly [11]. This is already in use today for heat pumps due to the thermal storage capacity of heat storages and the building envelope for DSM use cases [12]. For example, in summer, cooling can be turned off for some time by changing the light color to bluer light without causing the occupants of a building to perceive the indoor temperature as too warm. Turning off cooling during high electricity price phases can be completed until the indoor room temperature exceeds the threshold value. This duration depends on different influencing factors, such as outside temperature, the heat storage capacity of the building, or individual heating loads [12]. In winter, it would be precisely the opposite use case, in which the heating would be switched off for some time. However, it is also possible to cool rooms under the conventional threshold value in summer when prices are particularly low and vice versa during winter. Next to volatile electricity prices, (local) grid bottlenecks can be (financial) incentives to adjust electricity consumption for heating or cooling [6]. Therefore, to address this research gap and evaluate the potential, we formulate the following research question (RQ):

RQ: Can light-color dimmable room lighting support the energy transition and offer energy flexibility potential?

We address the RQ by simulating a German industrial facility with light color dimmable room lighting. To this end, we apply a real options analysis (ROA) approach based on binomial trees to derive the economic savings arising from the increased flexibility as heating can be postponed for longer periods and cheaper electricity prices can be exploited. Therefore, we first provide the theoretical background in Section 2. We then examine the light color's effect on humans' comfort perception in Section 3 before elaborating on our case study in Section 4. Section 5 presents the results and discusses the energy flexibility potentials of light color's influence on people's comfort perception before deriving implications. We conclude in Section 6.

2. Theoretical Background

2.1. Sector-Coupled Energy Efficiency and Flexibility

The energy supply in different sectors has grown historically and mainly was based on fossil energy sources and a low cross-sectoral exchange [11]. New solutions had to be developed and established due to the scarcity of fossil fuels, associated energy prices, and increasingly stringent climate targets. Cross-sector electrification is a crucial element in achieving climate targets, as there is efficiency potential in the electrification of many applications and processes, especially by integrating renewable energies [13,14]. Prominent examples in the building and transportation sectors are heat pumps and electric cars [15]. However, electrification and sector-coupling also pose new challenges for the energy industry [11]. Volatile renewable energies must be integrated into the energy system, and many consumers must be supplied with energy in the right amount, time, and place [6]. Thus, smart energy systems deal with the energy sectors' targeted connection and interaction to increase energy efficiency and flexibility of supply, demand, and storage [11,16].

In recent years, research focused primarily on enhancing energy efficiency in energy systems to cut energy consumption. Examples are manifold [17] and range from anomaly detection in energy consumption [18] over research on forecasting energy consumption [19,20] to the optimization of greenhouse energy use [21]. However, with the rapid increase in volatile renewable energies, balancing supply and demand becomes

increasingly important. Research in this context is grouped under the concept of DSM, which is a solution for providing the electricity grid with the necessary flexibility to support secure and resilient operations where energy demand changes by end-use customers from their normal demand patterns [22,23]. This means that end-use customers, such as manufacturing companies, control their systems and plants differently from their usual mode of operation [5,24]. DSM can be activated by so-called trigger signals such as price incentives, ensuring grid stability, and eliminating grid bottlenecks [25]. Flexibility is mainly provided by energy storage, industrial processes, or controllable loads such as electric cars or heat pumps [26]. However, literature has not considered flexibility that accounts for human beings and their characteristics.

2.2. Real Options Analysis

Typical investment evaluation methods include the net present value (NPV) or internal rates of return. However, literature found the NPV to underestimate the value of projects exhibiting managerial flexibility [27,28]. On the other hand, ROA can reflect managerial flexibility in the evaluation [29] by assuming the managerial flexibility to take the form of real options. For instance, depending on the development of an investment over the first-time steps, expansion and contraction options can be defined. In the context of the investment timing flexibility depending on price development, deferral options are modeled. To this end, many studies assume risk neutrality and build upon the option pricing approach by Cox et al. [30] to evaluate the option prices with the help of binomial trees. We focus on deferral options because we are also confronted with heating deferrals when investigating optimal heating time.

