SUSOLTECH

The Norwegian Research Centre for Sustainable Solar Cell Technology

The Research Center for Sustainable Solar Cell Technology

Annual Report 2023

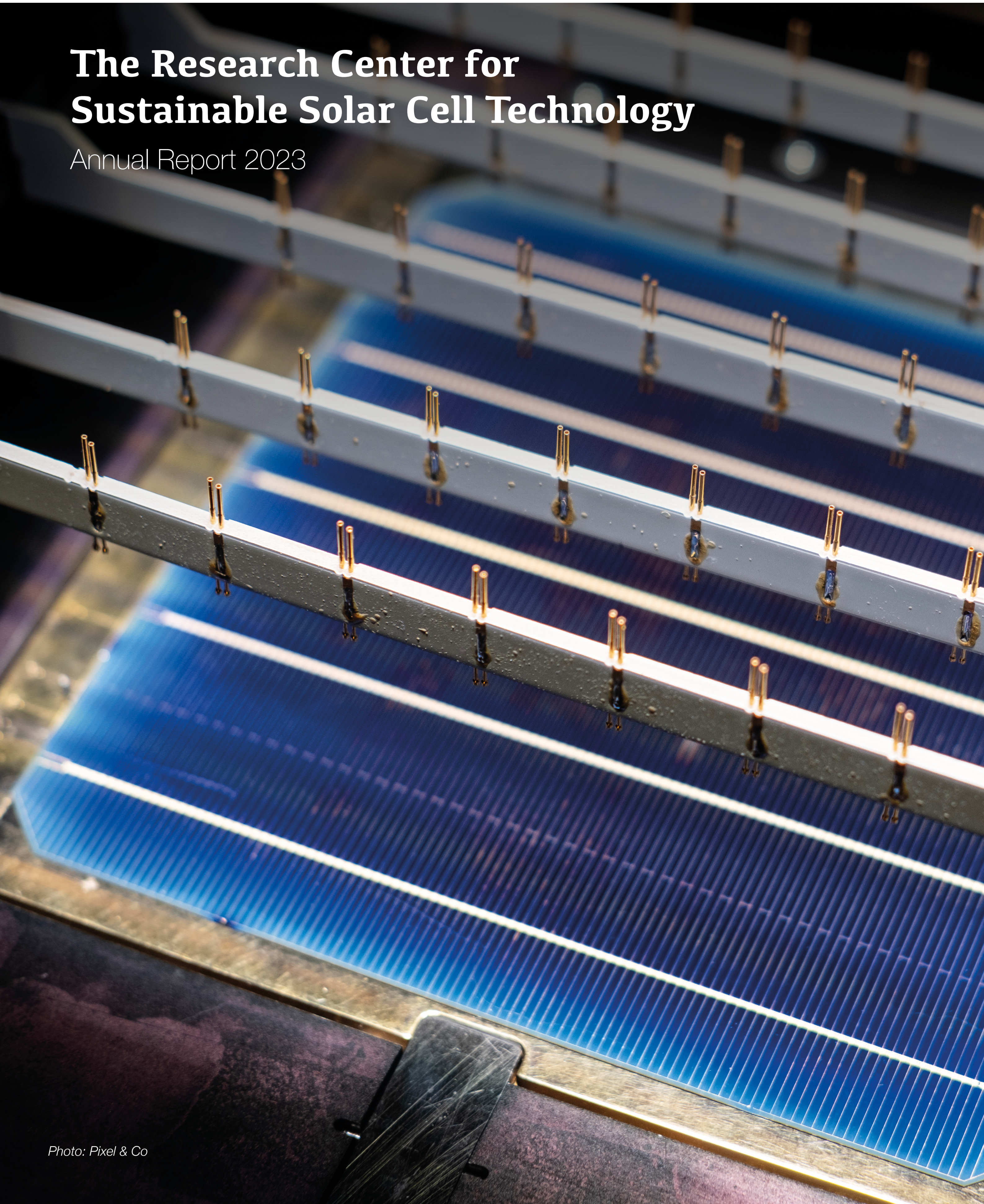


Photo: Pixel & Co

Letter from the Center Director

Even though the solar cell (PV) industry is used to seeing records fall, 2023 was an impressive year. Close to 400 GWp of new PV power plants were installed this year, representing a year-on-year growth of more than 50% in annual installation rates. Measured by capacity, more than half of all power plants of any type installed in 2023 were PV power plants. This is simply massive. Investments on the order of 4000 BNOK have been estimated for 2023, showing the sheer scale of this global, industrial effort. PV is set to becoming the largest and cheapest source of electricity in the world in little more than a decade.

In Norway, this was reflected in a dynamic and broad PV industry, which continued to expand and increase revenues in both international and domestic operations along the industry value chain. A growth in annual installation rates of 100%, a very high figure, was recorded as installers succeeded in connecting more than 300 MWp of new PV power capacity to the grid. This is close to 40% of the total capacity ever installed in Norway, a well-known indicator of the fast growth of PV in many markets. With this success in mind, a political goal of reaching 8 TWh of PV power production capacity in Norway by 2030 was set. With the right toolbox, PV can become an important contributor to the domestic electricity mix.

The PV manufacturing industry, however, struggled both in Europe and Norway. Although there are large ambitions to re-establish European manufacturing value chains, the right toolbox to enable this important goal has not been found. This impacts companies in both Europe and Norway. Norway remains the sole host of companies in crucial parts of the upstream value chain, with companies such as Norsun and The Quartz Corp having unique capabilities in ingot and wafer production, as well as in required crucible materials. Norwegian companies and research groups excel in this field. Sadly, Norwegian Crystals, a long-term FME SUSOLTECH partner went bankrupt in 2023, and REC Solar also decided to discontinue their Norwegian operations.

Our research center, The Research Center for Sustainable Solar Cell Technology (FME SUSOLTECH) was established in 2017 and is one of 13 Centers for Environment-friendly Energy Research (FME) awarded funding from the Research Council of Norway (RCN). The core of activities is defined and performed in close collaboration between research groups and industry. FME SUSOLTECH addresses silicon-based and silicon-compatible PV technologies, the basis for approximately 95 % of all PV modules produced world-wide today, ensuring relevance for companies involved along the manufacturing value chain. The number of companies developing, installing, owning and operating PV power plants in Norway and abroad is growing rapidly. An important effort in FME SUSOLTECH has therefore been to develop capacity, competence and data required for the further growth of this important industry. This activity continued to grow in 2023.

In 2023, the partners of FME SUSOLTECH were Code Arkitektur AS, Equinor, Glass- og Fasadeforeningen, IFE, NMBU, Norges Bondelag, NorSun AS, Norwegian Crystals AS, NTNU, Oslobygg KF, PVA Tepla GmbH, The Quartz Corp, REC Solar Norway AS, SINTEF, Solenergi FUSen AS, Solenergiklyngen, the University of Agder and the University of Oslo. Combined, these partners form an active Center with unique access to world class competence and infrastructure for high quality and industry-relevant PV research. Across the following pages, you will find a presentation of FME SUSOLTECH and its main activities in 2023.

Erik Stensrud Marstein
Center Director

What is FME SUSOLTECH?

The Research Center for Sustainable Solar Cell Technology (FME SUSOLTECH) was started in 2017 and joins the leading Norwegian research groups with a strong cluster of companies from Norway and abroad. The anticipated future growth of the solar (PV = photovoltaic) industry will lead to huge commercial opportunities along the entire value chain of production. Norwegian companies, many of which specialize in sustainable production of high quality silicon materials for export, are well placed to support this growth. A particular opportunity arises from an increased focus on development of European value chains in strategically important industries. In order to strengthen the position of these companies in a fiercely competitive industry, new production processes combining further reductions in costs with improved material quality are needed. Moreover: sustainability will become increasingly important in coming years. The center research targets cost reduction, solar cell efficiency increases and sustainability by innovation along the full value chain of production.

The FME SUSOLTECH partners monitor the performance of PV power plants to demonstrate the effect of materials and processes on the overall cost and environmental footprint of solar electricity. This activity also supports sustainable and cost-effective growth of a growing domestic industry in installation and operation of PV power plants. This industry is currently in a phase of rapid growth because of cost reductions of PV systems, cost increases for power and stricter environmental regulation, particularly in buildings.

In addition to PV companies, FME SUSOLTECH's list of partners also includes large Norwegian energy companies and organizations drawing upon the partner's broad competence to develop entirely new business. The resulting center is the most important competence and innovation platform for a growing and broad domestic PV industry towards 2025.

The activity in the center is organized in four work packages.

These are:

- WP1: Sustainable silicon feedstock production
- WP2: High quality silicon ingots and wafers
- WP3: Highly efficient silicon solar cells and modules
- WP4: End use and impact

In addition to PhD students and post-docs, a large part of the research is performed by researchers from the research and industry partners of FME SUSOLTECH. An important aim of the center remains to increase the volume of collaboration, dissemination and publication. A related important task for FME SUSOLTECH is to arrange meeting places for the Norwegian solar cell community, including the Norwegian Solar Cell Conference (NSCC) and meetings and webinars focusing on industry-relevant topics. Many of these are arranged in collaboration with the Norwegian Solar Energy Cluster (Solenergiklyngen).

For more information about the Center and ongoing activities, see www.susoltech.no.

Center partners

In 2023 FME SUSOLTECH had 6 Research Partners, 3 Clusters and associations, 1 Public Partner, 1 International Partner and 7 Industry Partners. IFE is the host institution of FME SUSOLTECH and the Center Director is Prof. Erik Stensrud Marstein. Together, the Center partners span out large parts of the PV industry value chain, from silicon feedstock production through ingot, wafer, solar cell and module fabrication to design and operation of PV systems. Through its partners, FME SUSOLTECH has access to world class expertise, laboratory infrastructure and production capacity along the entire value chain.

The list of partners in FME SUSOLTECH in 2023 is as follows:

Partner list:

Research Partners	Public Partner	International Partner	Cluster	Industry Partners
IFE (host)	Oslo Bygg KF	PVA Tepla GmbH	Solenergiklyngen	Code arkitektur AS
NMBU			Norges Bondelag	Equinor AS
NTNU			Glass- og Fasadeforeningen	Norsun AS
SINTEF				Norwegian Crystals AS
University of Agder				REC Solar Norway AS
University of Oslo				Solenergi FUSen AS
				The Quartz Corp

Some of the key personnel in the Center Management Team. From the left: Leader of WP2 Dr. M. Juel (SINTEF), Center Director Prof. E. S. Marstein (IFE), Center Coordinator M. Estensen (IFE), Education and dissemination Per-Anders Hansen (IFE), Deputy Director Torunn Kjeldstad (IFE) and Leader WP1 Ass. Prof. J. Safarian (NTNU). (Photo: Jon Arne Wilhelmsen)

