Building
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CLEAN ENERGY TRANSITION AND DIGITAL TRANSFORMATION

Fundamentals
Case Studies
Strategies

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CLIMATE-NEUTRAL URBAN DISTRICT NEUE WESTSTADT, ESSLINGEN

The P2G&H Concept – Green Hydrogen with Waste Heat Utilization

Case Study by
M. Norbert Fisch

Green hydrogen has a key role to play in the drive to achieve the climate goal of net-zero greenhouse gas emissions and decarbonize the energy use of all consumption sectors. In the Neue Weststadt district of Esslingen in south-west Germany, the concept of P2G&H – Power to Gas and Heat – is being put to the test as part of an ongoing real-world laboratory project for a new "Climate-neutral Urban District". In this concept, green hydrogen is produced at the neighbourhood level close to the point of consumption and the waste heat it produces is utilized directly. The concept has been developed, planned and scientifically monitored – from implementation to the operation phase – by Steinbeis Innovation Center energyplus.

In 2010, the German Federal Ministry of Economic Affairs and Technology (BMWi) set out its plans for a transition to clean energy,[1] and the German government committed to ambitious targets to reduce greenhouse gas emissions[2] in its Climate Action Plan, in sync with the EU Green Deal.[3] To achieve these, the government will need to significantly ramp up the expansion of solar and wind energy farms: renewable energy production capacity will need to rise almost fivefold from the current level of approx. 110 GW (in Germany) to more than 500 GW by 2050 (Fig. 1).

This will cause a corresponding rise in surplus electricity output resulting from the fluctuating nature of renewable energy sources, which at present is non-usable. Rather than throttling overcapacity, as is currently the case, this surplus can be converted into hydrogen (Power to Gas, P2G) as a chemical energy carrier. Green hydrogen is therefore a key enabler of the clean energy transition. It can be used as a direct substitute for carbon fuels in many chemical processes, and, like natural gas, can be stored for extended periods of time without loss of capacity for later conversion back into energy – not only to cover dark lulls in renewable energy supply – through fuel cell CHP or gas turbine power plants.

Scientific studies confirm the central role that hydrogen has to play in the transition to a climate-neutral energy supply system. Over the coming two decades, green hydrogen will initially be used to advance decarbonization in industrial and mobility sectors, but from 2040 onwards its adoption in the building sector must also be accelerated if we are to reach the target of net-zero emissions. A study by Forschungszentrum Jülich on transformation strategies for the German energy system up to 2050 (FZJ, 2020)[4] predicts that hydrogen demand in Germany will reach 12 megatonnes (Mt) per year. Assuming that around half this hydrogen will be produced domestically, Germany will need to target an electrical output capacity of 50 to 60 gigawatts (GW) using electrolysis plants. A precondition for such green hydrogen production is that electrolyzers must operate during periods in which the proportion of renewable energy sources in the grid mix is as high as possible. With this approach, the mean number of full-load hours per year would lie between 4,000 and 5,000 hours. The waste heat that this level of hydrogen production would produce is estimated at around 110 terawatt hours (TWh) per year which, according to the BMWi in 2021, is roughly equivalent to the level of fossil-fuel fired district heating currently provided in Germany (approx. 104 TWh in 2020)![5]

From a strategic and economic perspective, the challenge is now to ramp up hydrogen production as efficiently as possible and to make best possible use of the potential of waste heat. The P2G&H concept follows exactly this principle. One approach is to construct decentralized electrolysis plants with a lower capacity (2–3-digit MW) close to customers of green hydrogen, for example in locations with good transport connectivity near urban conurbations. The resulting waste heat can then be efficiently used to supply local neighbourhoods using existing or newly constructed heat distribution networks. With this approach, the efficiency of hydrogen production can potentially be increased from approx. 55% to up to 85% (Fig. 2). In addition, producing energy and heat close to the point of consumption reduces transport distances and reinforces regional economic cycles.

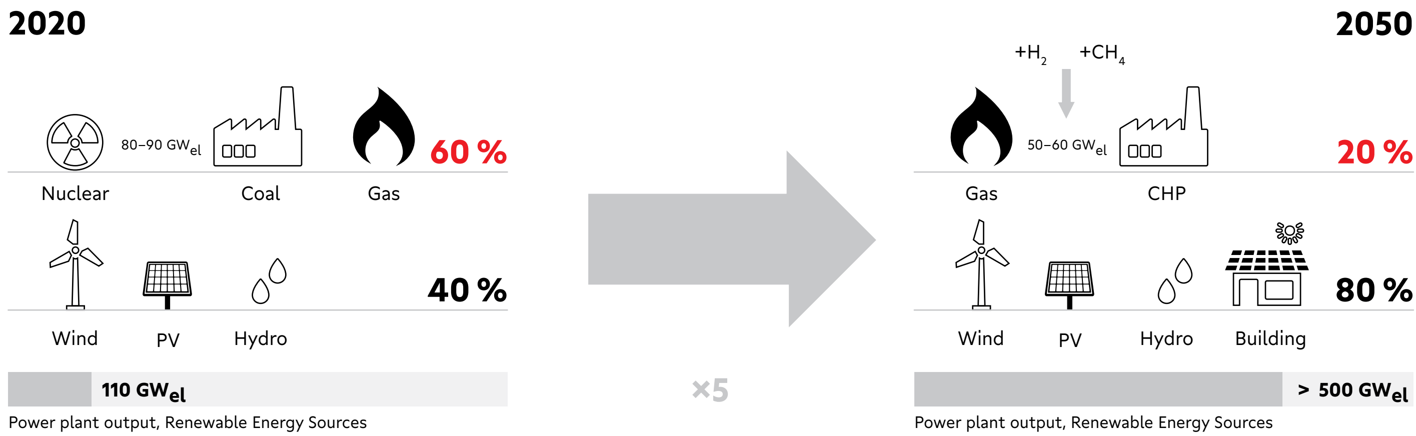
1 Energy concept for an environmentally sound, reliable and affordable energy supply, Federal Ministry of Economic Affairs and Technology (BMWi), now the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) (28 September 2010).

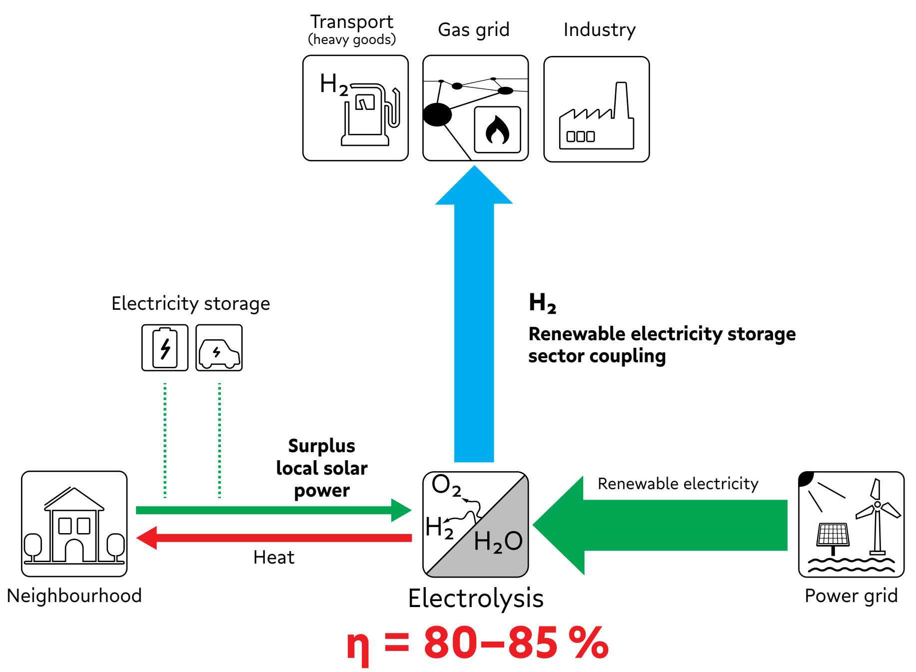
2 Deutscher Bundestag, publication 19/13900, 2019.