Binomial trees model price development by multiplication of an initial price with fixed factors $u > 1$ or $d < 1$ corresponding to upward and downward movements at discrete and equidistant time intervals Δt , thus spanning a lattice. To this end, p gives the probability of an upward price development by multiplication with u while $1 - p$ gives the probability of a downward price development by multiplication with d . Constructing a binomial tree thus first requires the calculation of these factors. Equation (1) defines the geometrical return r_i of historical prices x_i :

$$r_i = \log \frac{x_i}{x_{i-1}}. \quad (1)$$

Based on the return data, we derive the empirical standard deviation σ using r_f as the risk-free interest rate. This allows us to calculate the factors u and d as well as the probability p required for constructing binomial trees. Equations (2)–(4) state the calculations:

$$u = e^{\sigma \cdot \sqrt{\Delta t}}, \quad (2)$$

$$d = e^{-\sigma \cdot \sqrt{\Delta t}}, \quad (3)$$

$$p = \frac{e^{r_f \cdot \Delta t} - d}{u - d}. \quad (4)$$

3. Light Color's Effect on Human's Comfort Perception

With a share of almost 27% of the German final energy consumption for space heating and cooling, human comfort requirements are responsible for a large part of the energy consumption and hold potential for energy savings [8]. A person's comfort in an (indoor) environment depends mainly on temperature, humidity, air quality, light exposure, and acoustics [31]. Different scientific branches have studied these comfort aspects [25]. To design habitable indoor environments that meet sustainability and low energy consumption requirements, a precise understanding of human comfort sensibilities is necessary [32,33].

Conducting a semi-structured literature review revealed that research elaborated on light influence, or more precisely, the color of light expressed in the correlated color temperature of light that describes the color appearance of light [10,33]. We searched in the databases Google Scholar, Scopus, and AIS eLibrary with the keywords "Light color",

“comfort perception”, and “energy consumption” and found an increase in publications in recent years. Research suggests that reddish light creates a warmer environment than bluish light, called the hue-heat hypothesis [10,33]. Fanger et al. [34] found a difference of 0.4 °C in thermal perception for blue or red lighting. Bellia et al. [33] even found a difference of 1.7 °C in temperature perception at different correlated color temperatures. Further studies could confirm this correlation, even if they did not define a concrete value of the change in temperature perception [35–37]. In contrast, Baniya et al. [38] concluded that a change in correlated color temperature would not affect temperature perception. However, this is not regarded as entirely conclusive in literature due to the study’s small test sample size [10]. These findings have meaningful implications for building and supply systems’ planning, design, and operation. For instance, color-dimmable lighting systems can easily change light color and manipulate people’s perception of temperature [10]. This can increase the acceptable range of indoor temperatures and reduce energy consumption for heating and cooling. However, the effects of the potential energy savings are either insufficiently quantified or are not quantified, as Table 1 shows. All studies investigate the effect and its strength without analyzing implications for practice in detail. Furthermore, most studies assume that energy savings could result from a constant change of light color. However, this, in turn, neglects the potential of a time-dependent change of light color to exploit the potential of DSM in a changing energy system. With our study, we aim to address this limitation. We use the existing studies as a basis and change the perspective from the study of the effect to an application/practice-oriented perspective.

Table 1. Literature overview for energy savings by changing light color.

Source	Study’s Focus	Implications/Recommendations for Energy Savings
[10]	Investigation of the influence of light color on human temperature perception in an office-like laboratory climate chamber at the University of Sydney with 45 subjects.	Reductions in energy consumption might results due to higher heating, ventilation, and air conditioning (HVAC) set-points in summer. No further quantification of savings in energy consumption.
[33]	Verification of the effect of light color on thermal perception and indoor environmental quality in a mechanically conditioned test room and 163 volunteers.	Notable savings in energy consumption might result and influence indoor environment quality. No further quantification of savings in energy consumption.
[34]	Investigation of the influence of light color and noise und humans’ thermal comfort.	The effect of light color may be too small for practical significance.
[35]	Examination of the influence of colored light on aircraft passengers’ temperature perception with 199 subjects in a single-aisle aircraft test environment.	The savings can be quite substantial when accumulated over multiple aircrafts. No further quantification of savings in energy consumption.
[36]	Examination of the influence of colored light on aircraft passengers’ temperature perception in a mock-up cabin of a single-aisle aircraft with 59 subjects.	Light color might help to improve passengers’ overall comfort and result in energy savings. No further quantification of savings in energy consumption.
[37]	Investigation of the effect of light color on temperature perception in a controlled environment chamber at the Technical University of Denmark with 44 subjects.	Changing light color might reduce energy consumption of an office building by around 8%.
[38]	Investigation of the influence of light color on temperature perception in a test room at Aalto University in Finland with 16 subjects.	The effect found in the previously listed studies was not confirmed. Energy savings may not be possible without compromising thermal comfort.