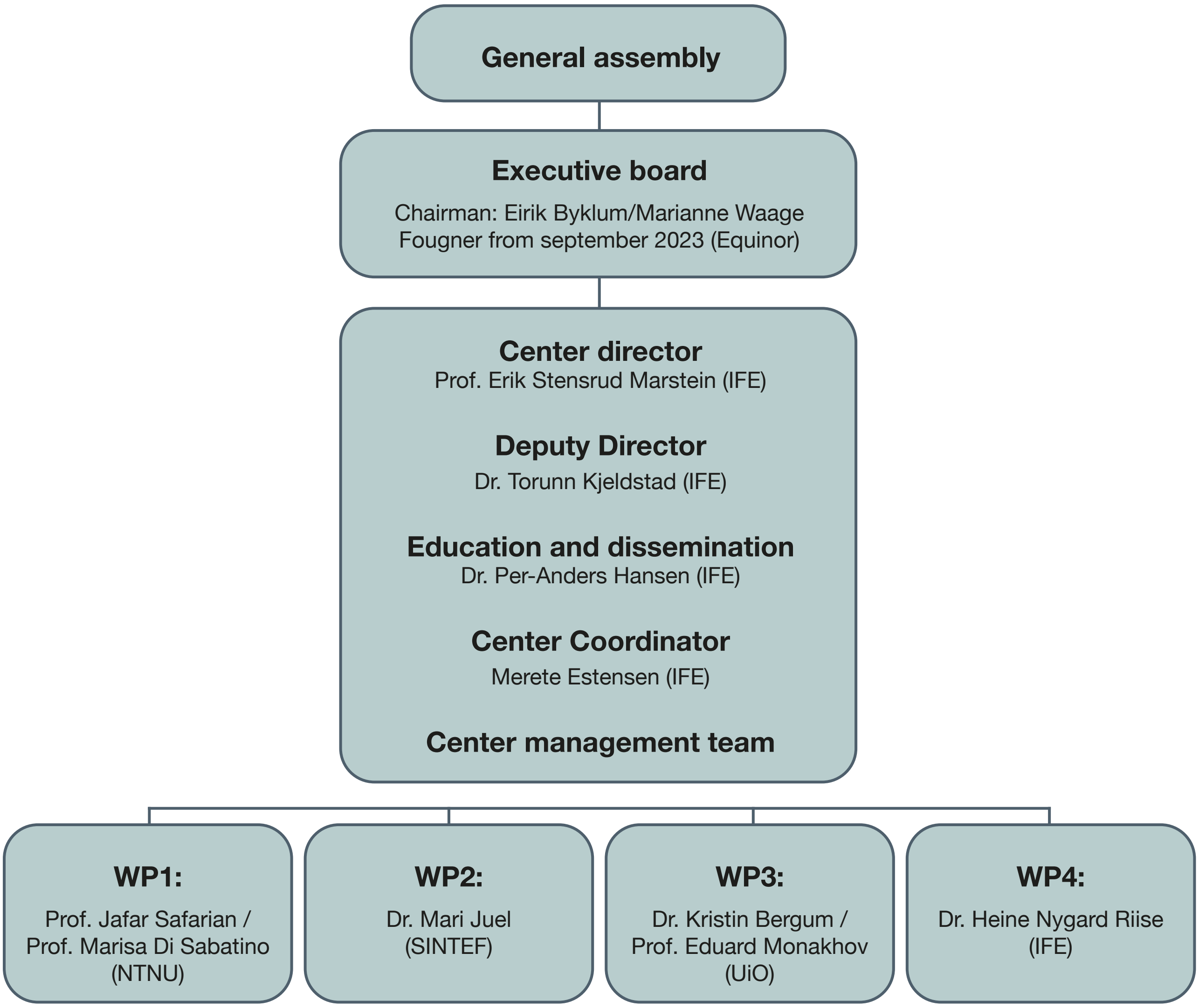
Center organization

In order to reach the overall goals of FME SUSOLTECH, good governance and an efficient organization is required. The upper decision making body of FME SUSOLTECH is the General Assembly, where all partners are represented. The day-to-day direction of the center is ensured by a 9 member Executive Board. In 2023, Marianne Waage Fougner (EQUINOR) replaced Eirik Byklum (EQUINOR) as Chairperson of the Executive Board. Prof Erik Stensrud Marstein (IFE) is the Center director of FME SUSOLTECH. In the daily direction, management and operation of FME SUSOLTECH, the Center director is supported by a Center management team consisting of the Center Director, the Center deputy head, the Center coordinator and the four Work Package (WP) managers. The four largest research partners of FME SUSOLTECH, IFE, NTNU, SINTEF and the University of Oslo are represented in the Center management team. Prof. Marisa Di Sabatino stepped in as WP manager in WP1 in 2023 and Prof. Eduard Monakhov took over as WP manager in WP3 after Dr. Kristin Bergum, who transferred to IFE.

The Work package managers are each responsible for the research activities described in the following pages, which are structured into the following 4 Work Packages:

- **WP1: Sustainable silicon feedstock production – WP manager Prof. Jafar Safarian and Prof. Marisa Di Sabatino (NTNU)**
- **WP2: High performance silicon ingots and wafers – WP manager Dr. Mari Juel (SINTEF)**
- **WP3: High efficiency silicon solar cells and modules – WP manager Dr. Kristin Bergum and Prof. Eduard Monakhov (UiO)**
- **WP4: End use and impact – WP manager Dr. Heine Nygard Riise (IFE)**

The Centre organization is shown in the figure below:



Dissemination and networking

Dissemination
Renewable energy is a topic that is of very broad interest and the subject of much public debate. Among the renewable energy technologies, PV technology is emerging as a winning technology globally, and record annual installation rates are becoming the norm, both in Norway and globally. FME SUSOLTECH plays an important role in dissemination, both by putting important trends and movements on the agenda, but also by supplying updated information on the role of research in developing new solutions and industry, as well as on the great potential of solar energy to contribute to a sustainable future. These topics are at the core of the plans of FME SUSOLTECH and its partners. The Center is visible in scientific journals and at international conferences, as well as in various popular scientific, trade and public media.

FME SUSOLTECH arranges selected conferences to shape the agenda of the PV community. With the aim of increasing awareness, supporting domestic industry generation, as well as improving the conditions for solar cell research, center colleagues have given lectures and presentations for various audiences, as well as participated in meetings and processes, including lectures for policymakers and a broader energy industry, and important strategy processes like the Norwegian Energi21, the European Energy Research Alliance and the European Solar PV Industry Association (ESIA).

FME SUSOLTECH has established and developed a strong collaboration with the Norwegian Solar Energy Cluster (Solenergiklyngen). Together, the two have arranged several meetings and conferences and also produced several important reports including a Roadmap for the Norwegian PV industry towards 2030. This roadmap caught much interest in the media and political community. Solenergiklyngen joined FME SUSOLTECH as a partner in 2021, facilitating this type of collaboration in the future.
A full list of publications and presentations from the FME SUSOLTECH in 2023 is given in Appendix 2.

Norwegian Solar Cell Conference 2023 (NSSC 2023)

The research Center FME Solar United, the predecessor of FME SUSOLTECH, started to arrange the Norwegian Solar Cell Conference (NSSC). This has now turned into an established and important annual meeting arena for the PV community in Norway, with participants from the PV industry and research institutions in both Norway and Europe. In 2023, FME SUSOLTECH arranged the NSSC conference at Son Spa in May. In addition, the center also arranged its annual meeting in August.

Research activities in FME SUSOLTECH in 2023

The research in FME SUSOLTECH is a joint undertaking by all partners and addresses important topics for the further development of PV technology as a competitive energy technology. In the following sections, a brief overview of the main research activities within each of the four Work packages in FME SUSOLTECH is presented. A list of the resulting scientific and popular science presentations based on this research is found at the end of this report.

Participants from The Norwegian Solar Cell Conference (NSCC) 2023 at Son Spa, Vestby (Photo: Jon Arne Wilhelmsen)

Work Package 1 – Sustainable silicon feedstock production

In work Package 1 in FME-SUSOLTECH the research focus is on sustainable solar silicon feedstock production. The metallurgical route for solar silicon production is an emerging technology and there have been significant developments in this route in recent years, while the chemical route is still the dominant technology. The main metallurgical process for solar silicon production is the ELKEM Solar process that is run by REC Solar Norway, and the company has recently developed a new process for the recycling of silicon waste from the PV industry, and through Si-Kerf valorisation. The research in WP1 is implemented to establish fundamental knowledge and develop new technologies to produce solar grade silicon feedstock through both primary and secondary raw materials in cooperation with REC Solar Norway.

The development of new solar silicon production processes is a main goal in WP1, research activities in the WP1 about the magnesiothermic reduction of silica have been done to develop carbon free process for silicon production.

Azam Rasoul finished her PhD and defended her thesis, titled "Synthesis of Mg2Si and its use for silane production" in September 2023. She has been supervised by Prof. Gabriella Tranell and Prof. Jafar Safarian at NTNU.

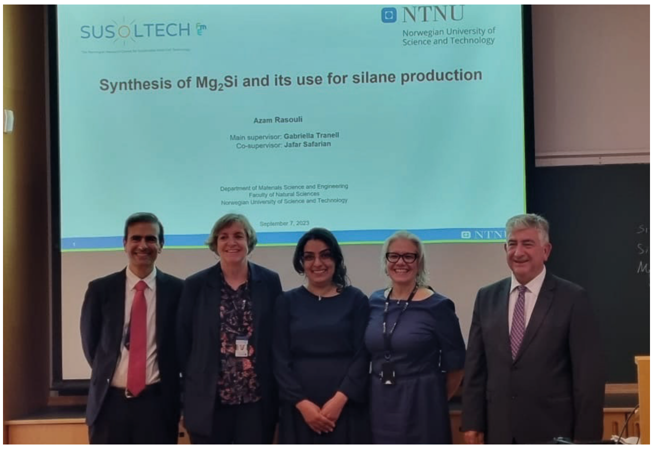


Figure 1: *Azam Rasouli`s PhD defence with opponents, administrator (prof. Merete Tangstad) and supervisor (prof. Gabriella Tranell)*

Research on characterization and recycling of Si-kerf has been carried out in WP1 in cooperation with REC Solar Norway, NTNU and UiO. In addition, the recycling of End-of-Life PV silicon via the application of vacuum refining was studied. We investigated the use of acid etching for de-metallizing the EoL solar cells, followed by vacuum refining to purify the recovered silicon fragments. Analysis of treated silicon revealed impurities including P, B, Ca, Ag, and Sn. Vacuum refining successfully removed Sn, Ag, O, N, and Mg from the silicon melt but required longer times to completely remove Ca and P. Due to its ability to bypass thermodynamic equilibrium limitations, vacuum refining offers a promising method for restoring recovered silicon to solar-grade purity.

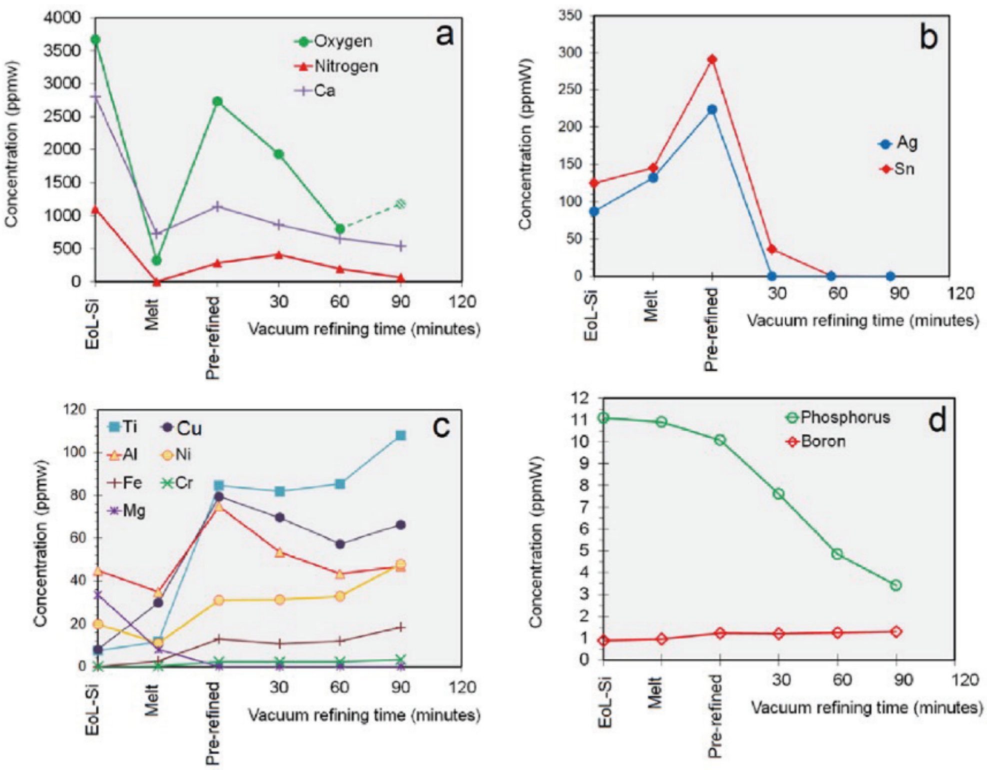


Figure 2: Impurity concentration dynamics during EoL PV Si refining

Regarding the recycling Si from end-of-life (EoL) panels, some results are shown in Figure 2. SINTEF has developed a machine learning model (MLM) based on laboratory experimental results on EoL silicon. The MLM can continuously update its ability to predict the refining of silicon by metal-slag treatment.

SINTEF has also investigated the novel way of upcycling silicon kerf to anode materials of lithium-ion batteries. To overcome the severe volume expansion of silicon, we developed a yolk-shell Si@void@C anode. Our innovative approach involves recycling kerf loss silicon waste from the solar industry into silicon nanoparticles (the "yolk") and encapsulating them within a protective carbon shell. This design effectively mitigates volume expansion. Our anode demonstrates a reversible capacity of 836 mAh/g at 0.1 A/g after 100 cycles with a Coulombic efficiency of 71.4%.

In 2023 the research results of Tinotenda Mubaiwa (PhD candidate at NTNU in WP1) were presented at European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC) on characterization and hydrometallurgical treatment of industrial silicon kerf. Some the results are shown in Figure 3. Different industrial samples were characterized with the view of identifying any similarities and differences between kerf samples from different suppliers and come up with recycling methods that cater for the different samples. Acid leaching using HCl, H2SO4 and HNO3 was also conducted as a pretreatment step, by removing metallic impurities as well as P. The results showed more than 80% removal efficiency in all the acids used. We also presented our results on combined treatment of acid leaching and inductive leaching at the Norwegian Solar Cell Conference (NSCC).

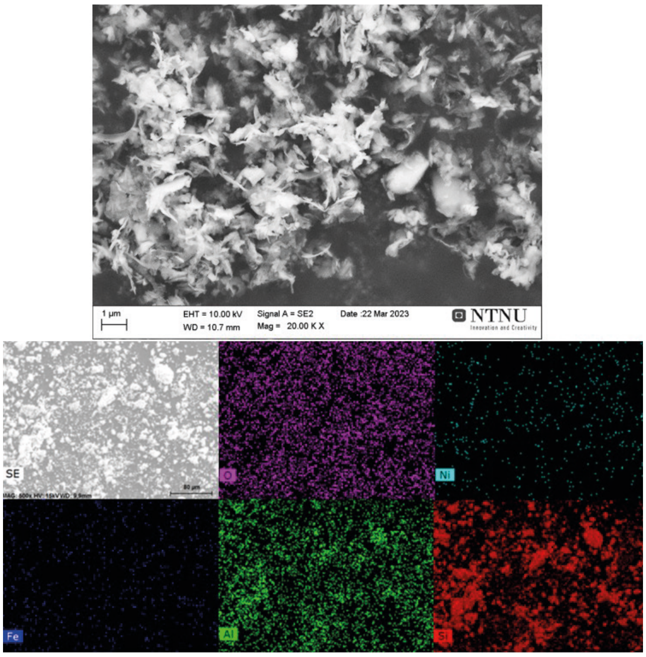


Figure 3: Presentation at EU PVSEC 2023 showing morphology and mapping of elements in Si-kerf https://userarea.eupvsec.org/proceedings/EU-PVSEC-2023/1BV.5.4/

Figure 4: Presentation at NSCC 2023 by PhD candidate Tinotenda Mubaiwa

Askh Garshol and Hannah Skarsvåg finished their bachelor thesis at NTNU with research focus on hydrometallurgical purification of Si-kerf followed by high temperature melting. The found that a part of the impurities can be removed from Si-kerf via acid leaching, and applying higher temperatures enhances the melting process. It was found that the addition of pre-fused slags and lumpy pure silicon particles improve the melting and homogenization. Moreover, the decarburization of silicon occurs when slag is added as a flux.

