Designing the sustainable energy transition

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INAUGURAL LECTURE

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EINDHOVEN UNIVERSITY OF TECHNOLOGY

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INAUGURAL LECTURE PROF.DR. ANGÈLE REINDERS

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Introduction

Hello Mr. Rector Magnificus, ladies and gentlemen, family and friends.

With this speech, I would like to introduce you to my field of energy research and my intended future research and educational activities as the chair of Design of Sustainable Energy Systems at Eindhoven University of Technology, a position which I have held since August 2018. To start with, I would like to thank the Executive Board of Eindhoven University of Technology, the Department Board of Mechanical Engineering and my colleagues in the Energy Technology group for my nomination and the trust they place in me. This chair provides a unique opportunity for me because as a young girl, I was already intrigued by both creating things and by sustainable energy. It therefore makes me happy to be able to combine both of my lifetime interests in this position.

Through this speech, I would like to inform you of my future plans for research and education while also sharing past experiences and my personal journey with you. By the end, I hope that I will have sufficiently explained why I believe that design-driven research is a significant means to support the sustainable energy transition that we face in the coming decades and why I am personally committed to this task.

Most of you know that I already gave an inaugural speech at another university (Reinders, 2011) eight years ago, in which I gave an extensive explanation of the motivations as well as the theoretical framework behind my research field. Here, I will briefly note that my continued basic motivation for conducting research on low-emission, sustainable energy technologies is that energy use causes close to 70% of global greenhouse gas emissions (IPCC, 2018), an amount which contributes to increased global warming. Fossil fuel-related CO_2 emissions have been growing consistently in past decades, leading to the highest rate of global growth in 2018 (IEA, 2019a). At the same time, the Paris Agreement of the United Nations (UN, 2015) stated that to strengthen the global response to the threat of climate change, the global temperature rise should stay below 2°C, preferably below 1.5°C. A global transition to sustainable energy systems is required to stay below this temperature threshold of 1.5°C.

Some definitions

Before continuing, I should give a definition of sustainable energy, also called renewable energy (IEA, 2019b), which refers to the practice of producing and using energy in a way that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). This can be interpreted in various ways, such as environmental sustainability, energy security, long-term availability and reliability, economic sustainability and the creation of jobs, as well as the prevention of wars over access to energy resources. In this speech, however, I will mainly address sustainable energy according to the definition of the IEA (IEA, 2019b): "energy that is derived from natural processes (e.g. sunlight and wind) that are replenished at a higher rate than they are consumed." In practice, the use of sustainable energy forms such as solar energy, wind energy, geothermal energy, hydro and biomass leads to significantly lower CO_2 emissions. The consequent long-term, structural transformation of a society which is mainly based on fossil fuel conversions to a decarbonized one with a high share of renewable energy is called the sustainable energy transition, or simply stated, the energy transition.

In addition, there exist plenty of definitions of Industrial Design, ranging from systematic engineering-based approaches to user-centered approaches or definitions with a merely artistic view. However, for the purpose of designing a sustainable energy transition, we might like to follow the globally-used definition given by the World Design Organization (WDO, 2019) for its solution-directed, transdisciplinary framework. The WDO defines Industrial Design as "a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences." According to an extended description, Industrial Design also "bridges the gap between what is and what's possible." Practically stated, it is a discipline that can stimulate the development of solutions in the context of the sustainable energy transition. However, while editing an Industrial Design book, my design colleagues and I discussed how a more meaningful definition of Industrial Design would be needed to understand its role in the engineering process. We agreed upon the following vision of Industrial Design: "making technology available for people." Other important aspects are the creativity and the cultural and economic value of Industrial Design. On a broader level, "design,

stripped to its essence, can be defined as the human capacity to shape and make our environment in ways without precedent in nature, to serve our needs and give meaning to our lives" (Heskett, 2002). If placed in the context of meeting "the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987), I believe that Industrial Design can play an important role in the sustainable energy transition.

The energy transition is a transdisciplinary process

The energy transition is one of the principle challenges that mankind currently faces. In order to reach the goals of the Paris Agreement, a 100% renewable supply will thus be necessary by 2050 (IRENA, 2019) (WEO, 2018). The Netherlands will contribute to these goals as well: according to the recently-published National Climate Agreement (Klimaatakkoord, 2019), national CO_2 emissions should be reduced by 49% by 2030 and by more than 95% by 2050. More specifically, the Netherlands should have a CO_2 emission-free electricity system by 2050. By 2020, all new buildings should be net-zero energy buildings; this target applies to the whole of the European Union. Additionally, seven million households and one million utility buildings must be natural gas-free by 2050. On top of that, mobility must be emission-free in the Netherlands by 2050.
However, the share of renewable energy within the total energy consumption in the Netherlands was just 7.4% in 2018, subdivided between wind energy (1.7%), biomass (4.5%) and solar energy (0.6%) (CBS, 2019). Given the goals for 2030 and 2050, we therefore face a tremendous change from a fossil fuel society to one based on renewable energy. This will involve many new designs of products, buildings and vehicles which can only be achieved by the huge efforts of a varied group of stakeholders, including policymakers, industry, business developers, citizens, scientists, engineers and designers. Moreover, societal acceptance, technology development and proper market design will all be key. As a result, I suggested in my 2012 book 'The Power of Design' that the interdisciplinary field of design could possibly bring these aspects together through the creation of products or systems which people can and would like to use (Reinders et al, 2012).

The three-layer model

It was very uplifting to see that larger organizations with more influence than I have as an individual also believe that such a transdisciplinary approach towards the development of sustainable energy systems is preferable to a solely technological approach. For instance, the European funding program ERA-Net Smart Grids Plus launched a new program in 2015 on the basis of the so-called three-layer research model for smart grids environments (ERA-Net, 2017) (Reinders et al, 2016a) (Reinders et al, 2018a). This comprises a stakeholders layer, a markets layer and a technologies layer and can be applied to sustainable energy environments, as shown in Figure 1.