3 European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions, European Commission, 2021, https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541.

4 M. Robinius et al., "Wege für die Energiewende. Kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050", Schriften des Forschungszentrums Jülich, Energie & Umwelt Series, Vol. 499, 2020.

5 Energiewende Direkt, https://www.bmwi-energiewende.de/EWD/Redaktion/Newsletter/2021/03/.





GREEN HYDROGEN

While hydrogen can be used as a substitute for fossil fuels, its full potential for mitigating climate change is only achieved when produced using renewable energy sources. This so-called green hydrogen is therefore the cornerstone of the P2G&H concept. To be compliant, the operators of electrolysis plants commit to producing green hydrogen, as per § 12i of the German Renewable Energy Sources Act from 14 July 2021 (BGBl. I, p. 2860), which stipulates that operators must undertake to use energy from renewable energy sources in Germany and to provide evidence in the form of guarantees of origin. The use of renewable energy minimizes the emissions burden of green hydrogen production. Supply agreements with regional wind and solar power plants, both existing and planned, are particularly suitable and additionally benefit local economies and in turn contribute to local acceptance.

The mode of operation of electrolysis plants as a component of the clean energy transition also benefits the energy system. To achieve net-zero emissions, it is necessary to flexibly control the integration of renewable energy power plants into the power

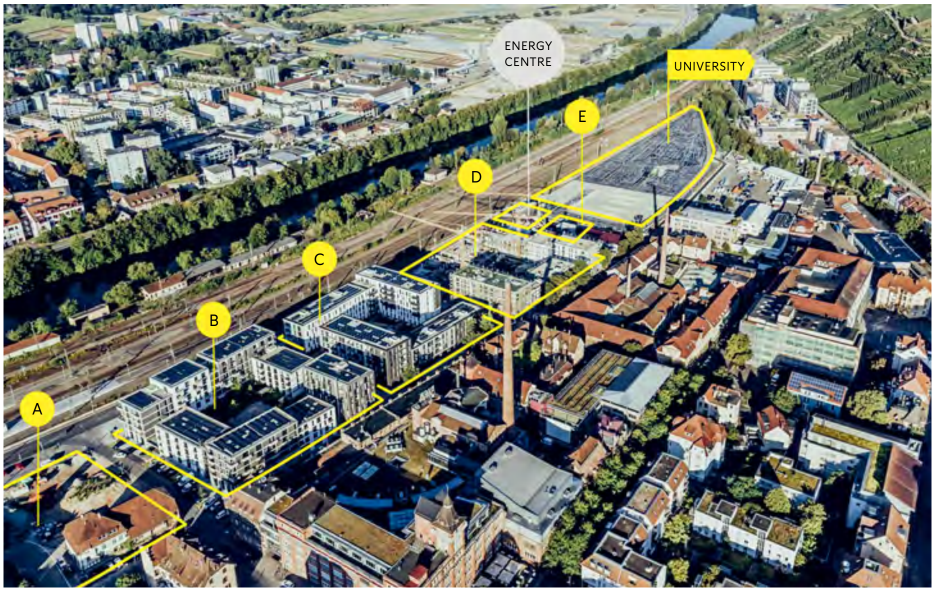
1

Necessary expansion of photovoltaic and wind energy capacities.

Based on: M. Norbert Fisch, 2019, lecture Zukunftsstadtkonferenz, Münster.

2

Conceptual approach of P2G&H – increased efficiency for the production and utilization of green hydrogen.



3

Neue Weststadt, Esslingen – residential blocks A to D, office tower E and university campus.

system. A study on the need for a new electricity market design commissioned by the BEE Federal Association for Renewable Energy in 2021[6] cites that electrolyzers can make a fundamental contribution to stabilizing the market and supply system in future by affording greater flexibility to the renewable energy market. The study concludes that the provision of an overall electrolysis capacity of up to 100 GW_{el} in Germany could strengthen the economic resilience and independence of the entire system.

A breakdown of electricity generation sources shows that in 2022 the greenhouse gas emission factor averages around 400 g/kWh in Germany. Assuming that electrolyzers are operated during periods with a high proportion of renewable energies, the emission factor falls to around 275 g/kWh for those periods.[7] With the increasing expansion of renewable electricity generation, the emission factors will decrease further. In a fully decarbonized electricity system, or if energy purchases are certified as being 100 % from renewable sources, the emission factor will eventually tend towards zero.

A FLAGSHIP PROJECT IN ESSLINGEN

Since 2016, an approx. 12 ha inner-city site in the Swabian town of Esslingen am Necker in south-west Germany has served as a real-world laboratory for researching the implementation of a clean energy transition. Conceived as a flagship project for climate-neutral urban districts, it is funded by the Federal Ministry of Economic Affairs and Climate Protection (BMWK) and the Federal Ministry of Education and Research (BMBF) as part of the "Solar Construction/Energy-Efficient Towns" funding initiative.

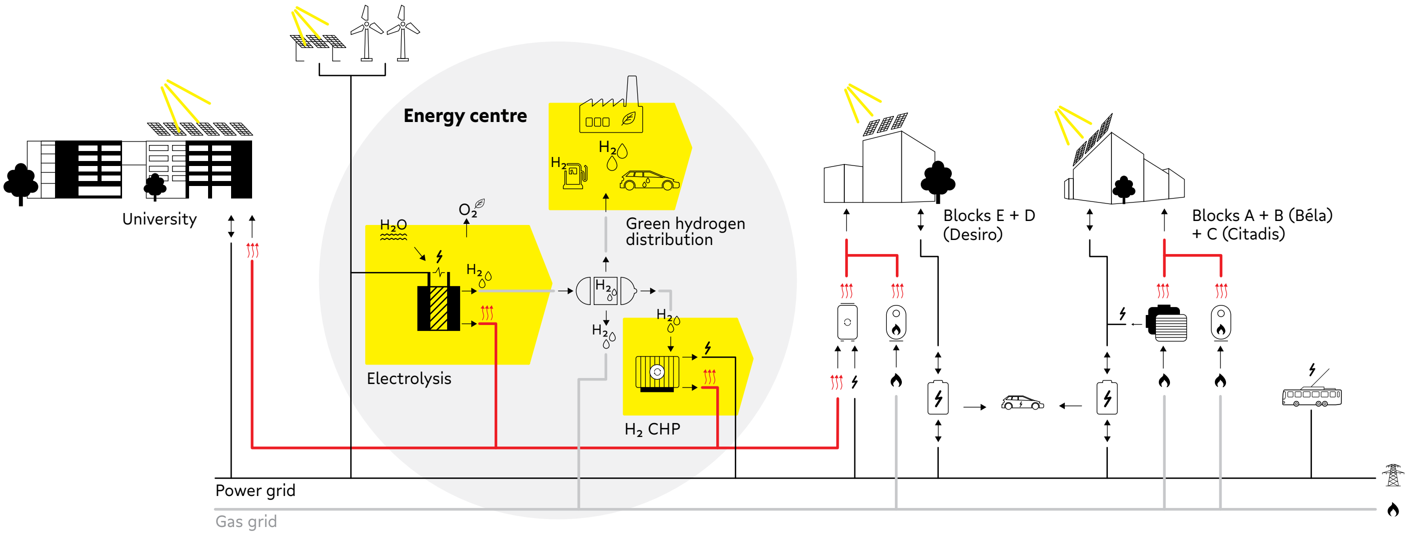
A joint venture between the City of Esslingen as the lead applicant and 13 partners in total, the project is being funded with EUR 12 million between 2016 and 2024. The overall scientific and organizational coordination is provided by Steinbeis Innovation Center (SIZ) energyplus in Stuttgart. An interdisciplinary team of researchers (from the fields of technology and social sciences), practitioners, facilitators and public participators was brought together to address the broad range of sectors and technical aspects within the project.

The goal of the new climate-neutral urban district is to reduce its annual carbon emissions to less than 1 tonne per inhabitant for housing and mobility by utilizing waste heat from the local production of hydrogen. This also contributes to the city's goal to reduce carbon emissions across the city by a quarter. The new district will also play an essential role in the ongoing drive to achieve further climate goals.