Figure 1 shows the reduction of energy consumption schematically. An exemplary outdoor temperature curve T_{OA} shows the three possible phases in which heating, cooling or neither heating nor cooling is required (death zone). The thresholds T_C and T_H limit the range of acceptable indoor temperatures. The energy consumption, which is determined as the integral of the temperature difference between indoor temperature and the respective threshold over time is given in gray. The blue-colored area indicates the potential energy saving through changes of the correlated color temperature. The amount of savings is ultimately determined by the magnitude of the effect on temperature perception. If the indoor temperature in buildings were reduced by $1.0\text{ }^{\circ}\text{C}$, energy consumption would be reduced by around 6% according to DIN V 4108-6/DIN V 4701-10 for climatic conditions similar to Germany [39,40]. Therefore, the use of appropriate lighting systems bears great potential to leverage further efficiency potential in the building sector. With advanced heating, ventilation, and air conditioning (HVAC), and color-dimmable lighting systems, indoor environmental parameters can be precisely adjusted. Since light color changes do not substantially increase energy consumption, the energy savings can be fully realized [10].

Figure 1. Visualization of potential energy savings through color-dimmable lighting.

4. Case Study for a German Industrial Facility

4.1. Data and Simulation Object

We simulate an existing German industrial facility in the south of Augsburg, Bavaria. For simplicity, we focus on heating only and exclude cooling. The industrial facility is full-time operated in shifts; hence heating is necessary throughout the entire day during the heating period from October 1 to April 30. To investigate the potential for energy flexibility, we assume electricity-based heat pumps with a German average coefficient of performance of 3.76 and Day-Ahead spot market prices (single-hour electricity prices) [41]. Thus, in the sense of sector coupling, economic benefits can be realized if heating can be postponed (deferral option) during high electricity price phases.

We have three datasets at hand to answer our RQ and simulate the potential of color dimmable lighting in connection to energy flexibility. The first dataset includes historical hourly temperature records for Augsburg, Germany. We restrict the dataset to the heating period from October 2020 to April 2021 and do not further preprocess the data. We use the temperature records as the basis for the simulation. The second dataset includes German Day-Ahead spot market prices (single-hour electricity prices) typical for industrial consumers. We use this data to derive the functional terms for our ROA approach, as given in Section 2.2. The third dataset covers details on the industrial facility, such as the effective heated area, surrounding area, or thermal transmittance (u-values). We use this dataset to derive the temperature changes over time. Table 2 provides further details on the data used.

Table 2. Data and parameters used for the simulation.

Parameter	Value
Method	Real Options Analysis based on Binomial Trees
Electricity price data	German Day-Ahead spot market prices (2017/2018)
Temperature data	Deutscher Wetterdienst (DWD): Location Augsburg [42]
Industrial production facility data: Coefficient of performance	3.76
Industrial production facility data: Production area	600 m ²
Industrial production facility data: Heat transmission coefficient	$k = 1/6$

4.2. Simulation Setup

The simulation starts at 00:00 on October 1 and sequentially runs through all individual hours in the heating period for an hourly granularity. We have the current outside temperature and electricity price available for each hour. As mentioned in Sections 1 and 2.2, we use binomial trees as the foundation for the ROA approach to model heating deferral as a deferral option. To this end, we set up the binomial tree by first deriving the periodical log-returns in the electricity data following Equation (1). So that Equation (1) can also be applied in the case of negative electricity prices, we temporarily shift the electricity prices upwards and later correct for this shift in the final analysis. Assuming risk-neutrality, we follow [30] and derive the development factors and respective probabilities required for the binomial tree as in Equations (2)–(4). We exclude the time t because it always equals one hour and let the risk-free interest rate r equal zero because interest rates are negligibly low for one-hour periods. For further details, we refer to the literature.