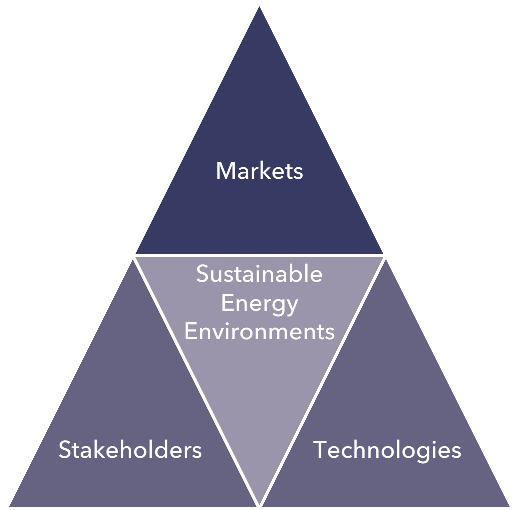

Figure 1. Three-layer research model for sustainable energy environments (adapted from ERA-Net Smart Grids Plus).

In order to provide a general understanding, a short description of each layer of the three-layer model is given below. The stakeholders layer covers a diverse group of entities that interact with sustainable energy systems and electricity grids, ranging from individual end-users, communities, network operators and aggregators to (local) governmental organizations. The markets layer comprises all financial and business-related aspects of sustainable energy systems, including investments, net present value (NPV), levelized cost of electricity (LCoE), electricity tariffs and pricing mechanisms. The technologies layer logically covers all of the technological aspects of sustainable energy systems, electricity grids and the necessary communications technologies (ICT), see Figure 2. Photovoltaic (PV) systems ('photovoltaic' means the direct conversion of light into electricity), wind turbines, micro-combined heat and power (μ-CHP), heat pumps, energy storage systems, home energy management systems (HEMSs), electric vehicles (EVs), EV charging stations, stationary fuel cells and hydrogen fuel cell electric vehicles (FCEVs) will all be operated in a smart manner (using ICT) in order to enable the real-time supply of energy information, demand-side management, demand shifting, forecasting algorithms and the trading of electricity between various stakeholders. This myriad of new technologies (and possibly others yet to come) will cause a strong diversification of energy systems. As the energy transition takes places over the forthcoming decades, this will result in the practical co-existence of centralized fossil fuel-based energy systems and decentralized sustainable energy systems with new energy products, more integration and smart management. For citizens, this implies that issues related to energy production and consumption will enter their daily lives more so than ever before. Naturally, these new, local sustainable energy systems (including the envisioned smart products, net-zero energy buildings and zero-emission vehicles) should be designed in such a way that they can be understood and used without compromising existing regulations and common practices in the energy sector. This will be an interesting challenge for all parties involved; we will probably all need to change our expectations.

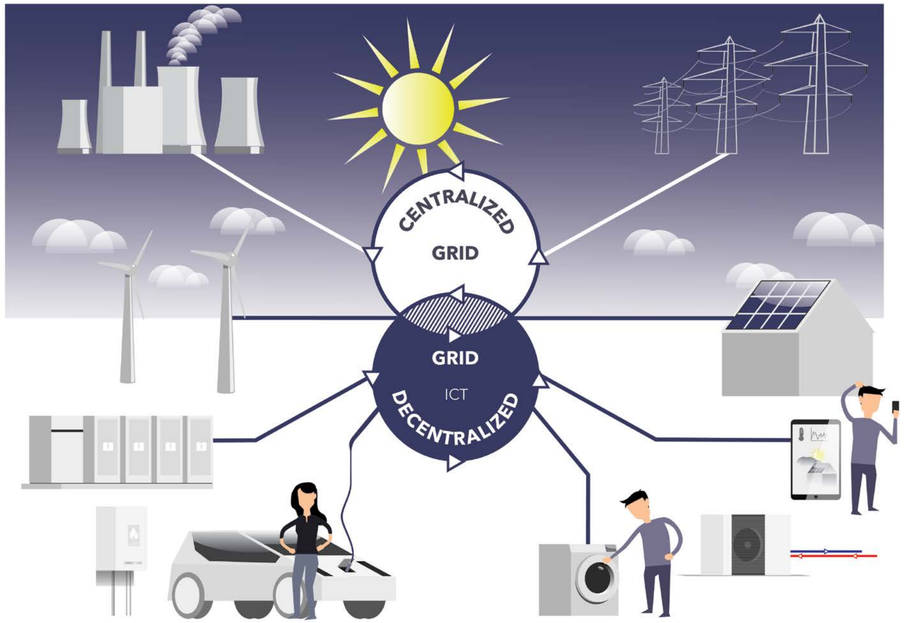

Figure 2. During the energy transition, citizens will be in touch with a myriad of decentralized, sustainable energy technologies, smart products and integrated energy solutions that co-exist with the centralized grid.

Energy access in remote areas

As for me, I changed my expectations while visiting the province of Papua in Indonesia in 2015. I was there for a research project on solar energy systems in remote areas of Indonesia, in which we (my PhD student at the time, Hans Veldhuis, and myself) were exploring socio-economic and implementation aspects together with the World Wildlife Fund and several Indonesian universities and SMEs. Surprisingly, just one high-tech, grid-connected solar PV system appeared to be a sufficient solution for the daily interruptions to social life and work caused by multiple blackouts of the outdated local electricity grid. Before starting that project, I honestly expected that the remoteness of the location would result in small, autonomous, low-tech solutions; reality, however, showed the opposite.

Both now and in the past, I have been interested in rural electrification in emerging economies or developing countries. According to my observations, it seems that where access to reliable energy services has become a very scarce commodity, scarcity drives innovation with strong end-user involvement. This was the case in my first rural energy project on solar home systems in Sukatani, Indonesia, and also during my next project on energy, poverty and gender issues in South-East Asia. I carried this out with the World Bank and found, unexpectedly, that it is usually women and not men who tend to solve residential energy issues. This was confirmed by many rural electrification projects that were carried out by the NGO PicoSol, which I founded with colleagues in Utrecht. From a multi-disciplinary perspective, these experiences were indispensable to the development of my design-driven view on research for renewable energy systems in Europe. While fossil fuels will become a scarce or detrimental commodity here over the next decades, their gradual phasing-out will similarly drive innovation. And because sustainable energy solutions in remote locations can be a source of inspiration for locations with less vulnerable energy supply chains, I remain interested in research on sustainable energy systems in remote areas and on islands. This is being carried out together with my current PhD students Kun Kunaifi and Amrita Raghoebarsing.