Dissemination

In 2023 the researchers in WP1 published eight peer-reviewed Journal papers and had six conference papers/ presentations. One master thesis and two bachelor theses were carried out in WP1, and in addition the work package results were disseminated during the WP1-WP2 project meeting in the Fall 2023 and at the Norwegian Solar Cell Conference in May 2023.

For more information, contact Work Package Manager
Dr. Marisa Di Sabatino (marisa.di.sabatino.lundberg@ntnu.no)

Work Package 2 – High performance silicon ingots and wafers

The material quality of silicon ingots and wafers depends on the silicon feedstock, crucible, furnace materials and the parameters of the crystallization process. The combination of reduced costs and the demand for increased efficiencies of industrial Si solar cells makes it critical to develop sustainable and cost-effective crystallization processes that produce silicon ingots of high quality. This is achieved through a strong understanding of the root cause for how harmful impurities are transported into silicon and how defects in the material are formed. I addition is it necessary to develop processes that reduce the concentration and effect of impurities and defects. In FME SUSOLTECH we are doing this by a close interaction between experimental tests, theoretical knowledge and numerical simulations.

Development and understanding the effect of new production processes for Czochralski (Cz) silicon is one of the main tasks in this work package. In addition, the development of kerfless Si technology which enables Si wafer production without sawing-related material losses are targeted by epitaxial growth of silicon wafer by e-beam sputtering.

Monocrystalline silicon

The research on monocrystalline silicon involves many of the center partners from both research and industry. NorSun operates production facilities for Cz-Si production in Årdal, while REC Solar has produced feedstock to their factory in Singapore. PVA Crystal Growing Systems and The Quartz Corp supply important equipment and materials to this branch.

The research topics in FME SUSOLTECH include understanding the formation of microdefects in high productivity Cz crystallization and develop routines for limiting such defects, developing a complete understanding of the role of the crucible in the Cz process and using this understanding to determine the parameters defining a good crucible, as well as solving the problem of yield-limiting structure loss during Cz Si production.

The development of direct measurement of hydrogen in silicon wafers by FT-IR developed in the center makes it possible to study H-related complexes in wafers during processing, or during degradation and regeneration of the minority carrier lifetime. At the Silicon PV 2023 conference in Delft, PhD student Nicole Aßmann presented her research indicating that the initial amount of hydrogen complexes is not affected by the presence of an emitter during the firing process. Additionally, she emphasized the significance of the low temperature of 5 K, despite the time-consuming nature of the method, it proves highly sensitive, which is crucial for hydrogen-related measurements. Furthermore, she proposed the option to retain the SiNx layer during the FT-IR if needed. These findings are published in the peer-reviewed conference proceedings of the Silicon PV 2023. Nicole co-authored two publications from Fraunhofer ISE, published in 2023, that investigate the link between firing processes and degradation processes. These studies unveiled a significant correlation between the peak firing temperature and the initial hydrogen concentration and demonstrated the potential to reduce hydrogen levels in the wafers through cooling processes. This ability to control hydrogen concentration is highly advantageous and has a substantial impact on the charge carrier lifetime.

At IFE the focus has been on degradation and regeneration mechanisms related to boron-oxygen defects in p-type silicon and the effects of hydrogen on the corresponding reaction kinetics. The work, which is a collaboration with UiO and the unique FT-IR capabilities mentioned above, resulted in a presentation at the 40th EUPVSEC in Lisbon. In addition, different routes for achieving excellent surface passivation using a very thin tunnelling layer capped by a doped polysilicon layer (aka TOPCon passivation) has been evaluated. The results will be presented at the NSCC in 2024.

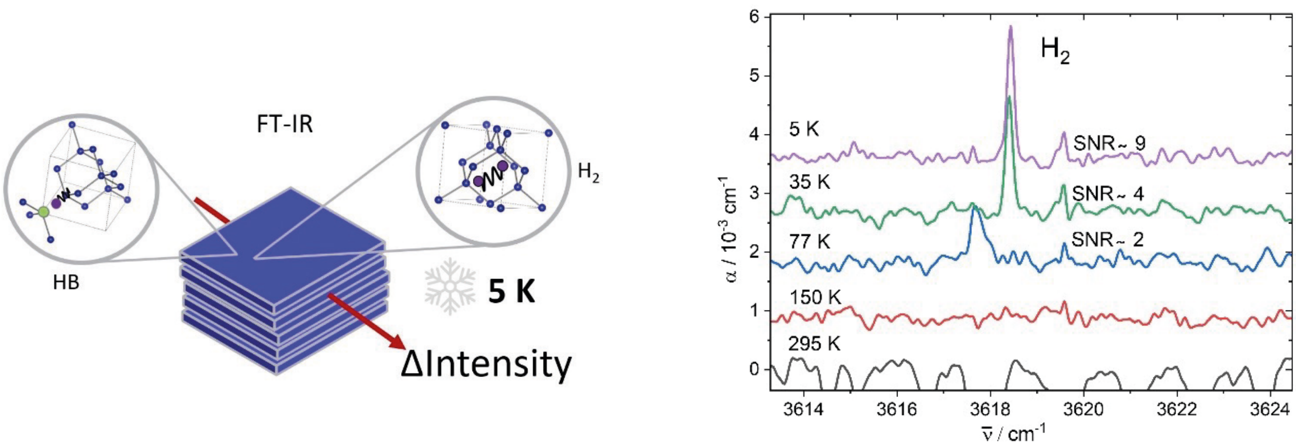


Figure 1. *Left) Sketch of FT-IR method used for measuring H in silicon wafer developed in FME Susoltech. Right) The H2 peak in the FT-IR spectra gets more pronounced and precise when the temperature decreases. (Nicole Aßmann, UiO, figuren til høyre er publisert i https://doi.org/10.52825/siliconpv.v1i.840)*

Figure 2. *Rune Søndenå presenting at the 40th EUPVSEC in Lisbon (Sept'23), Photo: Helge Malmbekk*

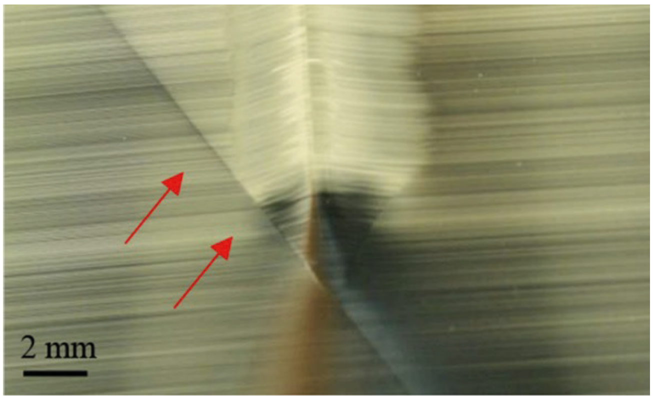


Figure 3. *An example of how the growth ridge indicating monocrystalline Cz-growth stops due to a slip line caused by a dislocation. (Ref: Rania Hendawi, Marisa Di Sabatino, Analyzing structure loss in Czochralski silicon growth: Root causes investigation through surface examination, Journal of Crystal Growth 629 (2024), 127564. https://doi.org/10.1016/j.jcrysgro.2023.127564)*

A high priority in the center is to better understand how the quality of the quartz crucibles influences the productivity and material quality for production of Cz Si ingots. This is the main research topic for PhD student Gabriela Warden has this as her main research topic in the center. In 2023 she performed uniformity studies of the OH-level and viscosity in fused quartz crucibles in close collaboration with the Max-Planck Institute in Düsseldorf. This work shows clearly that the OH-level and viscosity in crucibles is not uniform. However, there is a general trend that the OH-level decreases from the top to the bottom of the crucible and that it is a significant increase in the OH-level in the boundary layer between the bubble containing and bubble free layer.

Structure loss in Cz-Si ingots is causing both productivity and yield loss for Cz-Si ingot producers. Postdoc Rania Hendawi has in her investigations of structure loss of more than 100 industrial produced ingots been able to develop a non-destructive method for identification of the root cause of structure loss. Four main root cause categories as identified as illustrated in the fishbone diagram in Figure 1. This diagram also includes potential parameters that can influence the occurrence of the different categories. This activity has also been supported by SINTEF by testing different machine learning methods that can be used for classification.

Kerfless silion

In the activity related to developing a process for fabricating Si wafers based on e-beam, epi-growth of p-Si films on Si (100) substrates were demonstrated. Fully crystalline Si based layers (thickness up to ~140 micron) were fabricated at 1000 °C at a deposition rate of ~1.5 mm/min. Main focus in 2023 has been to reduce C-content in the deposited silicon, by avoiding contact between the graphite liner and melted silicon feedstock. In addition, a paper has been published [1].

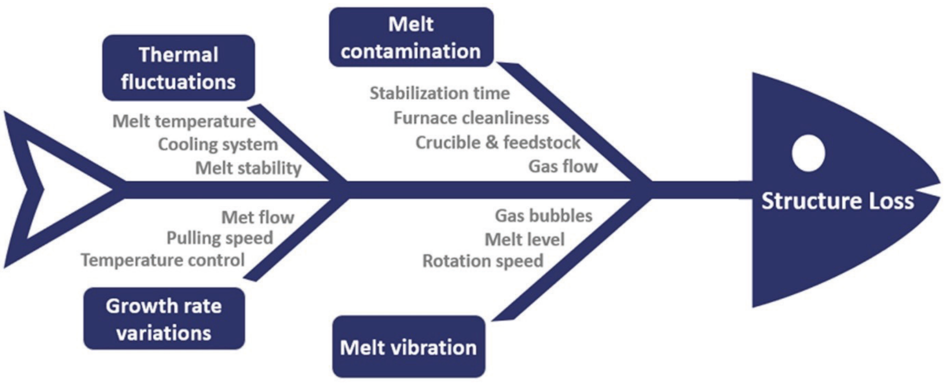


Figure 4. *The main root causes for structure loss in Cz growth of silicon ingots is illustrated in a fishbone diagram. (Ref: Rania Hendawi, Marisa Di Sabatino, Analyzing structure loss in Czochralski silicon growth: Root causes investigation through surface examination, Journal of Crystal Growth 629 (2024), 127564. https://doi.org/10.1016/j.jcrysgro.2023.127564)*

For more information, contact Work Package Manager Dr. Mari Juel (mari.juel@sintef.no)

1) High-Rate Epitaxial Growth of Silicon Using Electron Beam Evaporation at High Temperatures, Stange et al; Coatings 2023, 13(12), 2030; https://doi.org/10.3390/coatings13122030

Work package 3 – High efficiency silicon solar cells and modules

New concepts for high-efficiency solar cells

The researchers in the Centre continue their efforts towards solar cells with efficiencies beyond Schockley-Queisser limit. Presently, over 90% of all solar cells are made of silicon. Silicon solar cells have superior conversion efficiency in a relatively narrow spectral range around near-infrared and red light. The conversion efficiency for other spectral ranges, i.e., colors is, however, rather low. The total conversion efficiency is thus limited by around 30% for silicon solar cells. Several concepts are under considerations: photon conversion, tandem solar cells and intermediate band solar cell.

Photon conversion

The approach of photon conversion is based on the idea to convert the broad solar spectrum to a narrower spectrum that is optimized for silicon solar cells. Within this concept, a UV photon is to be converted into 2 or more red photons, and 2 or more infrared photons are to be converted into a red photon. Such solar cells are proposed to be based on efficient absorbers on the surface of the solar cell, where the excited state can be transferred to an emitter with minimal non-radiative decay. Previously, our focus was on exploitation of aromatic structures as absorbers and means of encapsulating these to provide long-term stability. These investigations were continue at UiO into 2023 with emphasis on combined stability under UV-illumination and elevated temperatures. Nanocomposite structures based on 2,6-Naphthalenedicarboxylic (NDC) compounds as emitter were made (Fig. X.1), and the focus was on eliminating sources for non-radiative recombination to allow for efficient luminescence.

Tandem solar cells

Silicon-based tandem solar cells are perhaps the most anticipated technology for the large-scale implementation in the industry. Within this approach the conventional, mass-produced silicon solar cells are used as the bottom cell, and the top cell is made of a material with optimized opto-electronic properties. Theoretical efficiency limit of silicon-based tandem cells is 45%, compared to 30% for silicon only solar cells. During the last years, ITRPV roadmap repeatedly predicted emergence of commercial silicon-based tandem cells on the market. Presently, the most promising materials for the top cell are hybrid organic-inorganic, halide perovskites. The main challenges include (i) presence of lead (Pb) and (ii) instability and degradation of the cells under the light and in moisture. However, the scientific and technological challenges related to the perovskites proved to be exceedingly difficult, and the commercial adoption of silicon-based tandem cells has been repeatedly postponed. So far, there are no commercial, large-scale produced perovskite solar cells, and the emergence of silicon-based tandem cells is now postponed to 2027 (see ITRPV 2023).