The urban design concept developed by Lehen drei Architekten Stadtplaner SRL, Stuttgart, in 2013 encompasses four urban blocks (A to D) with a total of around 500 residential units and a mix of 70 % residen-

6 *Neues Strommarktdesign*, study commissioned by BEE e.V., 2021, https://www.klimaneutrales-stromsystem.de/pdf/Strommarktdesign-studie_BEE_final_Stand_14_12_2021.pdf. *New Electricity Market Design Study*. Abbreviated English-language synopsis: https://klimaneutrales-stromsystem.de/pdf/english/20211213_BEE_New%20Electricity_Market_Design_Study_Short_version_ENG.pdf.

7 Based on own calculations, SIZ energyplus, Stuttgart.



4

Energy concept – waste heat utilization from green hydrogen production.

tial and 30 % commercial uses (Fig. 3). To the west of the new district square, a new building for Esslingen University of Applied Sciences was constructed with lecture halls, seminar rooms, offices, refectory, computer centre and a library (approx. 18,500 m² of usable space). The new university campus thus directly adjoins the residential and commercial blocks of the quarter and is close to both the city centre and railway station. At the edge of the district square, a 12-storey tower with offices and shops (approx. 7,500 m²) is planned, the so-called Crystal Rock (Block E), that will serve as a landmark for the site.

Designs for each of the individual urban blocks were determined through separate architecture competitions organized by the City of Esslingen and the developer RVI GmbH from Saarbrücken. The overall goals of the climate-neutral district were outlined in the competition briefs, stipulating, among other things, maximal use of roof surfaces for solar energy generation. The strong support and commitment of the city – represented by the mayor and the city administration – and the developer have been crucial to the success of the project.

ENERGY CONCEPT

The energy concept takes a holistic approach to cost effectiveness by reducing demand for heating and electricity and using energy generated from renewable sources. Ensuring the buildings are well insulated (almost to KfW efficiency house level EH 55) reduces the heating energy demand and results in a comfortable indoor climate.

Residential blocks A, B and C are supplied with bio-methane via the municipal gas mains (not actually but indirectly through the natural gas mix sourced by the Stadtwerke Esslingen, the municipal utility company). Cogeneration CHP plants and gas boilers in the respective buildings convert this into heat and electricity. The remaining residential block D, office tower E and the university campus building are connected to a local district heating network powered by the energy centre. This separation into two energy supply concepts came about as a result of delayed funding notices for the research project while the neighbourhood development advanced rapidly. Alongside the 1000 kW_{el} electrolyzer, the energy centre beneath the district square also contains a gas CHP plant (biomethane and H_2) and an electric heat pump to recover waste heat from the transformers and inverters, as well as a gas boiler. Its inner-city location also makes it possible to recover waste heat from the stack cooling (220 kW_{th}), greatly improving the efficiency of the system – an increase from approx. 55 % to over 85 % for the electrolysis. The waste heat from electrolysis (60–65 °C) covers about half of the overall annual heat demand (~1200 MWh/a) for the units it is connected to. To utilize the heat supplied by the district heating net-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work, the relevant apartments are equipped with low-temperature heating systems (surface heating) and fresh water stations for domestic hot water.

The innovative heart of the energy centre is an alkaline electrolyzer (30 % caustic potash), divided into two skid-mounted 500 kW_{el} capacity units, which together convert around 5,000 MWh of renewable electricity into 85 t of hydrogen per year. To produce 1 kg of H_2 requires about 60 kWh of green electricity and 18 l of drinking water. To accommodate the start-up process of the electrolyzer, a horizontally mounted stainless steel cylindrical hydrogen tank is installed next to the electrolyzer unit.

The original plan for marketing the green hydrogen envisaged the construction of a hydrogen refueling station on the nearby premises of Esslingen's municipal utility, to complement the existing natural gas filling station for cars. As the project progressed, the decision was made to concentrate solely on charging stations for electric vehicles, with hydrogen use planned instead primarily for fuel cells used in heavy goods vehicles. The original plan to build a hydrogen refuelling station was therefore not implemented.

Another option investigated but ultimately not pursued was to supply hydrogen by truck for use in industry or vehicle refuelling stations. However, the low capacity of trailer tanks, which can hold around 15 MWh (equivalent to ~1,500 l of heating oil), the 40 tonnes vehicle weight and high investment costs for a 500-800 bar compressor mean that the cost of green hydrogen is unfavourably high compared to conventional hydrogen.

To supply large quantities of hydrogen, a suitable distribution network is required. As part of the H2 GeNeSiS project funded by the State of Baden-Württemberg and the EU, a hydrogen pipeline is planned to run between Stuttgart and Esslingen. Once built, the district's energy centre will then supply it with green hydrogen.

As an interim solution, the green hydrogen produced at 11.5 bar will initially be fed via a 180-m-long DN 40 stainless steel pipeline laid in sand to a gas pressure regulating and metering station, where it will then either be added to the mix in the existing medium- and low-pressure gas supply where it contributes to decarbonizing the gas network or, in research operation, converted back into electricity in a bivalent CHP cogeneration plant (biomethane: 200 kW_{el}, H_2: 150 kW_{el}).

The individual supply components are integrated into a cross-sector digital information network (smart grid). The energy flow can then be regulated according to the electricity market and demand in the supply area using a central energy management system.

The flat roofs of the district have been utilized for solar generation by installing photovoltaic panels in an east-west orientation for maximum gain. The total output of ~1400 kW is used in the first instance to supply the electricity needs of the residents and for e-mobility, with any surplus used for H_2 generation or fed back into the power grid.

A separate management and operating company was founded by the research consortium partners for the new climate-neutral district. The Green Hydrogen Esslingen GmbH (GHE) acts both as the investor for the plant and the main applicant for approvals. The company can draw on the expertise of its partners in dealing with gas supply (Stadtwerke Esslingen) and electricity market trading (Polarstern GmbH), as well detailed systematic knowledge of the operation of electrolysis plants. The fact that the partners already hold licenses for the local distribution of gas and electricity simplifies the subsequent application procedures.

In 2022, the Climate-neutral Urban District Neue Weststadt was awarded first prize in the sustainability category as part of the BMWK Federal Ministry for Economic Affairs and Climate Action's "Real-world Lab" programme.

TRIAL OPERATION AND INITIAL EXPERIENCES

After installation of the components in the energy centre, the plant modules were verified for compliance with industrial health and safety regulations by the inspection and certification body TÜV SÜD. Alongside an explosion safety audit, all safety mechanisms were subject to a Hazard and Safety Operability Study (HAZOP). All installations for producing hydrogen using electrolytic

5 ←

Installation of the two container skids in the energy centre. Each contains a 500 kW_{el} electrolysis stack.

6 ↙

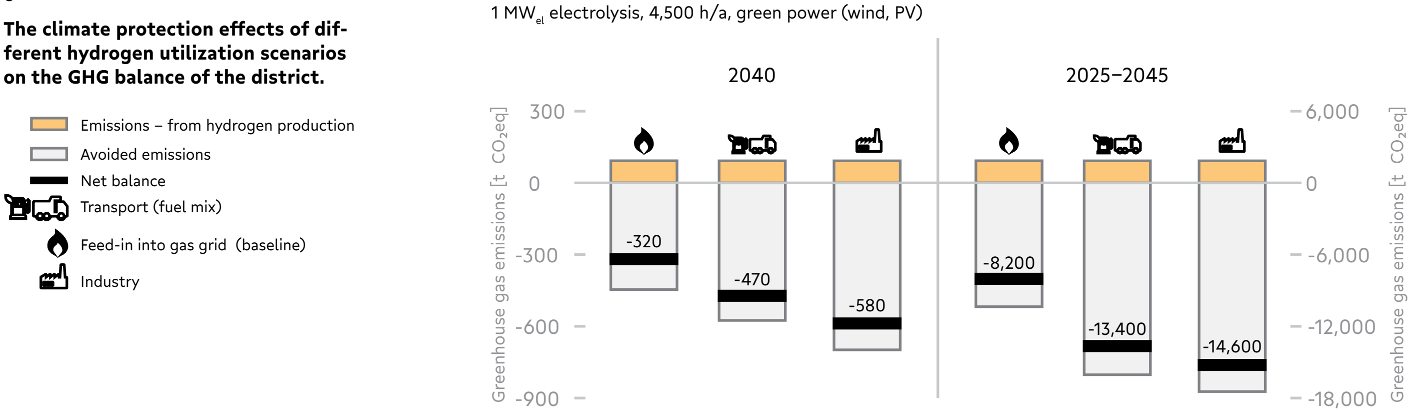
Underground energy centre beneath the district square – two electrolysis units, each with a capacity of 500 kW_{el}.