Co-evolution of smart energy products and services

In 2016, a new research project named CESEPS was able to start. CESEPS, which is an acronym for Co-Evolution of Smart Energy Products and Services, focused on the evaluation of various existing sustainable energy systems in residential smart grids within the context of the three-layer model (i.e. technologies, stakeholders and markets). In addition to this, new smart energy products and services were developed and tested during this project. The project was carried out with a very large consortium of five Dutch and three Austrian organizations (UU, TU Delft, WUR, DNV GL, eseia, AIT and TU Graz) and took three years before it was finally completed in 2019. In relation to this, I would like to acknowledge the research conducted in my group by postdoc Cihan Gerçek and researcher Alonzo Sierra as a follow-up on past research by former PhD students Daphne Geelen and Uche Obinna. Important focuses of the project were the quantifying of the local production of sustainable electricity in combination (ultimately) with storage, the capturing of stakeholder practices in smart grid pilots, the evaluation of various forms of e-mobility (such as solar-powered cars, e-bikes and fuel cell-powered cars) and the forecasting of the performance of smart energy systems through (co-) simulation. The general hypothesis before the start (and also the most important finding from the CESEPS project) was that the renewable energy transition is a multidisciplinary problem with various stakeholders and a considerable number of dependencies relating to geography and regulations. These require complex and complete solutions in order to become feasible and applicable on a wide scale. It was therefore recommended that multidisciplinary approaches, such as the three-layer model, become more established. For each layer in the three-layer model, the following general conclusions were drawn (CESEPS, 2019). These will serve as useful input for my new research activities in the Energy Technology group at TU/e.

In regard to the stakeholders layer, it was concluded that end-users are very interested in renewable energy! It is advisable to approach them as empowered co-providers and to develop smart energy products and services to give end-users responsibility and influence. Surprisingly, public organizations and grid operators play a more dominant role than energy companies in the development of smart energy systems.

For the markets layer: to develop a sound market, it is necessary to pay more attention to reducing barriers through better energy regulations and energy policy. This will involve multiple stakeholders, particularly governmental and regulatory bodies.
Regarding the technologies layer: from a technical point of view, each individual energy technology which has been applied in various pilots has performed well, but the combined technologies in interaction with end-users could be better optimized in order to realize self-sufficient renewable energy systems.
Finally, it was also concluded that smart energy products and services should provide end-users with the feeling of being part of the renewable energy system rather than simply interacting with black box technologies. It was therefore recommended that energy systems, products and services be developed that consumers want to use and can understand (as stated in the introduction of my speech), that serve their needs and that give meaning to the use of their sustainable energy systems.

Figure 3. The Innovation Flower of industrial product design, which shows objects (in different scales) that contain integrated solar cells such as a PV-powered jacket to charge cell phones, a solar-powered car, building-integrated PV and a conventional PV system.

Solving energy problems through design-driven research

The transdisciplinary framework mentioned before shows a partial overlap with the five aspects that I previously proposed (Reinders et al, 2012), all of which are relevant to the successful product design of sustainable energy technologies. These aspects are shown in Figure 3 and are as follows: (1) technologies and manufacturing; (2) financial aspects; (3) the societal context; (4) human factors, and; (5) design and styling. Together, these form the so-called 'Innovation Flower'. It was concluded that if these five aspects are decisive in the success of a certain product in the market, they would also be essential for the success of products containing sustainable energy technologies. In Figure 3, the Innovation Flower has been applied to solar photovoltaic (PV) technologies; however, this could also be done for any other arbitrary sustainable energy technology. Looking at the design examples shown in Figure 3, such as a solar-powered jacket, a car with an integrated solar energy system and a building-integrated photovoltaics project. It is notable that well-designed objects tend to pay attention to human factors and aesthetic appeal instead of being focused solely on increased energy performance and reducing costs, as was the common approach in PV module manufacturing. As Donald Norman stated, "attractive things really do work better" (Norman, 2004). To further develop this field, I have edited a new book called 'Designing with Photovoltaics', which will be published by Taylor and Francis in 2020 and covers interesting contributions by top designers Marjan van Aubel and Jeroen Verhoeven, design researchers Georgia Apostolou and Wouter Eggink and photovoltaic experts Alessandra Scognamiglio and Wilfried van Sark, as well many other pioneers in this field.

Integration of solar photovoltaic energy technologies

Colleagues always ask me why I am so fond of solar photovoltaic (PV) energy technologies (Reinders et al., 2017a). This is not just because of personal interests, but also because solar energy is the largest and one of the least exhaustible sustainable energy sources we have. Annually, the earth receives a total amount of solar irradiation that exceeds the global energy consumption of mankind by a factor of 9000. At the present state-of-the-art, many international organizations (IRENA, 2019a) (WEO, 2018) foresee PV technologies becoming one of the main contributors to achieving a prospective 100% renewable energy supply. Currently, the cumulative installed capacity of solar energy systems worldwide – 520 GWp (2018) of DC power – makes up 10% of the total global renewable capacity (IRENA, 2019b). This is growing explosively. In 2018, for instance, it doubled to 4.4 GWp (CBS, 2019) in the Netherlands alone, leading to a close to 3% share of solar power in national electricity production. In addition to this, PV technologies have specific, attractive integration features. These are their modular character, high efficiency, proven reliability, low maintenance requirements, low costs, absence of moving parts, lack of noise and very low emissions (Fthenakis and Raugei, 2016). The latter falls within the range of 18 to 28 g of CO_2 equivalents per kWh produced. As such, the average CO_2 emissions per kWh generated by PV systems in the field is under 2.5% of those produced by a coal-fired plant. As of this year, utility-scale PV systems are also the cheapest electricity source, with a levelized cost of electricity ranging from 24 €/MWh in Spain to 42 €/MWh in Finland (Vartiainen et al, 2019). This is remarkable as it means that PV electricity is already cheaper than the average spot market electricity across Europe. Adding to this is the fact that solar technologies can be colored, bendable and/or transparent. It therefore really does make sense to contribute to further developments in the field of photovoltaics through design-driven research projects.

Most of mankind's energy demand occurs in densely-populated locations such as the built environment. The logical consequence is that the design of products, buildings and cities has to be adapted to this new form of on-site energy production, distribution and consumption, leading to integrated solutions instead of solely technological approaches. Due to their technical and design features, PV cells can significantly contribute to these developments. However, the manner in which this takes place is not yet reaching its full potential. For instance, the National Roadmap for PV Systems and Applications (2018) states that a potential installation capacity of 200-250 GWp of PV systems will be required in order to reach the 2050 goals for CO_2 emission reductions in the Netherlands. This amount of PV power needs a large installation area of approximately 35 × 35 km^2, representing 85% of the area of the province of Utrecht.
The main concern is thus as follows: how can we integrate solar energy technologies in environments such as the built environment, areas with water, agricultural land and recreational space while making the most effective use of the surface area available and also achieving full societal support? The fact that citizens seem to be opposed to big solar parks (see Figure 4) or the visibility of PV systems on roofs is quite understandable - the view they have of beautiful natural landscapes or their neighbors' dwellings are 'polluted' by ugly PV systems.