Based on these parameters, we span a binomial tree looking 24 h into the future using the current electricity price as starting point and working forward from there. We deviate from the no-arbitrage assumption in ROA by accounting for a daily seasonal trend derived from the empirical data to depict reality as closely as possible. Additionally, the simulation estimates the future temperature development with the differential Equation (5):

$$\frac{\partial \tau}{\partial t} = k \cdot (T - \tau), \quad (5)$$

where τ and T are the indoor and outdoor temperatures, t is again the time, and k is the transmittance parameter derived from the third dataset (here 1/6). We initialize the indoor temperature with 20 °C. Once the temperature dips below a minimum threshold, heating is required (for Germany, this threshold is by law set to 17 °C for our specific case study [43]). Based on the energy prices and estimated temperature changes, we are left with an optimization problem we solve heuristically. To this end, we only examine the periods until heating must take place at the latest to save computation time. We evaluate each node in the binomial tree backward within this period using the deferral option. The simulation then keeps track of whether heating was necessary and sums up the costs accordingly. Additionally, we require the simulation to always heat back up to 20 °C after heating deferral to ensure that the results reflect the flexibility potential and not solely the reduced heat transmittance, as this has been studied before [10,36].

This simulation run is performed three separate times, (1) for no flexibility, i.e., heating in each period, (2) for flexibility, i.e., potentially postponing heating until we dip below a defined threshold of 17 °C, and (3) for flexibility and color-dimmable lighting assuming that a change of 1.5 °C in perceived comfort is achievable [33]. Figure 2 provides a schematic overview of the simulation setup and result derivation.

Figure 2. Schematic depiction of the simulation setup and result derivation.

5. Results and Discussion

We first look at the results from the case study before discussing the results and turning to implications and limitations. As expected, simulation run (I)—not considering flexibility at all—exhibits the highest overall cost accumulating to a total of EUR 22,213.96. This amount is approximately in line with values for comparable production facilities ranging from EUR 20,000 to EUR 30,000. Simulation run (II)—considering flexibility with a threshold value of 17 °C—already achieves savings of 6.3%, reaching total costs of EUR 20,800.08. Simulation run (III)—considering flexibility and color-dimmable lighting—further decreases the total costs to EUR 19,454.68, which is equivalent to a decrease of almost 6.5% compared to run (II) and almost 12.5% compared to run (I). Table 3 summarizes the results.

Table 3. Results of the different simulation runs indicating heating costs and CO₂-eq emissions.

	Simulation Run (I)	Simulation Run (II)	Simulation Run (III)
Heating cost	EUR 22,213.96	EUR 20,800.08	EUR 19,454.68
CO ₂ -eq emission savings of simulation run (III) per year	34,205.23 tons	17,811.85 tons	0.0 tons

In general, color-dimmable lighting exhibits two savings potentials: reducing energy demand and realizing energy flexibility in terms of DSM. Literature has already discussed reducing energy demand through color-dimmable lighting [9,32]. The idea is to shift the heating or cooling thresholds in the long term through the light color's influence and achieve energy savings over the entire period during which heating or cooling occurs. Assuming a difference of 1.5 °C in the temperature perception at the upper end of findings in literature [29], this approach achieves savings of approximately 9% in heating energy consumption (in similar climatic conditions as Germany) [35,36]. This reduction in heating energy consumption is equivalent to approximately 2.4% of the German final energy consumption and CO₂-eq emission reductions of over 24,000 tons per year, assuming state-of-the-art heat pumps and the average CO₂-eq emissions in the German electricity mix [7,39]. Regarding this case's (technical) feasibility, color dimmable lighting systems are now widely available at fair prices [44]. Additionally, most heating and cooling systems are customizable to the user's needs, making it easy to set the altered thresholds (by a professional) [12]. However, energy price forecasts need to be accessible for energy management systems to evaluate if considering energy flexibility is economical and sustainable in terms of CO₂-eq emission reductions.