7 ↑

Hydrogen storage tank (vol. ~34 m^3, max. 29 kg H_2, 11.5 bar) installed next to the electrolysis units.

8

The climate protection effects of different hydrogen utilization scenarios on the GHG balance of the district.



Road closure and trench excavation

Pipeline on sand bed

Backfilling of sand

Underground warning tape

Road surface closure

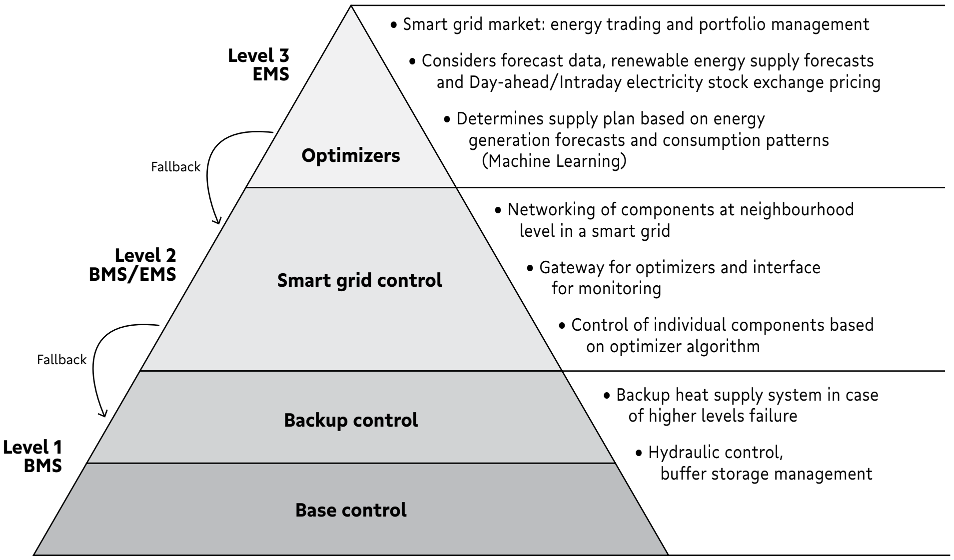
Gas pressure regulating and metering station

9 ↑

Construction of the H_2 pipeline to the natural gas grid and connection via a gas pressure regulating and metering station.

10 →

Levels of control: Building Management System (BMS), Energy Management System (EMS) and optimizers.



processes are subject to approval as set out in the Fourth Ordinance for the Implementation of the Federal Immission Control Act (BImSchV). The operator is additionally required to submit annual reports on the plant's operation including values for water consumption, wastewater discharge and noise emissions to the relevant authority. In Baden-Württemberg, responsibility for enforcing the Federal Immission Control Act lies with the regional councils.

The operation hours of the electrolyzer are dependent on the availability of electricity from renewable energy sources. As power generated on site through the roof-mounted photovoltaic panels is used primarily by the residents, the P2G system draws a large proportion of its power from outside the district via the power grid. Alongside electricity purchased directly from a wind park in the vicinity, green electricity is drawn via the grid using an algorithm that forecasts prices on the electricity stock exchange as an indicator of the share of renewable energy in the electricity mix (Fig. 12). The hydrogen produced by the plant is fed back into the gas supply. To this end a gas connection contract and corresponding feed-in tariff agreement was set up with the municipal utility company (Stadtwerke Esslingen).

Trial operation of the electrolysis plant started in March 2022. In the first few months, extensive defects in hardware and software were identified and rectified in cooperation with the manufacturers. The volatile pattern of operation also resulted in considerable teething problems in the industrial electrolyser used. Adjustments to the BImSchG permit and the retrofitting of a silencer in the oxygen blow-off pipe caused further delays to regular operation. The goal for 2023 was regular operation as envisaged in the original plan – optimized for "day-ahead" electricity purchases on the Leipzig electricity stock exchange and based on capacity forecasts for the company's own photovoltaic and wind power plants.

The exceptional rise in electricity prices in 2022 has impacted the economic viability of regular hydrogen production, even despite national subsidies, because the cost price of green hydrogen is largely determined by the price of the electricity used and only partially by the investment costs (Fig. 13). In Esslingen, the H_2 production price lies at around 6–8 EUR/kg or 20–27 ct/kWh while electricity purchase prices are approx. 8 ct/kWh (including subsidies for investment costs).

11

Maximum solar utilization of flat roofs – east-west oriented PV modules.

CONCLUSION – OUTLOOK

Green hydrogen is a key component in the transition to clean energy and plays an essential part in decarbonizing the industrial and mobility sectors. Central to the P2G&H concept is that green hydrogen is produced close to the point of consumption (industry, heavy goods transport) so that when situated in an urban context it can also supply heat to local districts. By utilizing waste heat and reducing transport distances to end users, this system approach is highly efficient. For direct waste heat utilization, consumers should ideally have heating systems that can operate with temperatures below 65 °C and have consistent year-round demand for heat. Heating systems in existing neighbourhoods with requirements for higher temperature levels can employ additional high-temperature heat pumps to boost waste heat temperature levels.

To achieve the climate policy goals of net-zero greenhouse gas emissions, we need a highly efficient means of providing emission-free energy so that we can in the first instance meet the expansion targets for electricity supply and in turn gain corresponding social acceptance. The decentralized approach of the P2G&H concept, as trialled here for the first time in the real-world research project for the Climate-neutral Urban District Neue Weststadt, demonstrates the feasibility and potential added value of this regional energy cycle economy.

The real-world laboratory paves the way for the adoption of electrolysis as an essential part of our future energy infrastructure, and it is imperative that this not be put back any further. Among other things, the BEE study (2021) calls for an accelerated expansion of electrolysis in Germany: "This not only promotes stronger market growth and provides a basis for higher annual rates of electrolysis expansion over the coming decades. This would bring about the necessary sector coupling and also stabilize the market for renewable energy sources."[8] The greatest beneficial effect of the P2G&H concept for the climate is that it can directly replace fossil fuel sources. In recognition of this, the state of Baden-Württemberg is funding the construction of an H_2 pipeline between Esslingen and Stuttgart as part of the H2 GeNeSiS project. This new marketplace for emission-free energy aims to connect generation plants, such as the electrolysis plant in Esslingen's Neue Weststadt, with large-scale consumers of conventional grey hydrogen in industry and of diesel in the mobility sector such as public transport providers, and heavy goods transport suppliers.

8 *Neues Strommarktdesign*, study commissioned by BEE e.V., 2021, https://www.klimaneutrales-stromsystem.de/pdf/Strommarktdesign-studie_BEE_final_Stand_14_12_2021.pdf. *New Electricity Market Design Study*. Abbreviated English-language synopsis: https://klimaneutrales-stromsystem.de/pdf/english/20211213_BEE_New%20Electricity_Market_Design_Study_Short_version_ENG.pdf.

Further Reading

▶ Neighbourhood planning, "Circular Construction Over Again", p. 142
▶ Heterogeneity, "Sustainability – Strategies for Action", p. 10
▶ Renewable energy, "The Clean Energy Transition in the Context of Sustainability", p. 20

12 ↗↗

Electrolysis operation times as influenced by power exchange prices and wind power supply forecasts, Saturday and Sunday, 18–19 June 2022.