Figure 4. A 30 MW PV system, SunPort Delftzijl, source: thesolarfuture.nl/nieuws-source/top-25-solar-pv-projects, 2019.

Hopefully, this won't affect the public acceptance of solar technology, but if we integrate photovoltaic energy systems into our surroundings better, the public will respond positively to the sustainable energy transition. The additional benefits of well-integrated solar energy systems with a high share of self-consumption could be, for instance, less overloaded local grids and additional grid flexibility. Design-driven approaches will undeniably be necessary for the integration of PV technologies in products, buildings and landscapes, see Figure 5.

To further explore this issue and to develop future solutions, I am coordinating a new design-driven research consortium on Solar Integration in the Netherlands. This will involve various research organizations, industries and citizen organizations. In particular, the collaboration with experts on economic regulations and law, social acceptance, system innovation processes and biodiversity will form an essential contribution to this new approach.

In the context of solar integration in cities, much knowledge has already been acquired when it comes to building-integrated PV projects. In the following section, I would therefore like to pay attention to two relatively new topics for design-driven research: (i) solar-powered electric vehicles and (ii) luminescent solar concentrators.

Figure 5. Two examples of designs that contain well-integrated PV technologies. Left: the Current Window by Marjan van Aubel, made of PV solar cells acting as stained-glass elements. Right: an example of a curved PV façade in the built environment, La Seine Musicale, by Shigeru Ban Architects, Paris, source: https://www.archdaily.com/874535/la-seine-musicale-shigeru-ban-architects, 2017.

Design-driven research on solar PV-powered electric vehicles

Electric vehicles (EVs) are becoming an increasingly attractive option to effectively and economically reduce the global fossil fuel consumption of road transportation. The transportation sector is currently responsible for almost a quarter of global energy-related CO_2 emissions. In general, the grid provides the electricity required to charge an EV's battery. To further facilitate the use of renewable energy and to minimize CO_2 emissions, it could be worthwhile to consider EV charging using PV cells integrated into in-car body parts or through specific solar photovoltaic (PV) charging systems. If solar power alone is not yet sufficient in order to travel a full trip over a certain distance, it could still easily extend the driving range of an EV by tens of kilometers for the time being.

At the University of Twente, I gained quite some experience with the development and testing of solar-powered boats, solar bikes and solar racing cars. However, little information or experience existed when it came to commercial applications of solar PV-powered EVs. From 2017 onward, various activities were therefore initiated, including the design and implementation of a solar charging station for e-bikes and contributions to the development of a new Task of the International Energy Agency PVPS program called 'PV for Transport'. A new research project, 'PV in Mobility', was acquired alongside TNO and three companies that develop innovative, solar-powered automotive solutions: Lightyear, IM Efficiency and Trens. A study was also conducted in my group (Sierra et al, 2020), in which it was explored how well PV systems – with the possible combination of battery energy storage systems (BESS) – might contribute to the charging of EVs (see Figure 6) as compared to gasoline-fueled cars. This study was carried out in four different countries: the Netherlands, Norway, Brazil and Australia. Unsurprisingly, it was found that solar PV-powered EVs can be operated more effectively in countries with high irradiation the whole year through, such as Brazil and Australia, than in countries with a high variability of irradiation over the year, such as the Netherlands and Norway. Depending on the location, PV charging can also reduce the CO_2 emissions of EVs by up to 93% when compared to gasoline-fueled cars. Financial feasibility was also assessed in all countries and, surprisingly, 100% PV charging is already a viable option in the Netherlands. On the basis of this study, it can therefore be concluded that solar PV-powered EVs can be a feasible and attractive option for emission reductions in the transport sector in most countries. This opens up many opportunities for new designs of PV-powered cars and other PV charging solutions which suit the needs of car drivers. This is what we are working on at present. Besides modeling, students and colleagues will also carry out data monitoring, life-cycle analyses, user studies and conceptual product development.

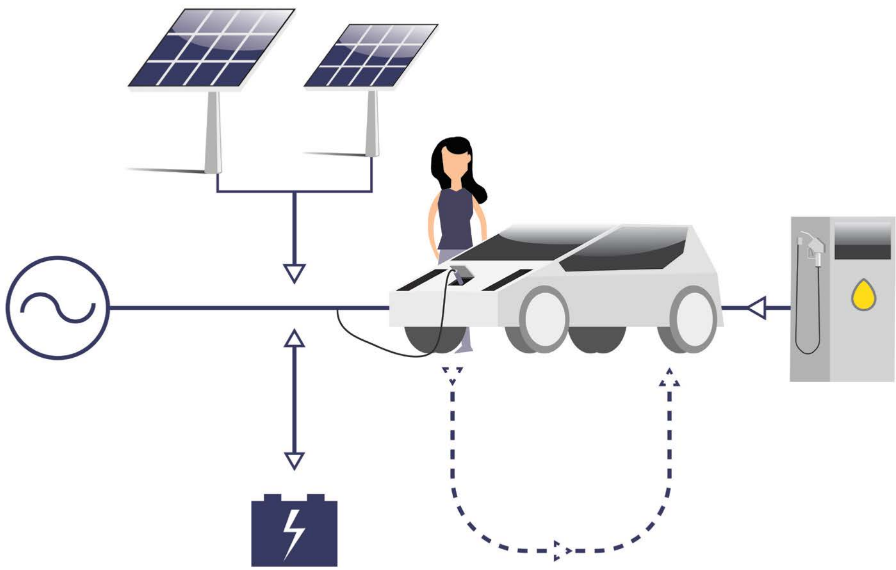

Figure 6. Scheme representing the solar PV charging and grid charging of EVs as compared to gasoline-fueled cars.

Design-driven research on luminescent solar concentrator photovoltaics

Last year, I started my part-time professorship at TU/e with design-driven research on one specific type of PV technology – luminescent solar concentrator photovoltaics (LSC PV), see Figure 7 – for the following reasons. Existing conventional PV modules, which usually have a dark color and a fixed thin, flat and rectangular shape, cannot meet the design requirements for proper integration. On the contrary, however, LSC's colorful features and form freedom (see Figures 8 and 9) offer a lot of design opportunities to enhance the overall functionality and experience of PV applications within products, the built environment and transport (Reinders et al, 2018b).