The results derived in this case study already highlight the savings potential from combining energy flexibility with color-dimmable lighting, which has not been considered in the literature so far. We assume even higher savings potential when lifting the restriction to heat back up to 20 °C, which would additionally realize the savings from reducing energy demand, although the savings are likely not additive. To this end, a reduction of 12.5% in heating demand for production facilities is equivalent to approximately 3.4% of the German final energy consumption and CO₂-eq emission reductions of over 34,000 tons per year. However, this is likely an underestimation, as lower electricity prices seem to strongly

correlate to higher shares of renewables in the electricity mix; thus, even higher CO₂-eq emission reductions are likely.

Further, our results have several managerial and policy implications. First, the savings potential identified in this study suggests promoting the effect in research and practice to pave the way for further analyses and practical applications. Second, creating the necessary conditions in energy management systems and building automation systems is relevant. As mentioned before, future energy prices must be accessible for optimization algorithms to reduce risk in operation [45,46]. If required, (retrofit) solutions must be developed for existing systems that do not have the option of obtaining external data via the Internet. Additionally, concerning current research on the smart grid, it is important to investigate possibilities for third-party control of heat pumps by, for example, distribution grid operators. Third, testing in real application scenarios to verify the effect's feasibility, economic efficiency, CO₂-eq savings potential, and impact on human comfort and develop technical automation solutions for broad application. Due to the complexity of the effect at the interface of different disciplines, we call for interdisciplinary research to develop economic, sustainable, and comfort compatible holistic solutions. Revised standards and guidelines for the sizing and design of heating, cooling, and lighting systems may result from real application scenarios. Fourth, even if not a central aspect of the investigations in this study, the regulatory framework must be adapted to reduce barriers and increase incentives for energy-flexible operation [5].

6. Conclusions

This study investigated whether light-color dimmable room lighting can support the energy transition and offer energy flexibility potential. To this end, we applied real options analysis and set up a simulation case study for a German industrial production facility. Our results show that heating demand reductions of up to 6.5% compared to flexibility without considering correlated color temperature on humans' comfort perception are achievable and up to 12.5% compared to the benchmark without flexibility and room lighting. Compared with literature showing savings of up to 8% without considering flexibility, further savings potential could be exemplarily demonstrated with this study. Extrapolated to all German production facilities, a reduction of the heating demand by 12.5% would reduce the German final energy consumption by 3.4% and cut CO₂-eq emissions by over 34,000 tons per year. This finding highlights the importance of sector-coupled energy systems to leverage energy flexibility and counteract the intermittent energy supply from renewable energy sources.

Naturally, this study disposes of some limitations and several assumptions. First, we applied ROA, a well-established method in literature for investment decision evaluation when managerial flexibility is involved. However, we had to make some assumptions, for instance, risk-neutrality; thus, the effects may unfold differently than depicted in this study. We expect the results only to differ slightly. Second, we did not evaluate and validate the potentials in practice, which future work might take on. Implementation requires concrete technical solutions. Existing energy management systems or building automation systems may provide the basis and control of the color lighting systems and the associated heating and cooling systems. Future research might tackle this limitation in (large-scale) real-world laboratories with an interdisciplinary team of scientists and practitioners. Third, the effect of color lighting needs further investigation. For instance, potential rebound effects and the duration of the effect remain unclear and whether the color change speed adversely affects human comfort. Additionally, effects on human health need to be investigated by an interdisciplinary research team. Fourth, we focused on an industrial production facility in Germany. For instance, other geographical regions may potentially alter the results. However, we expect similar results for other building types and geographical regions. Further research may elaborate on effects during cooling periods instead of heating for electricity-driven compression chillers.

Despite these limitations, this study demonstrates the potential of demand-side management and hopefully encourages researchers to explore further the interface of demand-

side management and human behavior to develop interdisciplinary solutions towards the set climate goals.