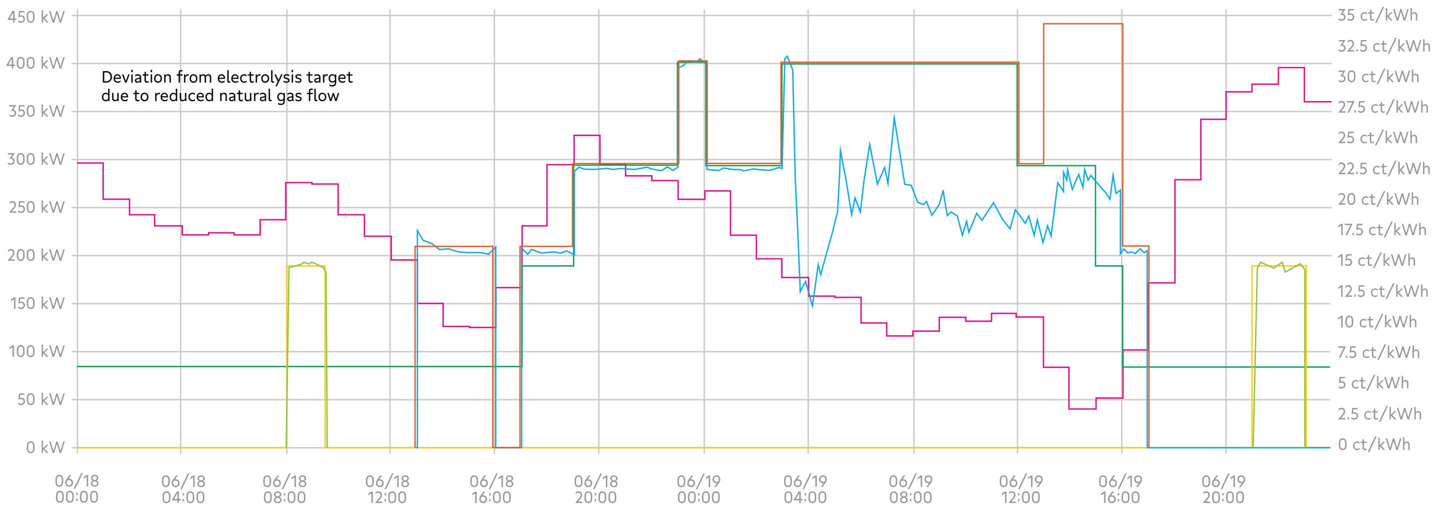
- Market price forecast [ct/kW]
- Wind energy forecast [kW]
- Target plan electrolysis [kW]
- Actual electrolysis [kW]
- Target plan CHP [kW]
- Actual CHP [kW]

13 ↗

Production costs for green hydrogen by means of electrolysis.

Investment scenarios

- 1,000 €/kW
- 2,000 €/kW
- 3,000 €/kW


Deviation from electrolysis target
due to reduced natural gas flow
450 kW
400 kW
350 kW
300 kW
250 kW
200 kW
150 kW
100 kW
50 kW
0 kW
35 ct/kWh
32.5 ct/kWh
30 ct/kWh
27.5 ct/kWh
25 ct/kWh
22.5 ct/kWh
20 ct/kWh
17.5 ct/kWh
15 ct/kWh
12.5 ct/kWh
10 ct/kWh
7.5 ct/kWh
5 ct/kWh
2.5 ct/kWh
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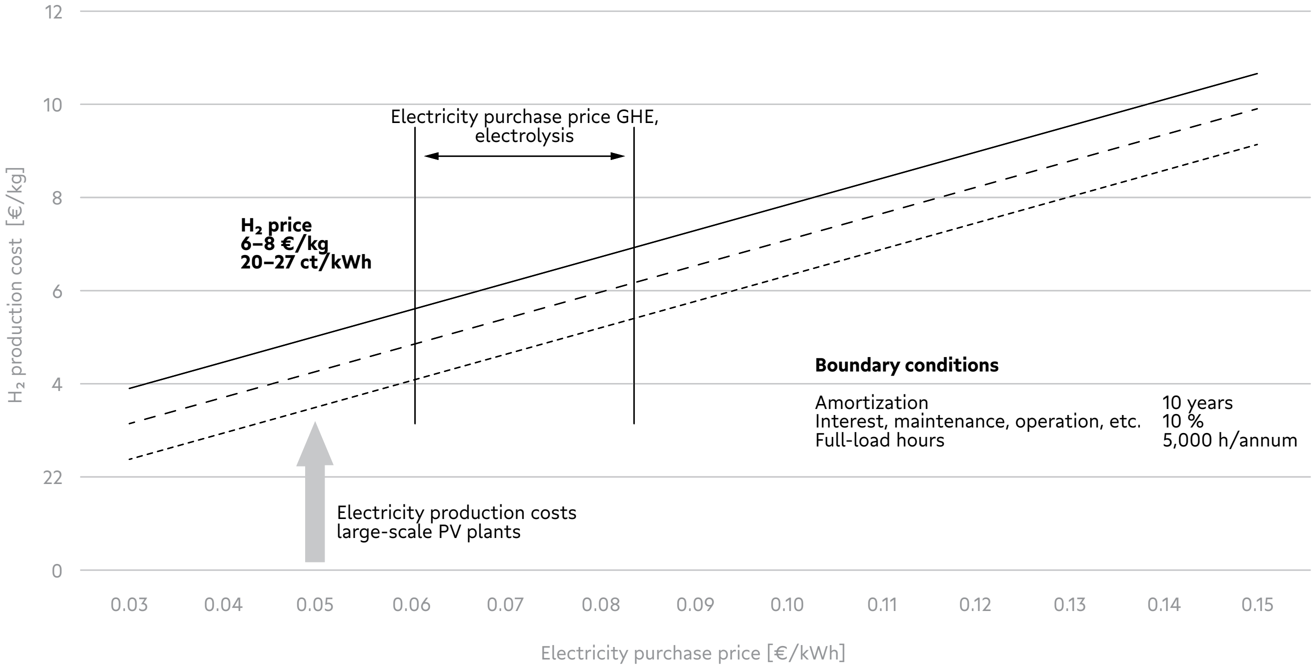
Electricity purchase price GHE, electrolysis
H₂ price
6–8 €/kg
20–27 ct/kWh
Boundary conditions
Amortization 10 years
Interest, maintenance, operation, etc. 10 %
Full-load hours 5,000 h/annum
Electricity production costs
large-scale PV plants
H₂ production cost [€/kg]
12
10
8
6
4
22
0
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
Electricity purchase price [€/kWh]

Appendix

ACKNOWLEDGEMENTS

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Felix Heisel, Dirk E. Hebel, Andreas Wagner and Moritz Dörstelmann

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Felix Heisel is Assistant Professor of Architecture at Cornell University's College of Architecture, Art, and Planning, where he directs the Circular Construction Lab (CCL), a cross-disciplinary research hub working towards the systemic redesign of the built environment as a material depot in a continuous cycle of use and reconfiguration. Heisel is one of the founding partners of the Circularity, Reuse, and Zero Waste Development (CR0WD) network in New York State, as well as a founding partner of 2hs Architekten und Ingenieur PartGmbB Hebel Heisel Schlesier, Germany, an office specializing in the development of circular prototypologies. He has received various awards for his work and published numerous books and articles on the topic, including *Building Better – Less –Different: Circular Construction and Circular Economy* (Birkhäuser, 2022, with Dirk E. Hebel), *Cultivated Building Materials* (Birkhäuser, 2017, with Dirk E. Hebel) and *Building from Waste* (Birkhäuser, 2014, with Dirk E. Hebel and Marta H. Wisniewska). Felix Heisel graduated from Berlin University of the Arts and has taught and researched at universities around the world, including the Berlage Institute, the Ethiopian Institute of Architecture, Building Construction and City Development, the Future Cities Laboratory Singapore, ETH Zurich, Karlsruhe Institute of Technology (KIT) and Harvard GSD.