An LSC PV is a technology (Goetzberger, 1978) (Yablonovitch, 1980) for harvesting solar energy that is comprised of a transparent element that serves as a lightguide and is connected to PV solar cells which act as receivers of irradiance and power converters, see Figure 7. This lightguide, which is usually made of a polymer, glass or other transparent material, has a refractive index higher than air and

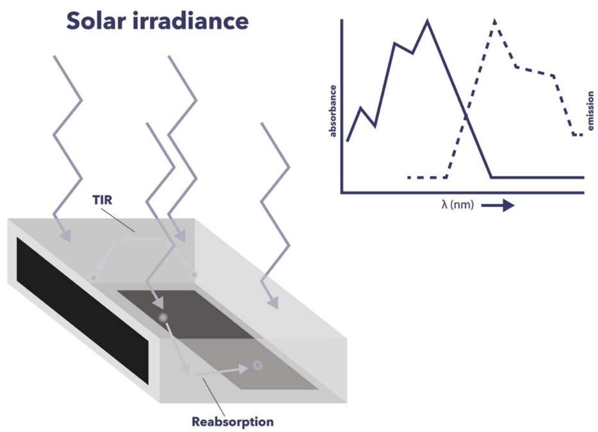

Figure 7. The design and working principle of a conventional LSC PV element with solar cells at the edges, showing the absorption spectrum (solid line) and emission spectrum (dotted line) of a dye in an LSC.

contains luminescent pigments, usually called dyes or luminophores. A large fraction of irradiance, as well as the diffuse part, is concentrated in the lightguide through total internal reflection (TIR) at the material's surfaces. Secondly, photons originating from solar irradiance enter the LSC, are absorbed by dye molecules and are subsequently re-emitted at other wavelengths that better suit the electric performance of peripheral PV solar cells that convert concentrated irradiance to electricity. Combining the concentration of irradiance and the transformation of the incoming spectrum in one solar device seems a promising path. In the past, however, LSC PV technologies haven't shown high efficiencies in the range of 2 to 7% (Reinders et al, 2018b). So far, they haven't been considered as a serious alternative to conventional PV technologies. However, they do have great opportunities for performance improvements while having great design features and the potential to capture diffuse irradiance for the generation of electric power. As a result, my aim is to further develop LSC PV elements for the enhancement of product applications of PV, leading to higher efficiencies beyond the 10% threshold for LSC PV technologies that is often claimed in literature (Van Sark et al, 2014) – 20%, to be specific.

In general, LSC's properties (low cost, colorful, bendable and transparent) offer a lot of design freedom, although most research on LSC PV devices seems to be focused on increasing the efficiency of very small samples in lab settings under standard test conditions. My design-driven research on LSC PV devices will therefore aim for: (i) the use of ray tracing simulations to develop new, optically-enhanced three-dimensional geometries (Vishwanathan et al, 2015); (ii) the indoor and outdoor testing of LSC PV devices and mini-modules, and; (iii) the design and prototyping of LSC PV applications, including user tests.

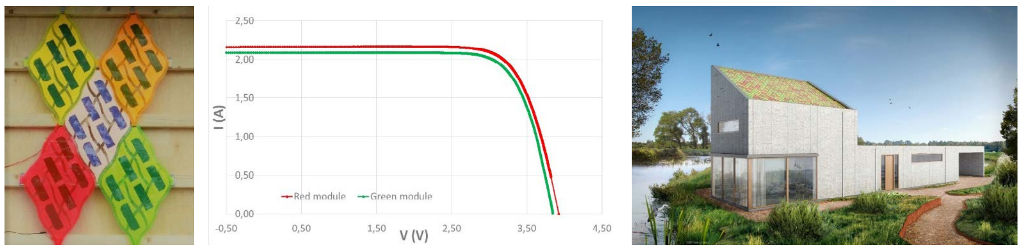

Figure 8. Left: LSC PV modules resulting from the LeafRoof project. Middle: I-V curves of the red and green modules under standard test conditions (Reinders, Debije et al. 2017). Right: an impression of a dwelling with customizable, integrated LeafRoof modules as an example of building-integrated PV (2016).

As an example, there has been extensive reporting on the simulation, design and prototyping of an LSC PV module called LeafRoof (see Figure 8), on which I worked for a few years with colleagues at TU/e, including Alex Rosemann and Michael Debije (Reinders et al, 2016b, Reinders et al, 2017b). For prototypes of two types of LeafRoof modules, current–voltage (I–V) curves were measured that resulted in world record efficiencies (at the time) of 5.8% for a red-colored PV module and 5.5% for a green-colored PV module. With an eye on performance, various geometric configurations have been evaluated in regard to silicon PV cell efficiency, various concentrations of dyes from the Lumogen dye series and different contours and thicknesses for the PMMA lightguide through numerical ray tracing simulations. The geometrical gain of this new type of PV module is 3.6. These results demonstrate colorful, robust solar energy collectors which can be produced in a wide variety of shapes that serve as viable, attractive devices for use in building-integrated systems. Additionally, thanks to the use of PMMA as a cell encapsulant, it was found through outdoor measurements that the LeafRoof modules are less susceptible to energy losses at elevated temperatures due to high irradiance and high ambient temperature conditions. This enhances the performance of silicon solar cells attached to a lightguide.

Furthermore, I conducted several design studies in 2016 on the possible applications of LSC PV with more than 40 students on the Master's in Industrial Design Engineering of the University of Twente (Reinders et al, 2018b). This was a unique approach to LSC PVs. These innovative studies resulted in a total of 16 prototyped conceptual designs, of which two are presented in Figure 9. These are an LSC PV transparent boat and building-integrated LSC PV elements which show the use of the design features of the LSC material: colorful, transparent,

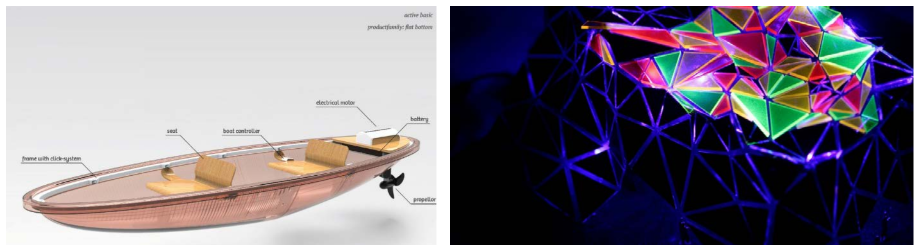

Figure 9. Left: LSC PV transparent boat concept by Master's students Jullian Claus, Rosan Harmens and Hieu Nguyen. Right: an impression of the roof of a sustainable event space with triangular building-integrated LSC PV elements by Master's students Rolf van der Toom, Steven Oonk and Kasper Schriek, (Reinders et al, 2018b).

luminescent and bendable. Due to the course's emphasis on innovation, the student design projects were very diverse, including a garden fence, an LSC PV-powered labyrinth playground, casings to charge cell phones, illuminating public stairs and colorful e-bike parking with LSC PV technologies.