Author Contributions: Conceptualization, S.W. and C.W.; methodology, S.W. and C.W.; software, S.W. and C.W.; formal analysis, S.W. and C.W.; resources, S.W. and C.W.; data curation, S.W. and C.W.; writing—original draft preparation, S.W. and C.W.; writing—review and editing, S.W. and C.W.; visualization, S.W. and C.W.; project administration, S.W. and C.W. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support of the Kopernikus-project Syn-Ergie by the Federal Ministry of Education and Research (BMBF) and the project supervision by the project management organization Projektträger Jülich (PtJ).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tcvetkov, P. Climate Policy Imbalance in the Energy Sector: Time to Focus on the Value of CO₂ Utilization. *Energies* **2021**, *14*, 411. [CrossRef]
2. Kühn, M.; Ask, M.; Juhlin, C.; Bruckman, V.J.; Kempka, T.; Martens, S. Interdisciplinary Approaches in Resource and Energy Research to Tackle the Challenges of the Future. *Energy Procedia* **2016**, *97*, 1–6. [CrossRef]
3. Hirsh, R.F.; Jones, C.F. History's contributions to energy research and policy. *Energy Res. Soc. Sci.* **2014**, *1*, 106–111. [CrossRef]
4. Rusche, S.; Rockstuhl, S.; Wenninger, S. Quantifizierung unternehmerischer Nachhaltigkeit in der Fertigungsindustrie: Entwicklung eines zielorientierten Nachhaltigkeitsindex. *Z. Energ.* **2021**, *45*, 317–343. [CrossRef]
5. Bachmann, A.; Bank, L.; Bark, C.; Bauer, D.; Blöchl, B.; Brugger, M.; Buhl, H.U.; Dietz, B.; Donnelly, J.; Friedl, T.; et al. *Energieflexibel in Die Zukunft—Wie Fabriken zum Gelingen der Energiewende Beitragen Können*; VDI Verlag: Düsseldorf, Germany, 2021.
6. Bauer, D.; Hieronymus, A.; Kaymakci, C.; Köberlein, J.; Schimmelpfennig, J.; Wenninger, S.; Zeiser, R. Wie IT die Energieflexibilitätsvermarktung von Industrieunternehmen ermöglicht und die Energiewende unterstützt. *HMD* **2021**, *58*, 102–115. [CrossRef]
7. Nasir, T.; Bukhari, S.S.H.; Raza, S.; Munir, H.M.; Abrar, M.; Muqet, H.A.u.; Bhatti, K.L.; Ro, J.-S.; Masroor, R. Recent Challenges and Methodologies in Smart Grid Demand Side Management: State-of-the-Art Literature Review. *Math. Probl. Eng.* **2021**, *2021*, 1–16. [CrossRef]
8. Federal Ministry for Economic Affairs and Energy. Energiedaten: Gesamtausgabe: Stand: Oktober 2019. Available online: https://www.bmwi.de/Redaktion/DE/Downloads/Energiedaten/energiedaten-gesamt-pdf-grafiken.pdf?__blob=publicationFile&v=34 (accessed on 29 August 2021).
9. Lund, H.; Möller, B.; Mathiesen, B.V.; Dyrelund, A. The role of district heating in future renewable energy systems. *Energy* **2010**, *35*, 1381–1390. [CrossRef]
10. Brambilla, A.; Hu, W.; Samangouei, R.; Cadorin, R.; Davis, W. How correlated colour temperature manipulates human thermal perception and comfort. *Build. Environ.* **2020**, *177*, 106929. [CrossRef]
11. Fridgen, G.; Keller, R.; Körner, M.-F.; Schöpf, M. A holistic view on sector coupling. *Energy Policy* **2020**, *147*, 111913. [CrossRef]
12. Aghniaey, S.; Lawrence, T.M. The impact of increased cooling setpoint temperature during demand response events on occupant thermal comfort in commercial buildings: A review. *Energy Build.* **2018**, *173*, 19–27. [CrossRef]
13. Lindner, M.; Wenninger, S.; Fridgen, G.; Weigold, M. Aggregating Energy Flexibility for Demand-Side Management in Manufacturing Companies—A Two-Step Method. In *Production at the Leading Edge of Technology*; Behrens, B.-A., Brosius, A., Drossel, W.-G., Hintze, W., Ihlenfeldt, S., Nyhuis, P., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 631–638, ISBN 978-3-030-78423-2.
14. Strüker, J.; Weibelzahl, M.; Körner, M.-F.; Kießling, A.; Franke-Sluijk, A.; Hermann, M. *Dekarbonisierung durch Digitalisierung: Thesen zur Transformation der Energiewirtschaft*; University Bayreuth: Bayreuth, Germany, 2021.
15. Choi, W.; Yoo, E.; Seol, E.; Kim, M.; Song, H.H. Greenhouse gas emissions of conventional and alternative vehicles: Predictions based on energy policy analysis in South Korea. *Appl. Energy* **2020**, *265*, 114754. [CrossRef]
16. Lund, H.; Østergaard, P.A.; Connolly, D.; Ridjan, I.; Mathiesen, B.V.; Hvelplund, F.; Thellufsen, J.Z.; Sorknæs, P. Energy Storage and Smart Energy Systems. 3–14 Pages. *Int. J. Sustain. Energy Plan. Manag.* **2016**, *11*, 3–14. [CrossRef]
17. Wenninger, S.; Kaymakci, C.; Wiethe, C.; Römmelt, J.; Baur, L.; Häckel, B.; Sauer, A. How Sustainable is Machine Learning in Energy Applications?—The Sustainable Machine Learning Balance Sheet. In *Proceedings of the International Conference on Wirtschaftsinformatik*, Nürnberg, Germany, 21–23 February 2022.
18. Kaymakci, C.; Wenninger, S.; Sauer, A. Energy Anomaly Detection in Industrial Applications with Long Short-term Memory-based Autoencoders. *Procedia CIRP* **2021**, *104*, 182–187. [CrossRef]