Dirk E. Hebel is Professor of Sustainable Construction and the Dean of the Faculty of Architecture at the Karlsruhe Institute of Technology (KIT), Germany. He is a founding partner of 2hs Architekten und Ingenieur PartGmbB Hebel Heisel Schlesier, practicing architecture with a focus on resource-respectful construction methods and materials. His work has been shown in numerous exhibitions worldwide, among them *Plastic: Remaking our world*, Vitra Design Museum Weil am Rhein, and *Environmental Hangover* by Pedro Wirz (both with Nazanin Saeidi, Alireza Javadian, Sandra Böhm and Elena Boerman), Kunsthalle Basel, both in 2022, as well as *Sorge um den Bestand*, BDA, Berlin and other venues, 2020–. Hebel published numerous books in the field of Sustainable Construction, most recently *Building Better – Less – Different: Circular Construction and Circular Economy* (Birkhäuser, 2022, with Felix Heisel) and *Urban Mining und kreislaufgerechtes Bauen* ("Urban Mining and Circular Construction") (Fraunhofer, 2021, with Felix Heisel). As Faculty Advisor together with Prof. Andreas Wagner, he won the first Solar Decathlon Competition 2022 held in Wuppertal, Germany, as part of the RoofKIT team (Regina Gebauer and Nicolás Carbonare).

Andreas Wagner is Professor of Building Science and Technology at the Faculty of Architecture at Karlsruhe Institute of Technology (KIT). After graduating in mechanical engineering from the University of Karlsruhe (TH), he worked for almost ten years in solar research at the Fraunhofer Institute for Solar Energy Systems (ISE) in Freiburg. In addition to teaching in Bachelor's and Master's programmes with a special focus on energy-optimized building, lighting design and simulation-based planning tools, his main research interests are concepts and performance analysis for energy-efficient buildings as well as comfort and user behaviour in office buildings. Andreas Wagner is (co-)author of more than 150 publications and six books and has reviewed more than 45 doctoral theses. He is a member of numerous scientific advisory boards for international journals and conferences. Since 2018, he has been Co-Operating Agent of the IEA EBC Annex 79 and, since February 2023, one of the two leaders of the working group "Energy Transition of the Built Environment" in the ESYS project of the German Academies of Sciences. He was Dean of the Faculty at KIT from 2000 to 2004 and from 2012 to 2015. In addition, he was a member of the steering committee and spokesperson for the area of "Efficient Energy Use" at the KIT Center for Energy for eleven years. Since 2021, he has been one of the spokespersons of the KIT Graduate School ENZo.

Moritz Dörstelmann is Tenure Track Professor of Digital Design and Fabrication (DDF) at the Faculty of Architecture at Karlsruhe Institute of Technology (KIT) and founding partner of the robotic construction company FibR GmbH. His academic work investigates digital circular construction concepts at the interdisciplinary interface of research and teaching through explorative prototyping of innovative material systems and construction technologies on 1:1 scale in application-oriented demonstrator projects. His construction company FibR realizes resource-efficient fibre composite lightweight structures as load-bearing structures, facades and interiors in architectural projects through computational design and robotic fabrication at industrial scale. At the intersection of application-oriented academic research and research-oriented industrial practice, Moritz Dörstelmann's work shows how digital design and manufacturing strategies can be used to explore a novel architectural design repertoire and enable socially relevant solutions to reduce resource consumption and enable circularity in construction.

Thomas Auer is Professor of Building Technology and Climate Responsive Design at the Technical University of Munich (TUM) and a partner at Transsolar. Based on a sound understanding of the architectural integration of energy and comfort strategies, he works with renowned architectural firms on numerous projects around the world. The resulting individual strategies are characterized by their holistic and innovative approach and have been awarded numerous prizes. Thomas Auer has taught at Yale University and many other universities and was appointed professor at TUM in 2014. His research focuses on the decarbonization of the building sector as well as climate adaptation and its impact on the quality of living. Its basis is always a robust optimization at the spatial, building and city levels. He is a member of the Akademie der Künste, Berlin, and the Convention of Baukultur at the Federal Foundation of Baukultur.

Matthias Berning is a senior scientist and project manager at ABB corporate research in Germany. He is part of the Sensor Solutions team, with a research focus on distributed sensing and information processing in different domains, including building automation. With more than ten years of experience in monitoring occupants and indoor environments, he is striving to exploit this information in building operation to optimize energy efficiency and comfort. During his studies in electrical engineering and information technology at the TU

Kaiserslautern, he started working on wireless sensor networks. He also used these in the field of pervasive computing during his doctorate at the TECO research group at Karlsruhe Institute of Technology (KIT).

Elena Boerman is a research associate in teaching, research and innovation at the Professorship of Sustainable Construction in the Faculty of Architecture at Karlsruhe Institute of Technology (KIT), where she studied architecture, obtaining her Master's degree in 2021. She received recognition from the Friedrich Weinbrenner Prize for her final thesis on urban planning and architectural strategies for dealing with existing building structures from the post-war modern era. Together with Sandra Böhm, she is responsible for setting up a novel material library at the Faculty of Architecture at Karlsruhe Institute of Technology (KIT) focusing on circular construction methods. She is a voluntarily member of the Karlsruhe chapter of Architects for Future, which she co-founded together with Alisa Schneider in 2020.

Kathrin Dörfler is an architect, researcher and educator in computational design and robotic fabrication. She has a Master's degree in architecture from the TU Wien and a PhD (Dr.-Ing.) in digital fabrication from ETH Zurich. Together with Romana Rust, she co-founded the architectural research studio dorfundrust. She undertook her doctoral thesis at Gramazio Kohler Research, ETH Zurich, as part of the National Centre of Competence in Research Digital Fabrication (NCCR DFAB). In 2019, Kathrin Dörfler joined the Technical University of Munich School of Engineering and Design (TUM SoED) as a tenure track professor to set up a research group for Digital Fabrication at the Department of Architecture. The research interests of her group lie at the interface between computational design and robotic fabrication, focusing on collaborative fabrication processes, on-site robotics and fabrication-aware design. In addition to research, Kathrin Dörfler has taught in Vienna, Zurich and Munich in architecture programmes as well as specialized postgraduate programmes in architecture and digital fabrication (MAS DFAB ETH Zurich).

Max Benjamin Eschenbach is a computational design researcher focused on the development of digital process chains as well as interactive and collaborative tools for digital design, planning and fabrication. He is currently a research associate and PhD candidate at the Digital Design Unit (DDU) of the Technical University of Darmstadt, working on computational tools for architectural design with reused components. He studied product design at the Kunsthochschule Kassel, where he also worked in research and teaching within the workshop for Digital Design & Fabrication (Digitale 3D-Technik) from 2019 to 2021.

M. Norbert Fisch is head of the Steinbeis Innovation Center energyplus (SIZ), Braunschweig and Stuttgart, CEO of EGS-plan Ingenieurgesellschaft, Stuttgart, and co-founder and shareholder of Green Hydrogen Esslingen. After completing his mechanical engineering studies with a focus on energy technology at the University of Stuttgart, he set up and managed the Department of Rational Use of Energy and Solar Technology at the university's Institute for Thermodynamics, and received his Doctorate of Engineering (Dr.-Ing.) in 1984. As head of department, he set future-oriented impulses and established numerous R&D projects for the technical use of solar energy. In 1996, he accepted an appointment as a professor at the Technische Universität Braunschweig and then headed the Institute for Building and Solar Technology (IGS) for 22 years. During this time he worked on well over 20 R&D projects in the fields of energy-efficient buildings, heat and cold storage, methods of optimizing the operation of non-residential buildings and the development and implementation of climate-neutral quarters. Since 2020 he has headed R&D projects at SIZ energyplus, an institute affiliated with the TU Braunschweig.

Daniel Fischer studied architecture in Karlsruhe, Tampere and Delft. After internships in Basel and Karlsruhe, he graduated cum laude with a degree in Digital Design & Architecture from TU Delft in 2018. After several years as a project architect, he joined the Professorship of Digital Design and Fabrication (DDF) at the Faculty of Architecture at Karlsruhe Institute of Technology (KIT) in 2021 with a particular research interest in digital wood construction and digital circular economy. He became a licensed and registered architect in 2022.