At the beginning of 2019, a summer school was subsequently organized on the topic of 'Exciton Solar + Design' in order to further explore the design potential of LSC PV applications. This summer school, which was hosted by Tim Schmidt and Ned Ekins-Daukes of the ARC Centre of Excellence in Exciton Science at UNSW Sydney, aimed to engage scientists, students and designers. It included formal lectures as well as practical outdoor measurements using LSC PV devices. Besides better insights into the field of LSC PV, the summer school resulted in several conceptual designs from the 15 participants, which were partially evaluated by ray tracing simulations in order to explore their optical performance. Figure 10 shows a power-generating solar lily and a ray tracing model of a new design for an LSC PV device that contains bifacial solar cells. In both cases, the usual flat shape of LSC PV devices is extended to the third dimension, resulting in different optical and electrical properties. The estimated efficiency of the bifacial LSC PV module, for instance, could reach more than 15% efficiency using silicon technologies, which is well above the commonly accepted 10% threshold for LSC PV devices (Reinders et al, 2020).

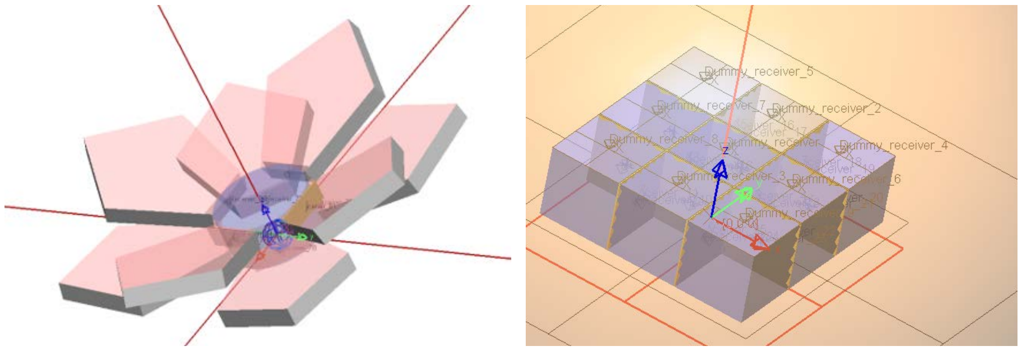

Figure 10. Left: CAD presentation of a power-generating solar lily made of LSCs and PV cells. Design and artwork courtesy of PhD students Hanbo Yang and Monika Michalska. Right: ray tracing model in LightTools for a bifacial LSC PV mini-module by Ned Ekins-Daukes, Angèle Reinders and Master's student Marcello Nitti.

Research plan and organization

In my research group within the Energy Technology group, I aim to involve Master's students, graduate students and postdoctoral researchers in LSC PV research through design-driven projects, research projects, interesting educational activities by challenge-based learning, engaging workshops and summer schools.

In this initial phase, the research will focus on the fundamental research challenges of LSCs, see Figure 11. I am glad that the first two colleagues, postdoc Reza Aghaie and PhD student Xitong Zhu, have recently joined my group at TU/e to explore the modeling of the optical, electrical and thermal properties of LSC PV devices and to characterize these devices using the indoor lab facilities at TU/e, including Camilo Rindt's wonderful large-area solar simulator. Moreover, we jointly decided to team up with Michael Debije's group at TU/e to be able to cover the complex chemical aspects of luminophores. In the future, design-driven research will be conducted on the upscaling of LSC PV devices for outdoor applications in buildings, urban furniture, greenhouses, transparent windows and vehicles, among others.
In this context, the outdoor monitoring of the performance and durability of LSC PV mini-modules will take place with the support of COST Action PEARL PV, SEAC and the University of Twente. The research will also focus on the manufacturing and environmental impact of LSC PV devices. In the final stage, the aim will be to design, prototype and demonstrate LSC PV applications, the findings of which will be fed back to the fundamental research lines.

The ambition is to involve SMEs and the photovoltaic industry in this project plan and to strengthen internal and national collaborations in this field of research.
I am looking forward to further collaborating within my department and with the Departments of the Built Environment and Chemical Engineering and Chemistry at TU/e, as well as with my colleagues at Solliance, Amolf and Utrecht University.
It would be great if one of the forthcoming LSC PV designs could be applied on-campus at TU/e or in a solar-powered EV. To conclude this section, the research topic of LSC PV is very suitable for international collaboration, which I wish to continue.

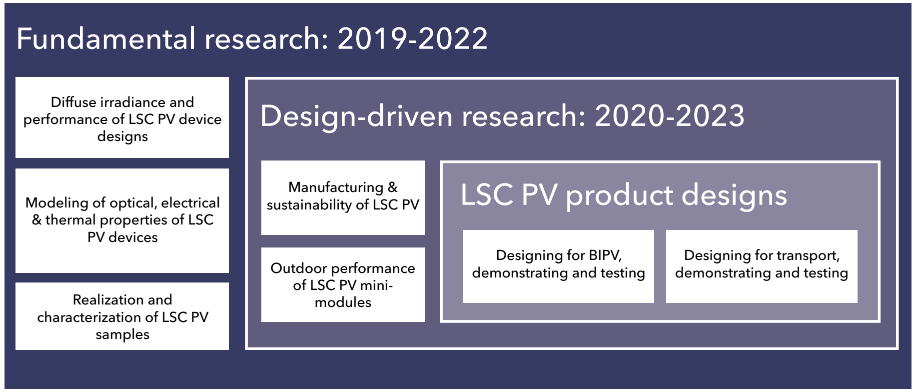

Figure 11. A scheme of the envisioned LSC PV research activities within the chair of Design of Sustainable Energy Systems for the period 2019-2023.