19. Wenninger, S.; Wiethe, C. Benchmarking Energy Quantification Methods to Predict Heating Energy Performance of Residential Buildings in Germany. *Bus. Inf. Syst. Eng.* **2021**, *63*, 223–242. [\[CrossRef\]](#)
20. Wenninger, S.; Kaymakci, C.; Wiethe, C. Explainable long-term building energy consumption prediction using QLattice. *Appl. Energy* **2022**, *308*, 118300. [\[CrossRef\]](#)
21. Watson, R.T.; Boudreau, M.-C.; van Iersel, M.W. Simulation of greenhouse energy use: An application of energy informatics. *Energy Inf.* **2018**, *1*, 1–14. [\[CrossRef\]](#)
22. The US Department of Energy. *Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them. A Report of the United States Congress Pursuant to Section 1252 of the Energy Policy Act of 2005*; U.S. Department of Energy: Washington, DC, USA, 2006.
23. Müller, T.; Möst, D. Demand Response Potential: Available when Needed? *Energy Policy* **2018**, *115*, 181–198. [\[CrossRef\]](#)
24. Bank, L.; Wenninger, S.; Köberlein, J.; Lindner, M.; Kaymakci, C.; Weigold, M.; Sauer, A.; Schilp, J. Integrating Energy Flexibility in Production Planning and Control—An Energy Flexibility Data Model-Based Approach. In Proceedings of the Conference on Production Systems and Logistics: CPSL 2021, Hannover, Germany, 10–11 August 2021; pp. 668–677.
25. Murthy Balijepalli, V.S.K.; Pradhan, V.; Khaparde, S.A. *Review of Demand Response under Smart Grid Paradigm*; IEEE: Kollam, India, 2011; ISBN 9781467303156.
26. Buhl, H.U.; Gabrek, N.; Gerdes, J.-N.; Kaymakci, C.; Rauland, K.; Richter, F.; Sauer, A.; Schneider, C.; Schott, P.; Seifermann, S.; et al. *Industrial Flexibility Options and Their Applications in A Future Energy System*; White Paper; Federal Ministry of Education and Research: Sankt Augustin, Germany, 2021.
27. Kogut, B.; Kulatilaka, N. Operating Flexibility, Global Manufacturing, and the Option Value of a Multinational Network. *Manag. Sci.* **1994**, *40*, 123–139. [\[CrossRef\]](#)
28. Schwartz, E.S.; Trigeorgis, L. (Eds.) *Real Options and Investment under Uncertainty: Classical Readings and Recent Contributions*; MIT Press: Cambridge, MA, USA, 2004; ISBN 0262194465.
29. Dixit, A.K.; Pindyck, R.S. *Investment under Uncertainty*; Princeton University Press: Princeton, NJ, USA, 1994.
30. Cox, J.C.; Ross, S.A.; Rubinstein, M. Option pricing: A simplified approach. *J. Financ. Econ.* **1979**, *7*, 229–263. [\[CrossRef\]](#)
31. Te Kulve, M.; Schlangen, L.; van Marken Lichtenbelt, W. Interactions between the perception of light and temperature. *Indoor Air* **2018**, *28*, 881–891. [\[CrossRef\]](#)
32. Mahmoud, S.; Zayed, T.; Fahmy, M. Development of sustainability assessment tool for existing buildings. *Sustain. Cities Soc.* **2019**, *44*, 99–119. [\[CrossRef\]](#)
33. Bellia, L.; d'Ambrosio Alfano, F.R.; Fragliasso, F.; Palella, B.I.; Riccio, G. On the interaction between lighting and thermal comfort: An integrated approach to IEQ. *Energy Build.* **2021**, *231*, 110570. [\[CrossRef\]](#)