Sebastian Herkel heads the Energy Efficient Buildings department at the Fraunhofer Institute for Solar Energy Systems (ISE), where he works as a scientist in applied research in the fields of energy efficiency and renewable energy systems in buildings. His focus is on the transformation of the building stock, efficient heat supply systems and integral energy concepts for buildings as well as on scientific analyses of building performance and the digitalization of planning processes.

Tianzhen Hong is a senior scientist at the Building Technology and Urban Systems Division of Lawrence Berkeley National Laboratory in California. His research focuses on novel methods, data, computing, occupant behaviour and policy for the design and operation of low energy and resilient buildings and sustainable urban systems. Dr. Hong actively contributed to international collaborations such as IEA EBC Annex 53, 66, 79 and 81. He led the research projects that developed two building energy software systems, CBES and CityBES, which won the R&D 100 Awards in 2019 and 2022, respectively. He is an IBPSA Fellow and ASHRAE Fellow. He has published more than 180 journal articles and is a highly cited researcher.

Jan Knippers studied civil engineering at the TU Berlin, completing his doctorate (Dr.-Ing.) in 1992. He worked for several years in an engineering office before being appointed professor at the University of Stuttgart in 2000 as head of the Institute of Building Structures and Structural Design. In 2001 he founded Knippers Helbig Advanced Engineering and in 2018 Jan Knippers Ingenieure in Stuttgart. Jan Knippers focus is on teaching, research and practice with computational design and fabrication processes as well as fibre-based materials and bionics for resource-efficient load-bearing structures in architecture. He is Deputy Executive Director of the Cluster of Excellence "Integrative Computational Design and Construction for Architecture" (IntCDC) and Dean of the Faculty of Architecture and Urban Planning at the University of Stuttgart.

Christoph Kuhn is an architect and professor at the Technical University of Darmstadt, where he heads the Department of Design and Sustainable Building. His teaching and research revolve around the design, planning, construction and operation of sustainable buildings. After freelancing and working as a partner in various architecture firms, he has been co-founder and owner of Kuhn und Lehmann Architekten in Freiburg since 2015. From 2010 to 2013, he was a university professor at the Faculty of Architecture at the Karlsruhe Institute of Technology (KIT) after holding a two-year assistant professorship at the same institution. From 2007 to 2013 he was a lecturer at the Institut National des Sciences Appliquées de Strasbourg (INSA).

Oliver Lang + Oliver David Krieg + Kristin Slavin, Intelligent City. Oliver Lang is the CEO and Co-Founder of Intelligent City, Dr.-Ing. Oliver David Krieg is the Chief Technology Officer, and Kristin Slavin is the Director of Product. Intelligent City is a technology-enabled urban housing company. The firm has been working on deep technology and process integration for over a decade, to design and construct sustainable, net-zero multi-family urban buildings at lower costs for owners, operators and tenants. Its system incorporates mass timber, design engineering, Passive House performance, automated manufacturing and proprietary parametric software. The company calls this the Platforms for Life (P4L) model. It is a scalable and adaptable proprietary technology platform created to deliver highly desirable urban housing.

Julian Lienhard is a partner in str.ucture GmbH, a Stuttgart-based engineering firm for special structures, lightweight construction and digital building processes. After completing his award-winning doctorate (Dr.-Ing.) on bending-active structures at the ITKE of the University of Stuttgart in 2014, he taught at various universities in Germany and abroad. In 2016 and 2017, he was a visiting professor at the HafenCity University Hamburg (HCU). Since his appointment in 2019 as professor at the Institute for Structural Design at the University of Kassel, Julian Lienhard has conducted research on new hybrid constructions and establishing interdisciplinary work in digital value chains.

Thomas Lützkendorf has been Professor of Sustainable Management of Housing and Real Estate at the Faculty of Economics at Karlsruhe Institute of Technology (KIT) since 2000. His teaching and research focuses on topics concerning the implementation of principles of sustainable development in the construction and building sector. Thomas Lützkendorf studied at what is now the Bauhaus University in Weimar, where he completed his doctorate in 1985 and his habilitation in 2000. As a chairman at DIN and an expert in standardization at CEN and ISO, as well as in the development and testing of sustainability assessment systems, he is involved in the development and dissemination of fundamental principles and tools for capturing, assessing and influencing the ecological, economic and socio-cultural performance of buildings during the design process. He is a founding member of the International Initiative for a Sustainable Built Environment (iiSBE).

Hilke Manot has been undertaking her PhD at the Department of Structural Design, University of Kassel since 2022, where she worked as a student assistant during her architecture studies. She is interested in the design and construction of sustainable concepts and solutions with a focus on urban mining strategies and the reuse of existing building elements to advance circular construction. Her research focuses in particular on the reuse of structural steel in hybrid systems with natural materials.

Achim Menges graduated from the Architectural Association School of Architecture in London. He is an architect in Frankfurt and a professor at the University of Stuttgart. Since 2008, he has headed the newly founded Institute for Computer-based Design and Construction (ICD) and, since 2019, the Cluster of Excellence "Integrative Computational Design and Construction for Architecture" (IntCDC). He was previously a visiting professor at Harvard University for six years and at various other universities in the USA and Europe. In practice and research, Achim Menges investigates integrative approaches to computational design, fabrication and construction, as well as genuinely digital construction methods for sustainable architecture.

Alexander Passer is Professor of Sustainable Construction at TU Graz. Since 2011 he has headed the working group of the same name, which deals with topics of Life Cycle Sustainability Assessment (LCSA), its application in the design process and the optimization of the life cycle performance of buildings, taking into account systemic interactions. The focal areas of research for operationalizing sustainability in construction are Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA), Multicriteria Decision Models (MCDM) and Building Information Modelling (BIM). Alexander Passer is the Austrian delegate of the Committees of CEN/TC350 and CEN/TC 442 as well as other national and international technical committees. Since 2018, he has been chairman of the Sustainability Advisory Board of TU Graz. Also since 2018, he has been on the board of the Climate Change Centre Austria (CCCA). In 2014, he was a visiting professor at the Chair of Sustainable Construction at ETH Zurich. Since 2013, he has been subject editor of the *International Journal of Life Cycle Assessment* for the subjects of construction materials and buildings.

Martin Pehnt is Scientific Director and board member of ifeu – Institute for Energy and Environmental Research in Heidelberg. For over 25 years he has campaigned for a sustainable and just energy transition and societal transformation. Pehnt studied physics, energy technology and management in Tübingen, Boulder, Berlin and Stuttgart and previously conducted research at the National Renewable Energy Laboratory in the USA and the German Aerospace Center. In numerous projects, he has analysed energy policy instruments and strategies for renewable energies and energy conservation. He examines the impact of technology, life cycle assessments and the effect of energy policy, and accompanies pilot projects. His special focus area is implementing the heat transition towards sustainable buildings and climate-friendly heating systems. Pehnt is active in numerous advisory boards, cooperatives and committees for the energy transition, including Hamburg Climate Advisory Council and the Climate Expert Council Baden-Württemberg.

Mette Ramsgaard Thomsen examines the intersections between architecture and advanced computational design processes, investigating the profound changes that digital technologies instigate in the way architecture is conceived, designed and built. In 2005 she founded the Centre for Information Technology and Architecture (CITA) research group at the Royal Danish Academy of Fine Arts, Schools of Architecture, Design and Conservation where she has piloted a special research focus on the new digital-material relations that digital technologies bring forth. CITA has been central in forming an international research field examining the changes to material practice in architecture. This has been led by a series of research investigations developing concepts and technologies as well as strategic projects including the international Marie Curie InnoChain ETN network and the European Research Council (ERC) project "An Eco-Metabolistic Framework for Sustainable Architecture" that fosters interdisciplinary sharing and the dissemination of expertise, and supports new collaborations in the fields of architecture, engineering and fabrication. At the time of writing, Professor Ramsgaard Thomsen is General Reporter and Head of Science Track for the UIA2023CPH World Congress "Sustainable Futures – Leave No One Behind" examining how architecture can contribute to the Sustainable Development Goals of the United Nations (UN SDGs). In 2022 she was appointed Cret Visiting Professor at the University of Pennsylvania Weitzman School of Design.