In the following section, I will provide more detail on the central research question (Q) and the interconnected sub-questions (Q1 to Q6) that should be addressed in the coming years in order to create viable, commercially-available LSC PV products.

Central research question, Q: How can luminescent solar concentrator photovoltaic devices be designed in such a way that they demonstrate a high efficiency in climates with a high share of diffuse irradiance and – crucially – can easily be integrated into applications, particularly in the built environment and transport?
Research sub-question Q1: How high is diffuse irradiance in various outdoor conditions and how does it affect the performance of various photovoltaic technologies, particularly LSC PVs?
Research sub-question Q2: Which combination of matrix materials, luminescent materials (particularly quantum dots), PV cells (silicon, IIV-V and CIGS cells), three-dimensional geometries, integrated optics and other design features will lead to a high usage of diffuse irradiance and high efficiency of LSC PV devices?
Research sub-question Q3: How can innovative ray tracing models support the optimization of the optical, thermal and electrical properties of LSC PV devices in regard to the design features mentioned in Q2 and the conditions of use in various applications?

Research sub-question Q4: How can new manufacturing technologies, including 3D printing and injection molding, lead to customized LSC PV solutions and improve the environmental impact and recyclability of photovoltaics, particularly LSC PV devices?
Research sub-question Q5: In what way can the colorful, shapeable and transparent features of LSC PV devices be optimally used in the design of LSC PV elements for building-integrated PV and product-integrated PV applications for transport while achieving high outdoor efficiencies and performance durability?
Research sub-question Q6: How will the business case of LSC PV products be embedded in the energy market and how will they be perceived and adopted by various stakeholders, including end-users?

On the basis of the research questions mentioned above, six different projects (see Figure 11) can be defined, which I will shortly introduce and describe below.

Project 1: Optimizing the concentration of diffuse irradiance in innovative LSC PV devices

Usually, a high share of diffuse light is considered to be a negative condition for the concentration of irradiance. However, diffuse irradiance is actually the main component of sunlight in most climates: diffuse irradiance's share of the hourly global irradiance ranges from 17% in arid climates to 100% under an overcast sky (Orgill and Hollands, 1977) (JRC-IET, 2017). As such, it forms a vast, insufficiently utilized component of solar power. As LSC PV devices have the specific feature of enhanced internal reflections, they can concentrate diffuse irradiance better than regular PV modules. To be able to quantify the so far underexplored effect of diffuse irradiance on the performance of various designs of LSC PV devices, it is important to get better insights into diffuse irradiance in a geographic context and in different use scenarios of LSC PV devices.

In this project, diffuse irradiance will therefore be evaluated on minute by minute, hourly, monthly and annual timescales using irradiance data from databases that contain ground-measured irradiance or satellite data. The new data bank of COST Action PEARL PV will also play an important role in this project. Data will be evaluated by means of available diffuse irradiance models and combined with spectrally-distributed irradiance data. Sun tracking mechanisms will eventually be included in this assessment. The expected output of this research project will be recommendations on optimized design configurations for innovative LSC PV devices, among other things.

Project 2: Modeling of the optical, electrical and thermal properties of innovative LSC PV devices
The main challenge of this research project is to combine and further develop innovative ray tracing models that can support the optimization of the optical, thermal and electrical properties of three-dimensional LSC PV devices beyond the existing design configurations of silicon PV cells – flat, thin sheet PMMA lightguides with Lumogen dyes. The resulting model will be used to explore which combination of matrix materials, luminescent materials (organic dyes, quantum dots and rare earths), PV cells (silicon, IIV-V, CIGS or perovskite solar cells), three-dimensional geometries, integrated optics and other design features will lead to a high usage of diffuse irradiance and a high efficiency of LSC PV devices. For the thermal modeling, collaboration will take place in the Energy Technology group with PVT expert Camilo Rindt.

The expected output of this project will be, among other things: (i) a usable model for researchers in the field of LSC PV technologies; (ii) better insights into the optical, electrical and thermal properties of innovative LSC PV devices; (iii) recommendations on the design configurations of highly-efficient LSC PV devices, and; (iv) better insights into the effects of three-dimensional shaping and integrated optics on the optical properties of LSC PV devices.

Project 3: Developing highly-efficient LSC PV devices: realization and experimental characterization
Theoretical design configurations of optimized LSC PV devices resulting from projects 1 and 2 will be realized and experimentally characterized through various electrical, thermal and durability tests under diverse conditions, as well as a new series of tests that will be developed for LSC PV characterization under diffuse irradiance.

The expected output of this project is a set of small-scale samples (5 x 5 cm^2) which have been realized and tested, resulting in: (i) validated efficiencies of optimized and realized LSC PV device designs; (ii) practical experiences with the realization of LSC PV devices and the resulting quality of such devices; (iii) a validated test program for LSC PV devices, including diffuse irradiance conditions, and; (iv) insights into the durability of realized LSC PV devices.

Research activities are already taking place in collaboration with TU/e colleague Michael Debije and postdoctoral researcher Reza Aghaei.

Project 4: Innovative manufacturing and recycling processes for LSC PV devices
In this project, new manufacturing technologies for LSC PV modules – including 3D printing, injection molding, casting, embossing and other innovative production methods – will be explored in the context of fast, easy, low-cost and sustainable production processes which will be benchmarked with existing manufacturing processes for conventional PV modules. Additionally, the environmental impacts of LSC PV devices will be quantified in relation to other types of PV cells and existing conventional silicon PV modules by means of a life-cycle analysis (LCA), and will be positioned in the context of various use scenarios and end-of-life treatments. One of the objectives will be to decrease the environmental impact and increase the recyclability of LSC PV devices through a proper manufacturing chain.

Project 5: Outdoor performance of innovative LSC PV mini-modules
In this project, research question Q5 will be the main focus for the realization of LSC PV mini-modules (size: approximately 30 x 30 cm), the design features of which result from the combined efforts in projects 1 to 3. These mini-modules will be tailored to the specific outdoor conditions of the application of LSC PV devices in building-integrated PV, urban furniture and product-integrated PV, specifically those in car body parts.

In this way, we can examine how the colorful, shapeable and transparent features of LSC PV devices can be optimally used in various applications. Outdoor measurements regarding the LSC PV's energy performance under real irradiance and temperature conditions will be carried out using the PV outdoor test facilities at SEAC, in the outdoor test bench of the University of Twente and at other geographic locations with different climates and different irradiance. The long-term durability under exposure to UV radiation and humidity will also be tested in this project, supported by experts from COST Action PEARL PV.