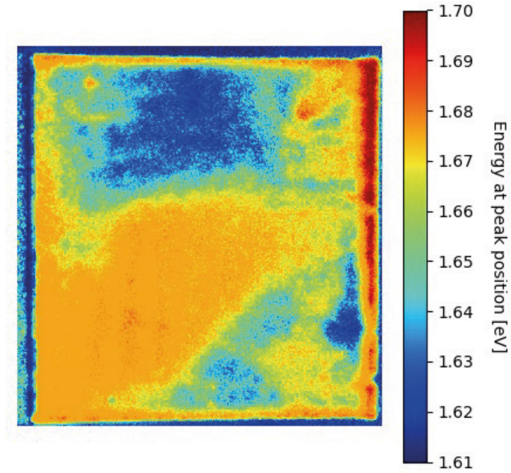


Fig. X.2. Mapping of the band gap in the perovskite films by hyperspectral photoluminescence.

Researcher at NMBU have previously developed hyperspectral photoluminescence (PL) spectroscopy, which is implemented for characterization of perovskites. Fig. X.2 demonstrates measurements of the band gap in the perovskite films deposited by spin coating. The bang gap is deduced from the intensity maximum in the PL intensity. This method is also useful for studies of the degradation of perovskite materials. The measurements prior and after the

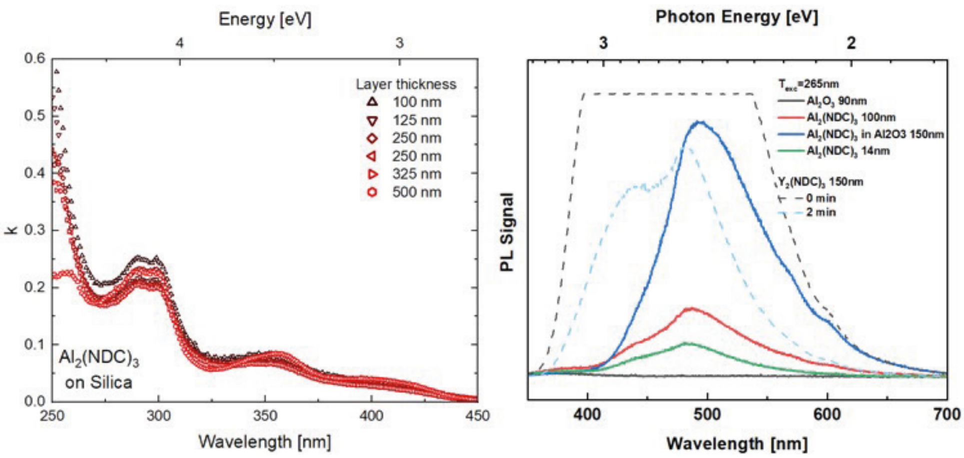


Fig. X.1. Photon conversion by Al2(NDC)3: Absorption of UV light at 250-350 nm (left) and emission of green-cyan light at 500-550 nm (right).

degradation may point out on the degradation mechanisms and the approaches to mitigate the degradation.

Researchers at UiO focus on alternative materials that are non-toxic, environmentally friendly and stable in operating conditions with respect to moisture and UV radiation. One of the materials under consideration is zinc oxynitride (ZnON). In 2023, efforts have been made to predict performance of silicon-based tandem cells with ZnON as the top cell material. Numerical simulations show that the ZnON/Si tandem solar cells can provide quantum efficiency for photon conversion close to 1 (Fig. X.3).

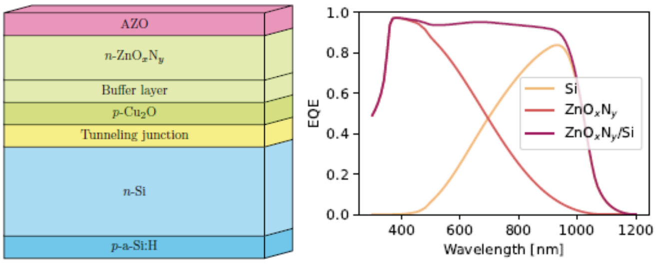


Fig. X.3. Structure of a ZnON/Si tandem solar cell (left) and the simulations of external quantum efficiency (EQE) for Si-cell, ZnON-cell and the complete tandem structure (right).

Intermediate band solar cells

An alternative high efficiency approach to tandem cells, is the so-called intermediate band solar cells, that has the same theoretical efficiency as for a tandem cell with the same number of bandgaps. The concept was introduced as early as 1997, and the cell design is much simpler than for tandem cells, since fewer layers are needed. The concept has been demonstrated at the laboratory scale, but only for toxic or scarce elements. Sustainable materials with the desired properties remain to be developed, and oxides (both with and without the perovskite structure) had been proposed with promising optoelectronic properties. One of such promising materials is titanium dioxide (TiO2) co-doped with Cr and N. The effect of varying Cr and N concentration on the optical properties has been studied by researchers at NTNU. Fig. X.4 demonstrates a 2-inch Si wafer with a deposited TiO2 film and co-doped with Cr and N. The wafer was used for opto-electronic characterization to evaluate on the feasibility for application in the intermediate band solar cells.

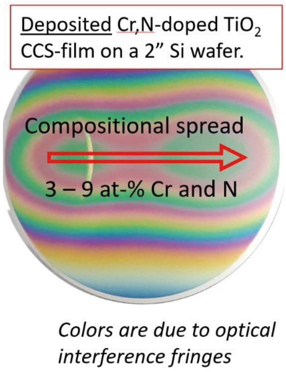


Fig. X.4. Si wafer with deposited Cr,N-doped TiO2.

Building integrated PV

Building-integrated photovoltaics (BIPV) has become an important area for application of solar cells. In this concept the solar cells are used to replace conventional building materials in such parts of the building as the roof, skylights, or façades. They can be incorporated as a principal or auxiliary source of electrical power into both new and existing buildings. The advantage of BIPV is that the cost of the solar cell installation is partially covered by the building construction cost. One of the main purpose of BIPV is to resolve the conflict between the architecture and building's aesthetics and the traditional appearance of solar panels.

A previously developed at SINTEF and IFE optical modelling framework for simulating both the colour perception and the efficiency of coloured Si solar cell modules was used to design and fabricate coloured modules based on optical interference from thin film multilayers. Such layers were deposited on the module glass in order to achieve saturated and bright colours while maintaining relatively high power conversion efficiency for the solar cell module. Plasma enhanced chemical vapor deposition was used to fabricate thin film multilayers on glass. Fig. X.5 shows the comparison between the experimentally achieved colors of the multilayer modules and theoretically predicted colors. An important characteristic of interference colours is that the reflected color may depend rather strongly on the observation angle. This effect can be reduced by using glass with a surface topography.

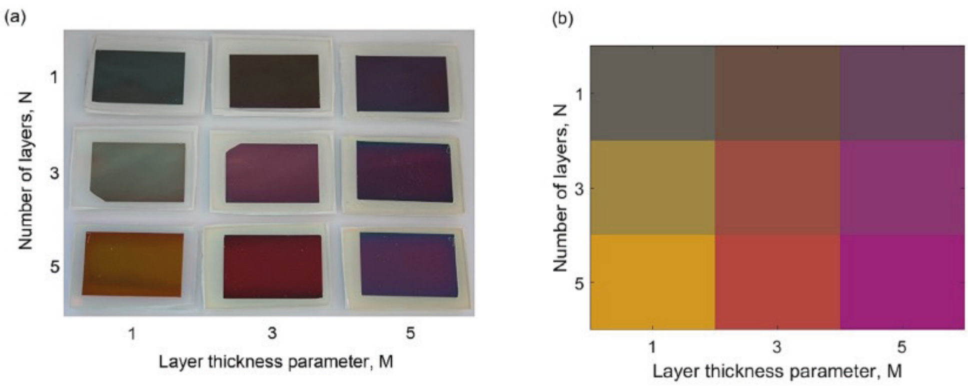


Fig. X.5. Visual appearance of the multilayer modules after the fabrication (a) and the expected colors from the numerical simulations (b).

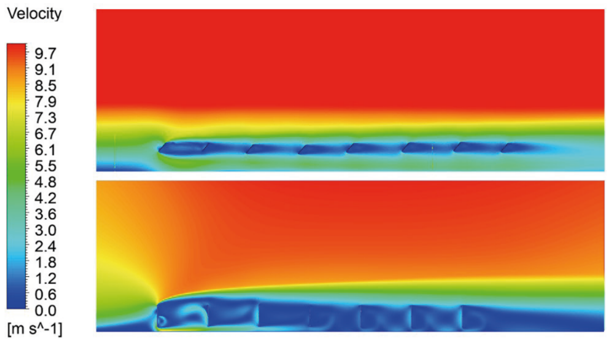
For more information, contact Work Package Manager Prof. Eduard Monakhov (eduard.monakhov@fys.uio.no)

Work package 4 – End use and impact

End use of PV is a broad topic and in WP4, considerations on sustainability and circularity of PV, field performance of PV plants, and combination of agriculture and PV (agri-PV or agrivoltaics) are being explored. The broad range of topics shows the complexity in solving the challenges and realizing the opportunities of the Norwegian solar energy industry. Below follows a summary of the most important work in WP4 in 2023.

Co-use of land

Increased focus on sustainable land use and nature management has led to research examining the impact of solar parks on surrounding areas, including microclimatic changes and effects on biodiversity. To explore this further, PhD Erlend Hustad Honningdalsnes at IFE/UiO has initiated extensive modeling and field measurements of solar radiation, wind speed (an example is shown in the figure below), temperature, and humidity.



Wind speed changes in agrivoltaic systems with elevated and tilted vs vertical PV panels.

In addition, analyses are being conducted to investigate how other land areas, such as agricultural land, can be optimally combined with energy production from solar panels. While we await data from Norwegian agriPV facilities, we have established collaborations with several international partners. The project has also contributed to a literature study and a IEA PVPS report on modeling agriPV.

SINTEF researcher Gaute Stokkan in front of the Skjetlein agrivoltaics pilot

Further, the agrivoltaics pilot at Skjetlein High School south of Trondheim was established, and FME SuSolTech has supported the work. The park was established as a collaboration between SINTEF, NTNU, ANEO, Grønt Hjerte and Skjetleiin High School, and supported by Regional Research Fund Trøndelag. It is a 50 kW plant consisting of four rows of double height, vertical bifacial solar panels, spaced 12 m apart. The park is instrumented with monitoring equipment for light and microclimate and is intended to test a novel system involving a traversing measurement unit for improved spatial data resolution. The primary result from the first season was that no negative effect on dry mass harvest was observed between the agrivoltaics site and the control plot located directly to the south. This indicates that it can be possible to introduce solar panels in forage production without a significant negative effect, however the results should be regarded as preliminary and must be followed up with further precision measurements in the following years.

Field performance of novel PV technology

An important part of WP4 is the collaboration between NMBU, UiA, IFE and NTNU on field degradation of PV modules. Combined, these research partners have a substantial infrastructure for testing modules and for monitoring the performance of PV systems. The infrastructure and experience of the partners are applied to discuss problems on how PV modules degrade, fail and perform in the field. The activity has (among others) led to a consorted effort to evaluate the field performance of a specific, novel PV technology developed in the center. The field performance is monitored at Ås (NMBU), Kjeller (IFE) and Grimstad (UiA).

Data analysis of PV system performance in Norway:

Master student Martin Krebs Kristiansen performed the study «Performance analysis of PV power plants across Norway – Developing a practical approach to analyze large-scale PV installations with limited metadata" [1]. The dataset was provided by Solcellespesialisten and prepared by Christoph Seiffert at IFE. The dataset consisted of 501 systems with limited meta-data, mainly located in Østlandet and Vestlandet (Figure 5.2), providing hourly data of PV power production over 1 year. Finding azimuth and tilt from satellite data and clustering, the yearly specific yield for the whole dataset was 866 kWh/kWp, with geographical differences as shown in the figure.

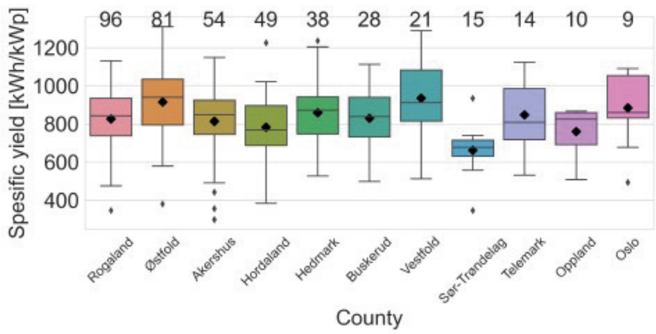


Figure 6.19: Boxplots of specific yield across counties

Irradiance data and modeling of PV performance in Norway: Using high resolution spectral data collected at UiA in Grimstad over a full year, it has been investigated how spectral variation affects the production from tandem cells with various band gaps [2]. The resulting efficiency maps show good agreement with similar maps made using the standard reference AM1.5G spectrum, indicating that the standard is well suited for optimization of tandem bandgaps in the represented Nordic conditions.

Performance Loss Rates in Norway

IFE has also continued their investigation into performance loss rates (PLR) (also known as degradation). Since PV installations at higher latitudes were not as common until recently, little is known about their degradation rates in Nordic climates. In 2023 Christoph Seiffert has attempted to close this gap by analyzing production data from several commercial PV installations across Norway.

This analysis builds on earlier work carried out by IFE [3]. While the analysis is ongoing, preliminary results indicate a performance loss rate of approximately PLR = -0.36 +/- 0.18% per annum.