Gilles Retsin is co-founder and CTO/Chief Architect of AUAR Ltd, a UK-based startup building a decentralized micro-factory network for regenerative timber housing, targeting 10,000 net-zero homes per year by 2032. He studied architecture in Belgium, Chile and the UK, where he graduated from the Architectural Association School of Architecture (PhD). His design work and critical discourse have been internationally recognized through awards, lectures and exhibitions at major cultural institutions such as the Museum of Arts and Design in New York, the Royal Academy in London and the Centre Pompidou in Paris. He has edited books on architecture, computational design and robotics and is also an associate professor at UCL, the Bartlett School of Architecture where he co-directs AUAR Labs, a research lab focused on innovating the full value chain of housing.

Matthias Rudolph is Professor of Building Technology and Climate-Responsive Design at the Architecture Faculty of Stuttgart State Academy of Art and Design. The focus of his academic work is on studying the interaction between ecology, site, space and form-finding as well as the microclimate adaptation of urban environments. He has more than 20 years of experience as a practicing Climate-Engineer. In interdisciplinary work with renowned architects within the company Transsolar, he creates strategies for climate-neutral buildings and urban developments in an international context. Matthias Rudolph is also a frequent lecturer at international conferences and industry events. Since 2017 he has been member of the executive board of the German Sustainable Building Council (DGNB).

Mattheos Santamouris is a Scientia Distinguished Professor of High Performance Architecture at the University of New South Wales (UNSW) and previously professor at the University of Athens. He was a visiting professor at the Cyprus Institute, Metropolitan University London, Tokyo Polytechnic University, Bolzano University, Brunel University London, Seoul University, National University of Singapore and UiTM Malaysia. He is Past President of the National Center of Renewable and Energy Savings of Greece. Mat Santamouris is author of 400 scientific articles, editor and author of 20 books and editor of numerous international journals. He is a reviewer of research projects in many countries including USA, UK, France, Germany, Canada and Sweden. He was ranked as the top world cited researcher in the field of Building and Construction by the Stanford University ranking system for 2019–2021, and figures prominently in many other academic rankings.

Peter Schossig has been working at the Fraunhofer Institute for Solar Energy Systems (ISE) in the field of thermal systems for over 25 years. Since 2017, he has been director of the Heat and Building division, which also includes research on the topic of heat pumps. After studying physics at the University of Freiburg, he completed his doctorate at the University of Karlsruhe (TH) on the topic of building-integrated heat storage. In recent years, he has significantly expanded the institute's work on heat pump development, especially with natural refrigerants, and extended the ISE's field of research to encompass grid-connected large-scale heat pumps and high-temperature heat pumps for industrial applications.

Kaiyu Sun is a principal scientific engineering associate at the Building Technology and Urban Systems Division of Lawrence Berkeley National Laboratory. Her research focuses on building energy modelling and development of simulation tools, the nexus between building energy efficiency and thermal resilience, automatic model calibration and occupant behaviour modelling. She is the lead developer of CBES: Commercial Building Energy Saver, which won the R&D 100 Award in 2019.

Martin Tamke is associate professor at the Centre for Information Technology and Architecture (CITA) in Copenhagen. He pursues design-led research on the interface and implications of computational design and its materialization. He joined the newly founded CITA in 2006 and shaped its design-based research practice, with a strong interdisciplinary focus in projects such as Durable Architectural Knowledge (DURAARK) or the international Marie Curie InnoChain ETN network. His latest research focuses on computational strategies and technologies for the transformation of the building industry towards sustainable and circular practices based on bio-materials. In 2019 Martin was appointed General Reporter for the scientific track of the UIA2023 Copenhagen World Congress of Architects and in 2022 guest professor at the University of Stuttgart at the "Integrative Computational Design and Construction for Architecture" (IntCDC) Cluster of Excellence. He is involved in the Danish-funded research project Predicting Response, the EU project Exskallerate, the ERC project "An Eco-Metabolistic Framework for Sustainable Architecture" and several industrial collaborations.

Oliver Tessmann is an architect and professor at the Technical University of Darmstadt where he heads the Digital Design Unit (DDU). His teaching and research revolves around computational design, digital manufacturing and robotics in architecture. From 2012 to 2015 he was assistant professor at the School of Architecture of the Royal Institute of Technology (KTH) in Stockholm. From 2008 to 2011 he was a guest professor at Staedelschule Architecture Class (SAC) and worked with the engineering office Bollinger+Grohmann in Frankfurt. In 2008 Oliver Tessmann received a doctoral degree (Dr.-Ing.) at the University of Kassel with research in the field of "Collaborative Design Procedures for Architects and Engineers". His work has been published and exhibited in Europe, Asia and the USA.

Konstantina Vasilakopoulou is a research-focused Lecturer at the School of the Built Environment of the University of New South Wales. She is the Acting Director of the Home Modification Information Clearinghouse and manages the school's Livability Lab. Her research interests focus on universal and inclusive design, light and lighting, energy efficiency in the built environment, urban climate mitigation techniques, etc. Her team undertakes research on the effects of the built environment on people's well-being, with a focus on the elderly and people with disability.

Anne-Kristin Wagner is an architect who researches and teaches in the field of sustainable building. Her current research focuses on reuse strategies and the life cycle assessment of materials and buildings. She has a strong interest in sustainability strategies in the building sector and at neighbourhood level to reduce the environmental footprint. She is a research associate and PhD student in the Department of Design and Sustainable Building at the Technical University of Darmstadt. Since graduating from TU Kaiserslautern, she has worked in energy consulting and sustainability certification for buildings at ee concept GmbH in Darmstadt.

Benjamin Weber studied architecture at Karlsruhe Institute of Technology (KIT), where he won the Solar Decathlon Europe as a member of the RoofKIT team. In his Master's thesis, which is a continuation of the competition, he dealt with the concept of building culture and historical rural building forms that serve as inspiration for circular, climate-adapted constructions made of locally available materials, and a climate-neutral low-tech concept in existing buildings. He was a fellowship student of the Norman Foster Foundation Energy Workshop and, since completing his studies, now works at haascookzemmrich Studio 2050 (one of the co-founders of the DGNB) on innovative, resource-saving projects around the world.

Max Wei is a staff scientist at the Sustainable Energy and Environmental Systems Department of Lawrence Berkeley National Laboratory (LBNL). His research focuses on developing greater resilience and equity in the built environment through urban-scale building modelling and policy development. He co-led the LBNL Resilience Task Force to develop greater resilience at the LBNL lab site and has led teams to develop modelling tools and quantification of the benefits of various passive and active measures for resilience to extreme heat. He has led the innovative integrated modelling of residential sector decarbonization scenarios across energy supply, buildings and transportation. Dr. Wei has over a decade of experience in the techno-economic modelling of emerging technologies and policy analysis of California decarbonization pathways. He co-led two past studies on pathways for California to meet its long-term climate goals for 2050; and has led studies quantifying the benefits of air conditioning with low global warming refrigerants and total cost of ownership of fuel cell-based co-generation in commercial buildings.

Vincent Witt is a research associate at the Professorship of Digital Design and Fabrication (DDF) at the Faculty of Architecture at Karlsruhe Institute of Technology (KIT), graduating recently with a Master of Science degree in Architecture. As part of his studies, he completed an internship in Basel. His Master's thesis explored digital design and novel fabrication processes in relation to urban mining and their integration into the architectural design process.

Erik Zanetti is a research associate at the Professorship of Digital Design and Fabrication (DDF) at the Faculty of Architecture at Karlsruhe Institute of Technology (KIT). He holds a Master of Science degree with a specialization in computational design from Delft University of Technology, as well as a Bachelor of Science degree in Architecture from Politecnico di Milano. Prior to joining DDF, he worked as a computational designer and digital fabrication specialist at FibR GmbH in Stuttgart and as an external lecturer at the University of Innsbruck. His research focuses on circular building practices and materials, which he investigates through the use of digital design and digital fabrication techniques.

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