Project 6: Designs for outdoor applications of LSC PV modules in BIPV and transport
The research which has been conducted on LSC PV devices will be applied to design activities for building-integrated PV and for the application of LSC PV technologies in car body parts.

Using the design methodologies from 'The Power of Design' (Reinders, 2012), various new conceptual designs of LSC PV elements will be developed for applications in buildings, urban furniture and vehicles. For all application categories, these conceptual designs will be evaluated on efficiency, costs, environmental impact and (in particular) aesthetic qualities, as well as user appreciation and interactions. The aesthetics will be assessed by user studies. At least two selected conceptual designs will be further developed into real-scale prototypes which will be installed (in the built environment and in a vehicle, respectively) as a demonstrator that will be experimentally evaluated through outdoor monitoring of the LSC PV's energy performance and user studies. Findings from this project will be fed back to optimize the design features of LSC PV devices.

Closing words and general comments

I hope that I have sufficiently introduced you to my field of design-driven sustainable energy research and that I have explained in clear words what my future research and educational activities as the chair of Design of Sustainable Energy Systems will encompass.

Though I have mentioned it several times already, I would like to again emphasize that international collaboration is truly essential when it comes to developing emerging research fields. I would therefore like to stress that the financial support for 'Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data', which I have received from COST Action PEARL PV since 2017, is extremely important for building networks, establishing new research directions and jointly publishing. Even this inaugural speech is associated with the COST Association as I could write it in relative solitude during a COST Association-funded visit (a so-called Short Term Scientific Mission) to the School of Photovoltaics and Renewable Energy Engineering of University of New South Wales, Sydney.

PEARL PV establishes contacts and research collaborations between more than 36 countries and 200 photovoltaic specialists. I feel blessed to be in touch with the best current PV system researchers. I would like to thank Peter Jansen, Markus Schubert, Eliza Loucaidou, David Moser, Wilfried van Sark, Nicola Pearsall, Mirjana Devetakovic, Jonathan Leloux, Gabrielle Eder, Aleksandra Krstic-Furundzic and many others for their frequent involvement. In this case, it isn't diamonds but pearls that are a girl's best friend.

Many thanks to all of my colleagues in my professional networks, such as ARISE, Solliance, the IEEE PVSC community, the IEA PVPS program and the NWA networks on Circular Economy and Energy Transition, for the lovely collaborations that we have, have had and will continue to have in the future. At present, I am lucky to work with many inspiring, talented colleagues who are willing to share their experiences with me. Please forgive me if I have not mentioned your name as there are so many of you. However, I have you in mind.

I would like to thank the Executive Board of Eindhoven University of Technology and the Department Board of Mechanical Engineering for their trust in me when they offered this professorship to me. I feel very grateful for this opportunity. In particular, I want to thank David Smeulders, chair of the Energy Technology group, for the great help and the continuous support as well as the pleasant working relationship. Similarly, I would also like to thank my close colleagues Camilo Rindt, Martin Huijzer and Linda Essink for being kind and stimulating colleagues who seem to have a special pleasure in looking after my projects on the days that I am not available at TU/e.

Looking further back in time, I would particularly like to thank my PhD supervisor Wim Turkenburg (Utrecht University) for being an example of staying committed to one's internal compass and being critical. I would also like to thank my long-term mentor Joop Schoonman (Delft University of Technology), who often served as a supportive conversation partner on energy research as well as university politics. Thanks too to Sheila Bailey (NASA) for being a great female role model at times in which the number of women in my research field was extremely low. Han Brezet is sincerely thanked for his trust in my first professorship. Finally, I warmheartedly thank Richard King (Arizona State University) for actively involving me in the IEEE PVSC conference organization, which gave me visibility in the PV community.

To my colleagues at the University of Twente and those of the Department of Design, Production and Management, I would like to express my appreciation for offering an environment in which I could develop my research directions. Thanks especially to Joop Halman for being my sparring partner during the design course Sources of Innovation, which has led to hundreds of innovative student projects. I would therefore also like to acknowledge all Master's students with whom I have collaborated in the past decades. They have formed a rich source of new ideas and creativity in the field of design-driven research.

To finish, I would like to acknowledge former PhD students Bram Entrop, Tim Gorter, Daphne Geelen, Hans Veldhuis, Georgia Apostolou and Uche Obinna, as well as the present PhD students in my research groups, Amrita Raghoebarsing, Kun Kunaifi and Xitong Zhu, and my postdoctoral colleagues Cihan Gerçek and Reza Aghaie, who are all warmly thanked for their time, energy and commitment to design-driven research on sustainable energy systems. Without your research activities, discussions and personal involvement in this new, emerging field of research, it wouldn't have had any chance to exist.

Most of all, I would like to thank my friends and family for many relaxed moments and their unconditional support.
Thank you for your attention.

Ik heb gezegd.

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Curriculum Vitae

Prof.dr. Angèle Reinders was appointed part-time professor of Design of Sustainable Energy Systems at the Department of Mechanical Engineering at Eindhoven University of Technology (TU/e) on August 1, 2018.

Angèle Reinders received an MSc in Experimental Physics at Utrecht University (1993) where she also received her PhD degree (1999) in Chemistry. As well as being a professor at TU/e, Angèle Reinders is an associate professor at University of Twente, and a visiting professor of the School of Photovoltaics & Renewable Energy Engineering of UNSW in Sydney, Australia. In the past she conducted research at Fraunhofer Institute of Solar Energy in Freiburg, the World Bank in Washington D.C., ENEA in Naples, Center of Urban Energy in Toronto and in Indonesia, and she was a professor of Energy-Efficient Design at TU Delft. Based on these experiences she developed a new approach towards energy research that is design-driven in scope. Since 2017 she has been the chair of the EU COST Action PEARL PV on the performance of PV systems and she is conducting projects on smart energy systems. She is known for her books 'The Power of Design – Product Innovation in Sustainable Energy Technologies' (2012) and 'Photovoltaic Solar Energy From Fundamentals to Applications' (2017) and for her involvement in the international IEEE PVSC conference which she chaired in 2014 and 2017. In 2010 she co-founded the IEEE Journal of Photovoltaics for which she serves as an editor. She is also involved in various tasks of the International Energy Agency PVPS program, including Task 1 on Strategic PV Analysis & Outreach and Task 17 on PV for Transport.

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