Degradation of PV performance in a Norwegian climate:

Oscar Kwame Segbefia has successfully defended his PhD degree entitled “Solar cell degradation – the role of moisture ingress” [4]. The figure is from a recent paper [5] where the moisture-induced degradation (MID) products in reclaimed solar cells from 20-year-old field-aged silicon PV modules is investigated using SEM-EDS analysis. Visual inspection revealed optical degradation of EVA encapsulation and dark discoloration of the TPT backsheets. Corrosion at the solder joint was dominant and attributed to the dissolution of lead and tin (main components of solder) and the Ag grids in moisture and acetic acid due to galvanic corrosion. In the presence of MID species, Pb is preferentially corroded (to form lead acetate complexes) instead of the expected sacrificial Sn in the solder. The EDS analysis showed increased levels of oxygen near the edge. It was concluded that the various MID species may account for the observed metal grids corrosion, cell cracks, optical degradation, and PID leading to the 1.2%/year degradation in the Pmax of the field- aged PV module.

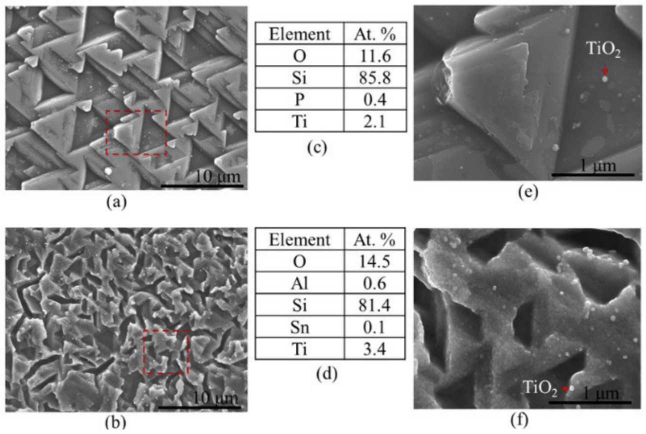
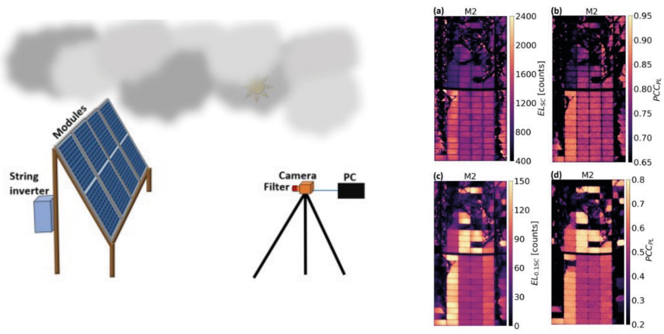


Fig. 9. SEM micrographs and EDS analyses of a solar cell extracted from the edge of PV Module X. (a)-(b) SEM micrographs and (c)-(d) EDS analyses acquired ca. 10 mm from the edge and just at the edge of the solar cell. SEM micropgraphs of the marked-out areas in (a) and (b) are shown in (e) and (f), respectively. The EDS analyses are represented in atomic % (at. %).

Photoluminescence (PL) imaging of PV power plants

The work with respect to PL imaging was largely closed at NMBU during 2023 with two master theses, defense of PhD thesis by Marija Vukovic and publication of two articles in AIP’s Journal of Applied Physics. The first article presents a new way of processing a PL image series by obtaining correlation coefficient between different signals in the images. The approach is particularly suited for PL images acquired during IV curve sweeps, an imaging method proposed by the colleagues at NMBU in 2022, and contributes to a more efficient data analysis. The second article shows that PL imaging is not limited to being conducted only under direct sunlight. It can be carried through under as little as 40 W/m2 measured during a heavily clouded, winter day. The PL images obtained in this way give additional information about modules’ damages. This is shown in the figure.



Left: PL imaging under heavy clouds. Right: Image obtained under direct sunlight and validated with an ELSC image (a-b), image obtained under cloudy conditions and validated with an EL0.1SC image (c-d). Images show the same module, but different information is obtained about the damage when imaged under different illumination conditions. From [6]

For more information, contact Work Package Manager Dr. Heine Nygard Riise (heine.riise@ife.no)

FME SUSOLTECH – Innovation and partner impact

The role of innovation for the domestic and European PV industry

Norway is in the fortunate situation of hosting a broad, internationally oriented, innovation-driven and competitive PV industry. The FME SUSOLTECH consortium includes the largest Norwegian companies producing or supporting sustainable production of high-quality silicon materials. This part of the industry is almost unique in Europe and is expected to play an important, complementary role in the establishment of European industrial value chains for PV manufacturing. Approximately 95% of all solar cells are made from this material, a situation that is not expected to change in the near future. For these partners, development of new processes and methods enabling even higher throughput production of higher quality silicon materials at lower cost while reducing the environmental footprint of their products is crucial.

In addition to these partners, FME SUSOLTECH has partners developing, installing, owning, operating or supporting the development of PV power plants of all sizes in Norway and abroad. Also for all of these companies, innovation is crucial for competitiveness. To increase the competitiveness of PV power plants both in buildings and on the ground, improved solutions enabling cost-effective design, installation and operation of the systems is important.

Supporting innovation and development of export-oriented green industries are also two important motivations for the establishment of the entire FME programme by the Research Council of Norway. Therefore, supporting innovation is an important goal of FME SUSOLTECH.

FME SUSOLTECH an engine for a broader R&D activity

FME SUSOLTECH has been an important source of new projects. The list of granted projects included both domestic research, competence and innovation projects funded by the Research Council of Norway and, often, Industry Partners, as well as EU projects. In 2023, two EU projects related to recycling along the PV industry value chain were awarded IFE and SINTEF, respectively, a credit to the strong scientific teams there. In addition come two competence projects and one innovation project. In the table below, a list of projects that can be traced back to FME SUSOLTECH is given. The role of FME SUSOLTECH in building a strong project volume in strategically important fields is important for all partners from both Research and Industry.

Some of FME SUSOLTECH's dissemination activities are also set up to support innovation. In collaboration with the Norwegian Solar Energy Cluster (Solenergiklyngen), FME SUSOLTECH strives to spread information related to the opportunities and challenges facing the domestic and European PV industry with the aim of supporting the development of strong production value chains of this critical technology in Europe. The formerly discussed Roadmap of the Norwegian PV industry was also important for illustrating the large potential for value creation and employment in a broad, domestic PV industry including both export-oriented companies supporting global and European PV value chains, as well as the substantially larger number of companies targeting PV power plants in Norway.

Name	Host	Type	Duration
Engineering Quartz Sand for Next Generation Solar Crucibles (EngQS)	TQC	IPN	2018-2021
High-purity amorphous silica	TQC	IPN	2018-2022
Solidification of Unseeded high-PERformance MULTIcrystalline silicon (SuperMulti)	REC Solar Norway	IPN	2018 - 2021
Crucibles for next generation high quality silicon solar cells (CruGenSi)	NTNU	KPN	2018 - 2021
BeSmart		EU	2018 - 2022
PV Adapt	SINTEF	EU	2018
LeTID in multicrystalline PERC cells (LetUP)	IFE	RP	2018 - 2020
Diamond sawing and surface treatment of high performance multicrystalline silicon wafers for high efficiency solar cell applicaitons (DiaMApp)	NTNU	RP	2018 - 2022
SiNoPACT	UiO	Other	2018
Erasing efficiency-limiting structural defects in high performance multicrystalline Si wafers (Erase)	REC Solar Norway	IPN	2019 - 2022
MATS - New MAterials for Tandem Solar cells	UiO	YRT	2019-2023
H2Si - Silicon Production from Quartz and Hydrogen	Elkem	IPN	2022-2024
Czochralski growth of low-oxygen silicon single crystals for high-efficiency solar cell applications (SUCCESS)	SINTEF	Other	2019 - 2029
ChiNoZEN	NTNU	Other	2019
Nacamed 2	Nacamed	IPN	2020-2023
HighVis, Development of a new Al-enriched quartz sand product for next generation solar crucibles with superior viscosity	TQC	IPN	2020-2022
SisAl Pilot	NTNU	EU	2020-2023
High Efficiency Silicon for the silicone value chain	Elkem	IPN	2019-2022
Giant Single-Crystal technology for Premium solar cells	NorSun	IPN	2020 - 2024
Ultra-Sustainable semiconductor Substrates for tomorrow's solar cells	NorSun	IPN	2020 – 2025
SUNPOINT	IFE	KPN	2021-2024
Icarus	SINTEF	EU	2021
Silicon production using hydrogen as reductant	---	FP	2021 - 2026
Hybrid produksjon av fornybar energi i alpine forhold	Fred Olsen	IPN	2021 - 2025
Enhancing optimal exploitation of solar energy in Nordic cities through the digitalization of the built environment (HELIOS)	NTNU	RP	2021 - 2026
Bygningsintegrerte solceller for norske tak (Soltak)	BIPV Production of Norway	IPN	2021 - 2024
Recycled kerf for mono silicon feedstock	REC Solar Norway	IPN	2022 - 2024
The new green energy-saving application of photochromic-based dynamic solar control films for retrofit windows.	Sunphade	IPN	2022 - 2024
SunUP - Solar photochemical H2 production through novel routes	UiO	RP	2021 - 2022
Innovasjonsprosjekt om lumineserende filmer for overflatetermometri, + patentsøknad	UiO	Other	
KSP PREDICT	IFE	KSP	2023 – 2027
KSP ENVISOL	IFE	KSP	2023 – 2027
QUASAR	SINTEF	EU	2023 – 2027
RETRIEVE	IFE	EU	2023 – 2027
Increased silicon ingot diameter and enhanced energy efficiency through numerical simulations	Norsun	IPN	2023 - 2026

List of funded projects. IPN = Innovation Project in Industry, KPN = Competence Project, RP = Researcher Project and YRT = Young Researcher Talent

Education and training

Education and training of candidates at MSc, PhD and postdoctoral levels with relevant competence for the PV industry and research community is an important task of FME SUSOLTECH. The growing, domestic and global PV communities need increasing access to competent candidates. In addition the PhD and postdoctoral positions funded either through the FME SUSOLTECH grant or as own-effort from the research partners, a substantial number of MSc students also perform their thesis work in the Center. The full list of candidates performing their thesis work in FME SUSOLTECH in 2023 is found in the attachments.

Interview with a center colleague: Dr. Marija Vukovic

Marija started working in FME SUSOLTECH as a PhD student at NMBU in 2018. Prior to this, she finished a MSc degree in Environmental physics and renewable energy, also at NMBU. Her PhD topic was in-field diagnostics of modules using photoluminescence imaging and was successfully defended in 2023. She now works as a researcher at IFE, mainly with the PEANUTS project in collaboration with Scatec and Equinor. In PEANUTS, she works on models for optimizing module cleaning schedules in PV parks based on soiling and irradiation data combined with cleaning costs.

What has been your main research field during your time in the FME SUSOLTECH?

My PhD topic was using photoluminescence imaging to find faults in PV modules. The aim was to be able to do this efficiently and in-field while the module is in operation. This is a large advantage compared to methods where the modules operation has to be interrupted or if the module has to be taken down and sent elsewhere. This costs time and money for the owner and operator of PV plants. Photoluminescence imaging like this is quite new though and there were very few existing papers to build on. My main work was therefore to develop the methodology. That means the image acquisition, image analysis and how to interpret the results.

How do you do these investigations?

We have a miniature PV plant at NMBU which consists of a couple of modules. I bring my camera, a laptop and power supply, mount the camera in front of the modules and start taking image series. This is a bit more complicated than it sounds. At first, we learnt that out camera wasn't good enough. To obtain good enough data quality, we had to go away from hyperspectral cameras and rather use single-channel near-infrared cameras with a band-pass filter for the luminescence we are looking for at about 1150 nm. The hyperspectral cameras were also very heavy. We also had to wait for stable good weather as we were dependent on sufficiently stable solar irradiation. Then comes the data analysis. We are looking for quite small variations in noisy and varying environment. At the very end of my PhD, we also involved two colleagues in image analysis, which improved the results further.

What are your most exciting results?

That we managed to record images, analyse them and successfully detect faults without having to connect anything to the module itself. We discovered that the string inverter behaved in a particular way which resulted in a very useful pattern in the luminescence. We were able to use this pattern to single out the silicon luminescence over the background solar reflection and other noise. This pattern made the luminescence signal more than sufficient to detect the faults we were looking for.

Do you see any benefits from working in the FME SUSOLTECH?

To be honest, I probably had a bit too high expectations as to how efficiently results would flow to the industry in such a centre. I was expecting the industry partners in FME SUSOLTECH to pick up these results. I got better contact with for example IFE and the University in Agder through the WP4 meetings. In fact, it was during a meeting in FME SUSOLTECH in 2020 that the idea with the string inverter pattern came up. I was presenting my results of imaging while actively controlling the string inverter, and someone asked if we had checked if the inverter was doing something during normal operations that we could rely on instead. The point is to vary the luminescence signal from the cell so that we can differentiate it from the relatively constant solar reflection. The next day I talked to my groups engineer and we decided to look into this. That resulted in us finding that the IV curve sweep that the inverter is doing regularly during normal operations can be used and is sufficient for our image analysis!

How do you think this field is in 5 years time?

This depends on whether or not this can be of economic benefit for the industry. I'm sure some devoted academics will continue to progress this field regardless. It is still the beginning of this field and a lot of new developments lie ahead, like combinations with drones. But for the PV plant operators, it all depends on whether it makes economic sense and that the gains in up-time and reduced maintenance costs outweighs the cost of monitoring by the imaging technique we have developed.