34. Fanger, P.O.; Breum, N.O.; Jerking, E. Can colour and noise influence man's thermal comfort? *Ergonomics* **1977**, *20*, 11–18. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Albers, F.; Maier, J.; Marggraf-Micheel, C. In search of evidence for the hue-heat hypothesis in the aircraft cabin. *Lighting Res. Technol.* **2015**, *47*, 483–494. [\[CrossRef\]](#)
36. Winzen, J.; Albers, F.; Marggraf-Micheel, C. The influence of coloured light in the aircraft cabin on passenger thermal comfort. *Lighting Res. Technol.* **2014**, *46*, 465–475. [\[CrossRef\]](#)
37. Toftum, J.; Thorseth, A.; Markvart, J.; Logadóttir, Á. Occupant response to different correlated colour temperatures of white LED lighting. *Build. Environ.* **2018**, *143*, 258–268. [\[CrossRef\]](#)
38. Baniya, R.R.; Tetri, E.; Virtanen, J.; Halonen, L. The effect of correlated colour temperature of lighting on thermal sensation and thermal comfort in a simulated indoor workplace. *Indoor Built Environ.* **2018**, *27*, 308–316. [\[CrossRef\]](#)
39. DIN V 4108-6:2003-06, *Wärmeschutz und Energie-Einsparung in Gebäuden—Teil_6: Berechnung des Jahresheizwärme- und des Jahresheizenergiebedarfs*; Beuth Verlag GmbH: Berlin, Germany, 2003.
40. DIN V 4701-10:2003-08, *Energetische Bewertung Heiz- und Raumlufthtechnischer Anlagen—Teil_10: Heizung, Trinkwassererwärmung, Lüftung*; Beuth Verlag GmbH: Berlin, Germany, 2003.
41. Federal Ministry for Economic Affairs and Energy. Erneuerbare Energien in Zahlen: Nationale und Internationale Entwicklung im Jahr 2019. Available online: https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/erneuerbare-energien-in-zahlen-2019.pdf?__blob=publicationFile&v=6 (accessed on 30 August 2021).
42. Deutscher Wetterdienst. Weather data of Augsburg (Germany) in hourly resolution. 2022. Available online: https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/hourly/air_temperature/historical/stundenwerte_TU_00232_19550101_20201231_hist.zip. (accessed on 10 January 2022).
43. Federal Institute for Occupational Safety and Health. Technische Regeln für Arbeitsstätten: ASR A3.5 Raumtemperatur; 2021. Available online: <https://www.baua.de/DE/Angebote/Rechtstexte-und-Technische-Regeln/Regelwerk/ASR/ASR-A3-5.html> (accessed on 10 January 2022).
44. Miller, N.J.; Leon, F.A. OLED Lighting Products: Capabilities, Challenges, Potential; 2016. Available online: <https://www.osti.gov/biblio/1374109> (accessed on 10 January 2022).
45. Rockstuhl, S.; Wenninger, S.; Wiethe, C.; Häckel, B. Understanding the risk perception of energy efficiency investments: Investment perspective vs. energy bill perspective. *Energy Policy* **2021**, *159*, 112616. [\[CrossRef\]](#)
46. Ahlrichs, J.; Rockstuhl, S.; Tränkler, T.; Wenninger, S. The impact of political instruments on building energy retrofits: A risk-integrated thermal Energy Hub approach. *Energy Policy* **2020**, *147*, 111851. [\[CrossRef\]](#)