Photo: Jon Arne Wilhelmsen

Interview with a center colleague: Dr. Rania Hendawi

In 2022, Rania joined FME SUSOLTECH as a postdoc at NTNU in WP2. Her primary focus is addressing structure loss through developing non-destructive testing for defect detection. This is in collaboration with the industry to increase production rates of mono-crystalline silicon ingots, including companies like NorSun, Norwegian Crystals and PVA Tepla. Prior to this, her background is in industrial and chemical engineering, with a specialization in high-temperature processes. She has extensive experience working with metals and ceramics, particularly in areas such as coatings, solidification, thermodynamics, and crystallization. During her PhD at NTNU, she collaborated with industry partners on improving silicon crystallization techniques for high-quality solar cells in the CruGenSi project. This research involved developing reusable crucibles and novel coatings to minimize melt contamination effectively.

What has been your main research field during your time in the FME SUSOLTECH?

My objective is to tackle one of the most challenging issues in the monocrystalline Si industry: structure loss. This phenomenon, initiated by dislocation generation leading multi-crystalline growth, causes significant production problems. I characterize monocrystalline Si ingots afflicted by structure loss to understand its root causes. The aim is to enhance production yield and reduce costs. Currently, 20-30% of grown ingots are remelted due to this problem. However, the high-stress levels in these ingots make cutting and characterization exceptionally difficult. To address this, we have developed a non-destructive examination method to categorize ingots and pinpoint the causes of structure loss. By doing so, we aim to provide the industry with valuable insights to optimize processes to reduce structure loss cases based on our findings.

How do you do these investigations?

My investigations were conducted on industrial ingots grown by Czochralski pullers, with data collected on-site through visits to our industry partners. During these visits, I captured hundreds of images for analysis. In addition, we selected some intriguing ingots to bring back to our NTNU labs for further characterization. From these images and log data for the ingots, we produce datasets that we analyse. Based on these analyses, we establish likely causes of the structure loss event. Maybe equally important, we rule out many of the long list of possible causes as unlikely to be important. We then present and discuss our results in regular meetings with our research and industry partners where they also provide valuable feedback and insights into our findings.

What are your most exciting results?

When I first started taking these images, I saw that it was like taking pictures of a mirror. I was worried I wouldn't be able to see anything! But now we have managed to find several interesting features on the Si ingots. These features serve as clues to the root causes of failure and offer insights into each ingot's thermal history. Interestingly, our investigation highlights that more than 60% of failed ingots can be traced back to two primary factors: temperature control and melt contamination. These results and our understand of the relations between these fingerprint features and their root causes may even be further developed into in-line monitoring in the puller!

Do you see any benefits from working in the FME SUSOLTECH?

Working at FME SUSOLTECH has given me a deep understanding of the entire supply chain of silicon for solar cell applications. From the production of silicon to the installation of PV modules and even the recycling process at the end of their lifespan, I have gained insight into every step of the journey. It has been eye-opening to see how everything connects and to learn about the sustainable practices involved in each stage. I have also had the opportunity to network with experts from both industry and research fields. This has provided me with valuable insights and connections that have enhanced my understanding and experience in the sustainable technology sector.

How do you think this field is in 5 years time?

This research has opened new possibilities to enhance silicon production for solar applications. Take for instance the surface examination we conducted, yielding valuable insights. We can now further improve these insights by using machine learning, and training models based on our findings to automatically categorize ingots into major groups. Additionally, these findings can enable real-time detection of special features during crystal growth, allowing us to predict and prevent structural losses before they occur. Finally, this research allows us to move towards fully automated crystal growth processes and to optimize existing methods for higher production yield. However, to use machine learning on this topic, we need a lot more images and data. It is crucial to have access to a large amount of ingot images and data logs!

Photo: Jon Arne Wilhelmsen

Appendix 1

Personnel working in the Center

Key researchers working in the Center

Name	Institution	Main research area
Arve Holt	IFE	Member of the Executive Board
Bent Thomassen	IFE	High efficiency silicon solar cells and wafers
Chang Chuan You	IFE	High efficiency silicon solar cells and wafers
Christoph Seiffert	IFE	End use and impact
Dag Lindholm	IFE	End use and impact
Helge Malmbekk	IFE	End use and impact
Erik Stensrud Marstein	IFE	Centre Director
Gaute Otnes	IFE	End use and impact
Heine Riise	IFE	Work package manager, End use and impact
Iver Blix Loennecken	IFE	End use and impact
Jan Thomas Haraldsen	IFE	End use and impact
Josefine Selj	IFE	End use and impact
Junjie Zhu	IFE	High efficiency silicon solar cells and wafers/ End just and impact
Per-Anders Hansen	IFE	High performance silicon ingots and wafers/ Deputy Center Coordinator
Rune Søndenå	IFE	High performance silicon ingots and wafers
Sigurd Brattheim	IFE	End use and impact
Torunn Kjeldstad	IFE	Deputy Chairman
Magnus Moe Nygård	IFE	End use and impact
Mari Benedikte Øgaard	IFE	End use and impact
Marie Syre Wiig	IFE	End use and impact
Marija Vukovic	IFE	End use and impact
Vilde Stueland Nysted	IFE	End Use and impact
Ørnulf Nordseth	IFE	High efficiency silicon solar cells and Wafers
Alexander Ulyashin	SINTEF	Kerfless-Si
Alfredo Sanchez Garcia	SINTEF	Solidification of Si, End use and impact
Arne Røyset	SINTEF	BIPV
Bendik Sægrov-Sorte	SINTEF	End use
Birgit Ryningen	SINTEF	Solidification of Si
Birgitte Karlsen	SINTEF	Silicon production by metallurgical processes
Eivind Johannes Øvrelid	SINTEF	Solidification of Si
Gaute Stokkan	SINTEF	Multicrystalline Si & End Use
Irene Bragstad	SINTEF	Solidification of Si

Ingeborg Kaus	SINTEF	Research manager
Kai Tang	SINTEF	Si production by metallurgical processes
Mari Juel	SINTEF	WP2 Manager
Marit Synnøve S. Stange	SINTEF	Kerfless Si
Mina Elise Holter	SINTEF	End use
Pål Tetlie	SINTEF	End use
Rudie Spooren	SINTEF	Member of the Executive Board
Runar Dahl-Hansen	SINTEF	Kerfless Si
Stefan Andersson	SINTEF	Si production by metallurgical processes
Tor Olav Løveng Sunde	SINTEF	Kerfless Si
Tore Kolås	SINTEF	BIPV
Yijiang Xu	SINTEF	Solidification of Si
Arnkell Jonas Petersen	NMBU	Agri modeling
Espen Olsen	NMBU	Silicon materials science
Ingunn Burud	NMBU	Image analysis
Iver Frimannslund	NMBU	Impact of snow on PV plants
Fredrik Arnesen Stulen	NMBU	Thin film solar cells
Andreas Svarstad Flø	NMBU	Hyperspectral imaging
Barbara Matusiak	NTNU	BIPV
Gabriella Tranell	NTNU	Solar silicon production by metallurgical processes
Jafar Safarian	NTNU	Work package manager: Sustainable silicon production
Ingrid Hallsteinsen	NTNU	Functional materials and chemistry
Marisa Di Sabatino	NTNU	Silicon crystallization and defects
Mari-Ann Einarsrud	NTNU	Functional materials and chemistry
Randi Holmestad	NTNU	Transmission electron microscopy
Morten Kildemo	NTNU	Nanophotonics and polarimetry
Turid Reenaas	NTNU	Intermediate band cells
Anne Gerd Imenes	UiA	End use and Impact
Rune Strandberg	UiA	End use and Impact
Andrej Kuznetsov	UiO	Wafer texturing
Eduard Monakhov	UiO	Oxide-based tandem solar cells
Kristin Bergum	UiO	Work package manager: High efficiency silicon solar cells and wafers
Ola Nilsen	UiO	Photon conversion
Philip Michael Weiser	UiO	Light element impurities in Si

Postdoctoral researchers with financial support from the Centre budget

Name	Nationality	Period	Sex M/F	Topic
Rania Hendawi	Jordan	22'01-23'12	F	Structure loss in Cz-Si

PhD students with financial support from the Centre budget

Name	Nationality	Period	Sex M/F	Topic
Azam Rasouli	Iranian	19'09-22'08**	F	Silicon production by
Gabriela Warder	Polish	20'11-24'10	F	Quartz crucibles for Czochralski silicon production
Ivar Loland Råheim	Norsk	21´09-25´09	M	Spectral imaging of solar cell materials
Marija Vukovic	Croatian	18'08-22'05**	F	Spectral imaging of degradation in solar panels
Nicole Assmann	German	21'09-25'09	F	FT-IR of hydrogen in Silicon
Vegard Rønning	Norwegian	19'05-23'10	M	Photon conversion
Tinotenda Mubaiwa	Zimbabwe	22'08-25'08	M	Si-kerf recycling
Erlend Hustad Honningdalsnes	Norwegian	22'12-25'11	M	Sustainable PV Parks

PhD students working on projects in the Centre with financial support from other sources

Name	Founding	Nationality	Period	Sex M/F	Topic
Oscar Kwame Segbefia	UiA	Ghana	19´05-22´06**	M	Solar Cell Degradation: defect analysis and mitigation schemes

*Defence of PhD thesis in 2023**
*Defence of PhD thesis in 2024 ***

Master students

Name	Sex M/F	Topic	Supervisor
Adrian Bjørge Ulven	M	Analysis of spectral irradiance variations and their impact on performance of different photovoltaic modules	Anne Gerd Imenes
Amalie Robsahm	F	Simulation of a vertical bifacial PV system compared to measured values	Espen Olsen, Heine Nygard Riise
Camilla T.-T. Truong	F	p-type emitters in tandem solar cells	Kristin Bergum, Eduard Monakhov, Kjetil Karlsen
Erik Gaupseth	M	Characterization of Cr and N doped TiO2	Turid Reenaas, Randi Holmestad
Harry Mahli	M	Analysis of an Agrivoltaic System at	Marisa Di Sabatino Skjetlein High School, Norway
Jacob Wilder Ng	M	Characterization of Cr and N co-doped TiO2	Turid Reenaas
Jan Harald Aasen	M	Fabricating tandem solar cells	Kristin Bergum, Kjetil Karlsen, Vegard S. Olsen
Madelen Flesland	F	AgriPV i Ås – en mjodellbasert simulering av energiproduksjon og plantevekst	Espen Olsen Erlend Honning- dalsnes
Marcus G. Michaelsen	M	Optical and structural characterization of doped and undoped TiO2 thin films, using PL and XRD	Turid Reenaas, Hogne Lysne
Martin Krebs-Kristiansen	M	Performance analysis of PV power plants across Norway	Anne Gerd Imenes
Rasmus Hoholm	M	Simulations of optoelectronic properties of TiO2	Jon-Andreas Støvneng, Morten Kildemo, Turid Reenaas
Sarah Nyeki	F	Characterization of optoelectronic properties of doped and undoped TiO2	Turid Reenaas, Morten Kildemo
Mirabai Hillestad	F	Diagnosis of Bifacial PV Modules Using Photoluminescence Imaging from the Rear in Direct and Diffuse Irradiance	Ingunn Burud
Andreas Ranje	M	Autonom landbruksrobot i en solcelledrevet jordbærpolytunnel med batterilagring	Espen Olsen
Mari Valle Kjelby	F	A study of correlation between photo-luminescence and IV-curves in solar modules	Espen Olsen
Mathea Salmi Marjavara	F	Visualization and quantification of PID in solar modules using PL imaging in daylight	Espen Olsen
Vilma Helena Erika Kristiansson	F	Temperature-dependent carrier lifetime measurements on silicon wafers and bricks	Marisa Di Sabatino Alfredo S. Garcia

Publication list – 2023 FME SUSOLTECH

The activities have resulted in the following presentation in mass media:

1. Hvordan kan solcellene bli mer effektive? Øystein Rygg Haanæs and Kristin Bergum, Energi og Klima, https://www.energiogklima.no/to-grader/ekspertintervju/hvordan-solcellene-bli-mer-effektive
2. Marisa di Sabatino explains the benefits of solar panels, Marisa Di Sabatino, Nyans | Solar — Marisa di Sabatino explains the benefits of solar panels - YouTube, Nyans Podcast
3. #51 - Omelett med slegge og q-tips, Einsteins fartsgrense, og Andreas ville veid mer om han ble født i Oslo, Per-Anders Hansen, Jøss⁉: #51 - Omelett med slegge og q-tips, Einsteins fartsgrense, og Andreas ville veid mer om han ble født i Oslo on Apple Podcasts, Jøss! Podcast
4. Soldeling på Skjetlein, Gaute Stokkan, NRK, Kveldsnytt, Kveldsnytt – 23. juni – NRK TV
5. Solkraft, Energipodden – Jakten på den gode energi, Erik Stensrud Marstein, Podcast 27. mars 2023
6. Har funne løysinga på solceller i snø, Erik Stensrud Marstein, NrK Nordland, 2. januar 2023
7. 2022 ble et rekordår for norsk solenergi, Erik Stensrud Marstein, TU.no, 17. januar 2023
8. Kan bli solkraftrevolusjon i Norge, Erik Stensrud Marstein, NrK Nyhetsmorgen, 3.februar 2023
9. Vil 33-doble solkraft i Norge på syv år, Erik Stensrud Marstein, NrK.no, 3.februar 2023
10. Solcellepaneler som bygningsmateriale, Erik Stensrud Marstein, Glass og Fasade, No. 1/2023
11. Mange år med ventetid for å bygge solkraft, Erik Stensrud Marstein, NrK.no, 1. mars 2023
12. Kan øke produksjonen 60 prosent på samme areal, Erik Stensrud Marstein, Europower.no, 18. mars 2023
13. Gi en premie for CO2 dokumentasjon for solceller, Erik Stensrud Marstein, EnergiAktuelt.no, 31. mars 2023
14. For å klare 8-10 TWh solkraft i 2030 må barrierer fjernes, Erik Stensrud Marstein, EnergiAktuelt.no, 3. mai 2023
15. Kraftproduksjon langs vei og jernbane, Erik Stensrud Marstein, NrK Nyhetsmorgen, 5. mai 2023
16. 7000 fotballbanar med solkraft skapar bråk, Erik Stensrud Marstein, NrK Vestland, 14. mai 2023
17. Global solkraftrekord i fjor, Erik Stensrud Marstein, TU.no, 24. mai 2023
18. IEA: Det investeres nå mer i solenergi enn i oljeutvinning, Erik Stensrud Marstein, TU.no, 25. mai 2023
19. Smakebiter fra forskningen, Erik Stensrud Marstein, Glass og Fasade, No 2/2023
20. Nytt samarbeid kan gi 500 MW før 2030, Erik Stensrud Marstein, Montel.no, 14. august 2023
21. Det er krise for bransjen, Erik Stensrud Marstein, TU.no 26. august 2023
22. Forsker: Det er veldig tøffe tak for norske produsenter for tiden, Erik Stensrud Marstein, TU.no, 30. september 2023
23. Bransjekommentar, Erik Stensrud Marstein, Byggfakta Nyheter, 30. september 2023
24. Solindustrien blør på tross av nytt veikart fra regjeringen, Erik Stensrud Marstein, EnergiAktuelt.no, 2. oktober 2023
25. Klimautvalget går ikke rundt grøten, Øyvind Zambrano Lie, https://energiteknikk.net/2023/10/klimautvalget-gar-ikke-rundt-groten/ 27. oktober 2023
26. Bråstopp for solceller til eneboliger: – I privatmarkedet er det helt stopp, Trine Kopstad Berntsen, Bråstopp for solceller til eneboliger: – I privatmarkedet er det helt stopp - Tu.no 30. oktober 2023
27. Ber NVE vise retning i klimapolitikken, Trine Kopstad Berntsen, Ber NVE vise retning i klimapolitikken - Energiteknikk, 25. oktober 2023
28. Det er ikke bare Norge som sliter med ustabile nett på grunn av solcelleanlegg. Likevel økes satsingen på solkraft i andre land, Trine Kopstad Berntsen, For norske nettselskap er solceller et problem – slik løser de det i andre land - Tu.no
29. Selvfølgelig må fornybarnæringen si fra om dårlig energipolitikk, Trine Kopstad Berntsen, – Selvfølgelig må fornybarnæringen si fra om dårlig energipolitikk | Europower, 15. juni 2023. Debattinnlegg
30. No skal nye, statlege bygg ha solkraft, Trine Kopstad Berntsen, No skal nye, statlege bygg ha solkraft (mre.no), 13. juni 2023
31. Varsel om 50 solparkar skaper bråk, Trine Kopstad Berentsen, https://www.nrk.no/vestland/varsel-om-50-solparkar-skaper-brak-1.16401768, 14. mai 2023.

32. Ny regel: Borettslag og sameier slipper avgifter på egenprodusert strøm, Trine Kopstad Berntsen, Ny regel: Borettslag og sameier slipper avgifter på egenprodusert strøm - Tu.no, 13. mai 2023
33. For å klare 8-10 TWh solkraft i 2030 må barrierer fjernes, Trine Kopstad Berntsen, - For å klare 8-10 TWh solkraft i 2030 må barrierer fjernes - EnergiAktuelt AS, 2. mai 2023
34. Mener kraftbehov kan gi taktskifte for solenergi, Trine Kopstad Berntsen, Mener kraftbehov kan gi taktskifte for solenergi – E24, 26. april 2023
35. Brenner for kortreist solkraft til Tesla-lading – stoppes av regelverk, Trine Kopstad Berntsen, Brenner for kortreist solkraft til Tesla-lading – stoppes av regelverk (+) | DN, 12. mars 2023
36. Vil 33-doble solkraft i Norge på syv år: – Realistisk, Trine Kopstad Berntsen, Vil 33-doble solkraft i Norge på syv år: – Realistisk – NRK – Klima, 3. februar 2023
37. Dette er krise for bransjen, Maja Busch Sevaldsen, – Dette er krise for bransjen - Tu.no, 26. august 2023
38. Norsk solindustri mot stupet utan meir statleg støtte, Maja Busch Sevaldsen, Norsk solindustri mot stupet utan meir statleg støtte – NRK Vestland, 26. januar 2023

The activities have resulted in report, lecture, articles, presentations in meetings/conferences for public sector, business, and industry:

1. Forskning og teknologiutvikling i solcelleverden, Per-Anders Hansen, NTVA / Polyteknisk forening, 23. feb 2023, Oral presentation.
2. Reducing Time and Costs of FT-IR Studies of Hydrogen Species in Si Wafers and Solar Cell Structures, Nicole Aßmann, Rune Søndernå, Benjamin Hammann, Eduard Monakhov, NSCC 2023, Mai 2023. Son Norway, Oral presentation
3. Surface Examination of Structurel Loss in N-type Czochralski Silicon Ingots, Rania Hendawi, Eivind, Øvrelid, Gaute Stokkan, Marisa Di Sabationo, NSCC 2023, Mai 2023. Son Norway, Oral presentation
4. Investigation of Hydroxyl (OH) Groups Uniformity in Fused Quartz Crucibles Used for Czochralski Silicon Production, Gabriela Kazimiera Warden, Petra Ebbinghaus, Martin Rabe, Mari Juel, Bartłomiej Adam Gaweł, Andreas Erbe, Marisa Di Sabatino, NSCC 2023, Mai 2023. Son Norway, Oral presentation
5. Investigation of process parameters on the distribution of the specific resitivity in Ga-doped Cz-crystal, Frank Mosel, NSCC 2023, Mai 2023. Son Norway, Oral presentation
6. Marhine Learning Methods for Structure Loss Classification in Czochralski Silicon Ingots, Alfredo Sanchez Garcia, Rania Hendawi, NSCC 2023, Mai 2023. Son Norway, Oral presentation
7. Plasma enehanced ALD of thin passivation layers for silicon solar cells, Per-Anders Hansen, NSCC 2023, Mai 2023. Son Norway, Oral presentation
8. Recent progress in Si films deposited by high-rate electron beam deposition, Marit Stange, Tor Olav Sunde, Runar Dahl-Hansen, Alexander Ulyashin, Alexander Azarov, NSCC 2023, Mai 2023. Son Norway, Poster presentation
9. Method Development for Temperature Dependent Lifetime Spectroscopy, Vilma Kristiansson, Alfredo Sanchez Garcia, Marisa Di Sabatino, NSCC 2023, Mai 2023. Son Norway, Poster presentation
10. Synthesis of Mg2Si and its use for silane production, Azam Rasouli, Annual meeting FME Susoltech 2023, 24th May 2023, Son Norway
11. What do we know about quartz crucibles now? A summary of my PhD-project, Gabriela Kazimiera Warden, Annual meeting FME Susoltech 2023, 24th May 2023, Son Norway
12. Structure loss in Cz-Si, Rania Hendawi, Annual meeting FME Susoltech 2023, 24th May 2023, Son Norway
13. Optimizing electrical properties of ZnON for Si-tandems, Kjetil Karlsen, Annual meeting FME Susoltech 2023, 24th May 2023, Son Norway
14. Colored PV modules based on optical interference coatings, Tore Kolås, Annual meeting FME Susoltech 2023, 24th May 2023, Son Norway
15. A comparative Study of Marchine Learning Techniques for Bifacial Photovoltaic Power Forcasting, Alfredo Sanchez Garcia, Mina Elise Holter, NSCC 2023, Mai 2023. Son Norway, Poster presentation
16. Predicting and optimising the performance of coloured solar cell modules based on interference coatings, Tore Kolås, Arne Røyset, Ørnulf Nordseth, Chang Chuan You, NSCC 2023, Mai 2023. Son Norway
17. Coloured PV modules based on optical interference coatings, Tore Kolås, NSCC 2023, Mai 2023. Son Norway

18. Appearance and efficiency in building integrated photovoltaics, Arne Røyset, Tore Kolås, Presentation at NETApp Workshop on Material Appearance, Gjøvik, Norway, November 22nd, 2023
19. Combinatorial pulsed laser deposition, Hogne Lysne, Thomas Brakstad and Turid Reenaas, NSCC 2023, Mai 2023. Son Norway
20. Welcome and Status, Erik S. Marstein, NSCC 2023, 22. Mai 2023. Son
21. Characterization and leaching purification of industrial Si-kef, Tinotenda Mubaiwa, NSCC 2023, 22. Mai 2023. Son
22. Investigation of silane gas production through Mg2Si reaction with HCl acid solution, Azam Rasouli, NSCC 2023, 22. Mai 2023. Son
23. Numerical device simulations of ZnOxNy for Si-based tandem solar cells using Silvaco Atlas, Ingvild Bergsbak, NSCC 2023, 22. Mai 2023. Son
24. The effect of annealing on ZnON for solar cell applications, Kjetil Karlsen, NSCC 2023, 22. Mai 2023. Son
25. Analysis of the theoretical PV power potential on buildings in Norway, Stine Fleischer Myhre, NSCC 2023, 23. Mai 2023. Son
26. Extraction of photoluminescence with Pearson correlation coefficient from images of field-installed photovoltaic modules, Marija Vukovic, NSCC 2023, 23. Mai 2023. Son
27. Assessing the potential for PV snow mitigations to increase PV deployment on existing building roofs, Iver Frimannslund, NSCC 2023, 23. Mai 2023. Son
28. The Effect of PV Panels on Microclimatic Growth Conditions and Crop Yield in Agrivoltaic Systems, Erlend Hustad Honningdalsnes, NSCC 2023, 23. Mai 2023. Son
29. Photoluminescence imaging from the rear of bifacial solar modules in both diffuse and direct sunlight, Mirabai Hillestad, Marija Vukovic, Marko Jakovljevic, Ingunn Burud, Espen Olsen, NSCC 2023, 22. Mai 2023. Son, Poster
30. Analysis of which factors make PID more visible in ΔPL images and the trends between them, Mathea Salmi Marjavara, Marija Vuković, Ingunn Burud, Gisele A. dos Reis Benatto, Rodrigo Del Prado Santamaría, Sergiu V. Spataru and Espen Olsen, NSCC 2023, 22. Mai 2023. Son, Poster
31. Method Development for Temperature Dependent Lifetime Spectroscopy, Vilma Kristiansson, Alfredo Sanchez Garcia, Marisa Di Sabatino (NTNU/SINTEF), NSCC 2023, 22. Mai 2023. Son, Poster
32. Energikrisen i Europa og det norske kraftmarkedet, Tomasgard, M. Belsnes, M. Bjørndal, A. Elverhøi, K. Espegren, T. Fæhn, S. Jaehnert, G. Kjølle, M. Korpås, E.S. Marstein, P. Røkke, N.H. Sandberg, J.O.G. Tande, T.K. Thiis, T. Winther og T.H.J. Inderberg, Asgeir Tomasgard (NTNU, redaktør) energikrisen-i-europa-og-det-norske-kraftmarkedet.pdf (uio.no) Januar 2023
33. Solkraft i Norge - en kort innføring i den norske solbransjen, Erik Stensrud Marstein, Justervesenet, Gardemoen 5. januar 2023
34. Nye utviklinger i solkraftindustrien, Solceller på Kommunale tak (NVE), Oslo/nett, Erik Stensrud Marstein, 17. februar 2023
35. Hva er framtidsmulighetene med solkraft på Vestlandet, Solkonferanse, Stord/nett, Erik Stensrud Marstein, 21. mars 2023
36. Solkraft – en oppdatering, Faglunsj, Olje- og Energidepartementet, Erik Stensrud Marstein, 29. mars 2023.
37. Solkraft, Innlandets Ingeniørkonferanse, Erik Stensrud Marstein NITO, Gjøvik, 21. april 2023
38. Muligheter og utfordringer for utbygging av solkraftverk i norske bygninger, Erik Stensrud Marstein, Tekna lunsjmøte 27. april 2023
39. Welcome and introduction, Erik Stensrud Marstein, FME SUSOLTECH Annual Meeting, Son 24. Mai 2023
40. The status of the PV industry, Erik Stensrud Marstein, Solenergiklyngens strategisamling, 12. oktober 2023
41. Mot et nytt veikart for den norske solbransjen, Erik Stensrud Marstein, Bygg Reis Deg, Lillestrøm, 18. oktober 2023
42. Bygningsintegrerte solceller på Bygg reis deg, Erik Stensrud Marstein, NTL info, 18. oktober 2023

The activities have resulted in the following publications in refereed journals:

1. Understanding the impact of the cooling ramp of the fast-firing process on light- and elevated-temperature-induced degradation, Benjamin Hammann, Nicole Aßmann, Jonas Schön, Wolfram Kwapil, Florian Schindler, Sebastian Roder, Eduard V. Monakhov, Martin C. Schubert, Solar Energy Materials and Solar Cells, p 112462, Volume 259/2023, ISSN 0927-0248. 259, Elsevier, Redaktør: Ivan Gordon, doi: 10.1016/j.solmat.2023.112462.
2. Controlling the hydrogen concentration in boron- and gallium-doped silicon wafers, Rune Søndenå, Philip M. Weiser, Frank Mosel, Nicole Aßmann, Per-Anders Hansen, Edouard Monakhov, AIP Conference Proceedings, p 110008-1–110008-6., Volume 2826/2023, ISSN 0094-243X. 2826(1), AIP Publishing, doi: 10.1063/5.0141155

3. The Impact of Different Hydrogen Configurations on Light- and Elevated-TemperatureInduced Degradation, Benjamin Hammann, Nicole Assmann, Philip M. Weiser, Wolfram Kwapil, Tim Niewelt , Florian Schindler, Rune Søndenå, Eduard V. Monakhov, and Martin C. Schubert, IEEE Journal of Photovoltaics, p 224-235, Vol. 13, No. 2, 2023, IEEE, doi: 10.1109/JPHOTOV.2023.3236185.
4. Recent developments on manufacturing and characterization of fused quartz crucibles for monocrystalline silicon for photovoltaic applications, Gabriela Kazimiera Warden, Mari Juel, Bartłomiej Adam Gaweł, Marisa Di Sabatino, Open Ceramics, p 100321, Vol 13, 2023, e-ISSN 2666-5395, Elsevier, Redaktør: Paolo Colombo. https://doi.org/10.1016/j.oceram.2022.100321
5. Light and elevated temperature induced degradation in gallium- and boron-doped HPMC-Si wafers by hyperspectral imaging, T. Mehl, O.G. Berge, I. Burud, R. Søndenå, and E. Olsen, AIP Conference Proceedings, p 110009, 2826 (2023), Online ISSN 1551-7616, https://doi.org/10.1063/5.0148403
6. Universal radiation tolerant semiconductor, A. Azarov, J. García Fernández, J. Zhao, F. Djurabekova, H. He, R. He, Ø. Prytz, L. Vines, U. Bektas, P. Chekhonin, N. Klingner, G. Hlawacek, and A. Kuznetsov, Nature Communications 14, 4855 (2023)
7. High mobility of intrinsic defects in a-Ga2O3, A. Azarov, J.-H. Park, D.-W. Jeon, and A. Kuznetsov, Applied Physics Letters 122, 182104 (2023)
8. Thermal versus radiation-assisted defect annealing in b-Ga2O3, A. Azarov, V. Venkatachalapathy, I.-H. Lee, and A. Kuznetsov, Journal of Vacuum Science and Technology A 41, 023101 (2023)
9. Tuning defect-related optical bands by channeling implants in semiconductors, A. Azarov, A. Galeckas, F.C.-C. Ling, and A. Kuznetsov, Journal of Physics D: Applied Physics 56, 035103 (2023)
10. Optical interference coatings for coloured building integrated photovoltaic: modules: Predicting and optimising visual properties and efficiency, Tore Kolås, Arne Røyset, Ørnulf Nordseth, Chang Chuan You, Energy and Buildings, Volume 298, November 1st, 2023,
11. Characteristics of ZnON films and heterojunction diodes with varying O:N ratios, Kjetil Karlsen Saxegaard, Lasse Vines, Eduard Monakhov, and Kristin Bergum, Thin Solid Films, p 139968, Volume 782, 2023, ISSN 0040-6090
12. Extraction of photoluminescence with Pearson correlation coefficient from images of field-installed photovoltaic modules, Vukovic, M., Hillestad, M., Jakovljevic, M., Flø, A., Olsen, E., Burud, I, J. Appl. Phys, p 214901, 133/2023
13. Photoluminescence imaging of field-installed photovoltaic modules in diffuse irradiance, Vukovic, M., Liland, K.H., Indahl, U., Jakovljevic, M., Flø, A., Olsen, E., Burud, I., J. Appl. Phys, p 74903, 134/2023
14. Using transfer coefficients to model series-connected multi-junction solar cells with radiative coupling, Strandberg R., Applied Physics Letters, p 253902, 122/25/2023
15. The Recombination Parameter $\gamma $: Modeling and Comments, Garcia, A. S., Kristensen, S. T., & Strandberg, R., IEEE Journal of Photovoltaics, p 516, 13|4|2023
16. Temperature profiles of field-aged photovoltaic modules affected by optical degradation, Segbefia, O. K., Heliyon, p e19566, 9|9|2023
17. Moisture induced degradation in field-aged multicrystalline silicon photovoltaic modules, Segbefia, O. K., Akhtar, N., & Sætre, T. O., Solar Energy Materials and Solar Cells, p 112407, 258/2023
18. Influence of Temperature Coefficient and Sensor Choice on PV System Performance, M. Mussard, H. N. Riise, M. S. Wiig, S. Rønneberg and S. E. Foss, IEEE Journal of Photovoltaics, p 920, 13/6/2023
19. Magnesiothermic Reduction of Silica: A Machine Learning Study, Tang, Kai; Rasouli, Azam; Safarian, Jafar; Ma, Xiang; Tranell, Maria Gabriella, Materials, Academic article, 2023
20. Toward the recovery of solar silicon from end-of-life PVs by vacuum refining, Hoseinpur Kermani, Arman; Tang, Kai; Ulyashin, Alexander; Palitzch, Wolfram; Safarian, Jafar, Solar Energy Materials and Solar Cells, Academic article, 2023
21. Defects and fault modes of field-aged photovoltaic modules in the Nordics, Segbefia, O. K., Akhtar, N., & Saetre, T. O., Energy Reports, p 3104, 9|2023

The activities have resulted in the following published presentations from international scientific conferences:

1. Reducing Time and Costs of FT-IR Studies of Hydrogen Species in Si Wafers and Solar Cell Structures, N. Aßmann, R. Søndernå, B. Hammann, E. Monakhov, Silicon PV 23, Aprli 2023, Delft, Nederlands, Oral presentation
2. THE EFFECT OF HYDROGEN ON BORON-OXYGEN-RELATED DEGRADATION AND REGENERATION IN CRYSTALLINE SILICON, Rune Søndenå, Philip M. Weiser, Eduard Monakhov, and Halvard Haug, EU PVSEC 2023, September 2023, Lisbon, Portugal, Oral presentation
3. Surface Examination of N-type Cz-Si Ingots, Rania Hendawi, Eivind, Øvrelid, Gaute Stokkan, Marisa Di Sabatino, Silicon PV 23, Aprli 2023, Delft, Nederlands, Oral presentation.

4. Root Causes Analysis of Structure Loss during Cz-Si Growth, Rania Hendawi, Eivind, Øvrelid, Gaute Stokkan, Marisa Di Sabatino, International Conference on Crystal Growth and Epitaxy (ICCGE20), 30 July-4 August, Naples, Italy, Poster.
5. Investigation of Hydroxyl (OH) Groups Uniformity in Fused Quartz Crucibles Used for Czochralski Silicon Productuion, Gabriela Kazimiera Warden, Petra Ebbinghaus, Martin Rabe, Mari Juel, Bartłomiej Adam Gaweł, Andreas Erbe, Marisa Di Sabatino, EU PVSEC 2023, September 2023, Lisbon, Portugal, Poster.
6. Crystallization processes for photovoltaic silicon ingots: status and perspectives, Marisa Di Sabatino, Rania Hendawi, International Conference on Crystal Growth and Epitaxy (ICCGE20), 30 July-4 August, Naples, Italy; Poster
7. Radiation disorder induced ordering, A. Azarov, CMD30+FisMat2023 joint conference, Milan, Sep. 04-08,2023.
8. Defect migration energies in Ga_2O_3 polymorphs measured by variations of temperature and flux under irradiation, A. Azarov, J.-H. Park, D.-W. Jeon, E. Monakhov, and A. Kuznetsov, ICDS 32, Delaware, Sep.10-15, 2023
9. Fabrication and characterization of optical interference coatings for colored building-integrated photovoltaic applications, Chang Chuan You, Nathan Roosloot, Junjie Zhu, and Ørnulf Nordseth, Poster, The 34th International Photovoltaic Science and Engineering Conference (PVSEC-34), Shenzhen, 6-10 November 2023.
10. Efficiency maps for tandem solar cells using high resolution spectral data, Strandberg, Rune; Imenes, Anne Gerd, 50th IEEE PVSC, San Juan; Puerto Rico, 11-16 June 2023,
11. Autonomous Optimization of Agrivoltaic Systems with Vertical Bifacial PV Panels and the Grass Crop Timothy, Honningdalsnes, E.H., Bonesmo, H., Marstein, E.S., Völler, S., Riise, H.N., 40th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal, 18.-22. Sep 2023
12. Characterization and Hydrometallurgical Treatment of Industrial Si-Kef, Tinotenda Mubaiwa, Tyke Naas and Jafar Safarian, EU PVSEC 2023, September 2023, Lisbon, Portugal, Poster

The activities have resulted in the following reports, lecture, presentation at technical meetings:

1. Dark Annealing-Induced Evolution of HB in Silicon: A Comparative Analysis with Resistivity and H2 Concentration, Nicole Aßmann, WP1/WP2 meeting FME Susoltech, 8th November 2023, Trondheim. Norway
2. Evaluation of different passivation shemes, Per-Anders Hansen, WP1/WP2 meeting FME Susoltech, 8th November 2023, Trondheim. Norway
3. On the uniformity (or lack of it) of fused quartz crucibles, Gabriela Kazimiera Warden, WP1/WP2 meeting FME Susoltech, 8th November 2023, Trondheim. Norway
4. Root Cause Analysis for Structure Loss in Cz-Si Growth, Rania Hendawi, WP1/WP2 meeting FME Susoltech, 8th November 2023, Trondheim. Norway
5. Advancing Classification of Structure Loss in Cz Ingots with Machine Learning, WP1/WP2 meeting FME Susoltech, Alfredo Sanchez Garcia, 8th November 2023, Trondheim. Norway

The activities have resulted in the following communication effort for relevant target group:

1. Bønder, produsenter og fiskere må få betalt for å produsere maten mer bærekraftig, Gaute Stokkan, Video, Forlag; Rethink Food, 10 filmer om bærekraftig matproduksjon - Rethink Food
2. Kan sola redde oss fra energikrisen? Anne Gerd Imenes, Lørdagsuniversitet, Arendal, 4 February 2023, arr: Universitetet i Agder
3. Kan sola redde oss fra energikrisen? Anne Gerd Imenes, Solcelledagen 2023, Kristiansand, 16 February 2023, arr: Trade Winds Solar
4. Kan sola redde oss fra energikrisen? Anne Gerd Imenes, Grimstad Rotary Club, Grimstad, 9 March 2023, arr: Grimstad Rotary club
5. Klimakrise og energikrise: Kan sola være løsningen? Anne Gerd Imenes, Klimaseminaret på Dahlske VGS, Grimstad, 7 March 2023, arr: Dahlske skole

6. Klimakrise og energikrise: Kan sola være løsningen? Anne Gerd Imenes, Årsmøte Besteforeldrenes Klimaaksjon, Kristiansand, 28 March 2023, arr: Besteforeldrenes Klimaaksjon
7. Agri-PV, Erlend Hustad Honningdalsnes, Store Norske Leksikon / https://snl.no/agri-PV
8. Soldeling i landbruket, Gaute Stokkan, Erlend Hustad Honningdalsnes m.fl., Skjetlein, 26 Oct 2023
9. Glass & Fasade, UTGITT AV GLASS OG FASADEFORENINGEN // NR 1-2023, Glass & Fasade nr. 1 – 2023 (glassogfasade.no)
10. Glass & Fasade, UTGITT AV GLASS OG FASADEFORENINGEN // NR 2-2023, Glass & Fasade nr. 2 – 2023 (glassogfasade.no)
11. Glass & Fasade, UTGITT AV GLASS OG FASADEFORENINGEN // NR 3-2023, digitalarkiv - Magasinet Glass & Fasade (glassogfasade.no)
12. Glass & Fasade, UTGITT AV GLASS OG FASADEFORENINGEN // NR 4-2023, digitalarkiv - Magasinet Glass & Fasade (glassogfasade.no)
13. Synergier mellom energiproduksjon og naturbevaring, Fagdag for bakkemonterte solkraftverk i regi av Solenergiklyngen, 1. juni 2023

Scientific/scholarly publications (monograps publications) - Master/PhD thesis:

1. Toward monitoring of photovoltaic power plants with photoluminescence imaging, Vukovic, M, PhD. Thesis, NMBU, Brage NMBU: Toward monitoring of photovoltaic power plants with photoluminescence imaging (unit.no)
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3. Glow Discharge Optical Emission Spectroscopy for Elemental Characterization of Doped TiO2 Thin Films made by Pulsed Laser Deposition, Ng, Jacob Wilder, Master thesis, NTNU 2023, no.ntnu_inspera_147161409_118475908.pdf
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Appendix 3

Statement of Accounts

(All figures in 1000 NOK)

Funding

Funding source Amount	Amount
The Research Council	13,704
The Host Institution, IFE	5,511
Research Partners*	6,768
Industry partners*	6,750
Public partners*	200
Total Founding	**32,933**

Costs

Cost element	Amount
The Host Institution, IFE	10,970
Research Partners	14,721
Industry partners	5,550
Public partners	200
Equipment	1,492
Total Costs	**32,933**

*Give names for each group of partners

Center partners

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