Exploration nanocoatings and energy transition

Invest-NL

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This publication comprises the non-exhaustive results of research on the role of nanocoatings within the energy transition The results are based on the insights of a selection of TNO experts. Please contact Marth Breure and Jonathan van Ham for any inquiries or additional information regarding this publication

TNO innovation for life

Project details

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1. Introduction to the project

TNO innovation for life

Purpose and scope of work

What where the goals, scope and limitations of this work?

01 Develop understanding of the field of nanocoating technologies

Identify relevant nanocoating technological developments within and outside Invest-NL's portfolio to enable the energy transition.

Invest-NL could invest in these technologies to accelerate market adoption

02 Provide an educational overview on different evolving nanocoating applications in the energy-transition

Obtaining nanocoating (production) related innovations by 5, one-on-one interviews and one communal workshop with seven experts.

03 Identify feasible, novel developments in manufacturing technologies for batteries, electrolysers, photovoltaics and fuel cells

The focus (scope) relies on technologies that enable the energy transition. Other technologies were omitted for the sake of scoping.

04 No experts outside of TNO were contacted

This creates a potential for bias as only the expertise of TNO and the specialties researched by TNO were included

Research question

"What are the most relevant nanocoating innovations within batteries, photovoltaics, electrolysers and fuel cells?"

A. What is the current role of nanocoatings in batteries, photovoltaics, electrolysers and fuel cells and what are the current production technologies?
B. What are the biggest gamechangers: the most promising nanocoating innovations (TRL4-8) that can accelerate the energy transition?
C. What are top of mind players in the market for the development of nanocoating technologies?

Management summary

This report aims to answer: What are the most relevant nanocoating innovations within batteries, photovoltaics, electrolysers and fuel cells?

The core result is the conclusion that currently there are no production and deposition methods comparable in impact, success and relevance to Spatial ALD. As far as the experts are aware, neither are there any production and deposition methods currently being developed that can compare. This is concluded based on desk research, 5 interviews with a selection of 5 TNO experts and a collective workshop with 7 TNO experts.

During the whole process 18 gamechangers were nominated in total and ranked by the experts. Due to the limited existence of production and deposition innovations we expanded the gamechangers to promising nanocoating related innovations. These 18 gamechangers or also called ‘promising nanocoating related innovations’, were ranked on the criteria of impact, time to market and chance of success. This resulted in a visualized top 10 of promising nanocoating related innovations, which can be found in the chapter conclusions.

With this top 10, this report provides an overview of new developments in batteries, photovoltaics, electrolysers and fuel cells that can be realized by the use of nanocoatings and indicates the potential of various nanocoating solutions while considering its production technique. Please see the next slide for an overview of the top 10 promising innovations with description.

Management summary

#	Topics	Description	Batteries	Elektro-lysers	Photo voltaics	Fuel cells
1	Spatial ALD deposition	Application of Spatial Atomic Layer Deposition (coating at atomic level) to apply nanocoating to objects; its cheaper due using to less material and better performance and creates closed surface coatings.	■	■	■	■
2	Reduce Iridium or platinum in electrolysers	Increase material utilization by Spatial ALD nanocoating to reduce PGM to save cost and optimization of the expensive material: reducing the use of Iridium or platinum in electrolysers to increase production..		■		■
3	Replacing or reducing CRM in battery cathodes	Replacing lithium cobalt oxide to nickel manganese aluminum or replace graphite with silicon in contemporary (Lithium ion graphite batteries) due to cost and availability, but the new components lead to batteries with lower lifetime. The solutions could be new additives in the liquid electrolytes to form a newly optimized artificial interface between these materials.	■			
4	Protective steel NC for hydrogen transportpipes	Nanocoating to prevent steel degradation when transporting hydrogen (e.g. long distance distribution pipelines). This would be wet chemical coatings (scalable and cost effective) based on polymer and ceramic fillers		■		■
5	Monolithic device	A combined device to be made with combination of deposition methods: gas barrier, PTL (porous transport substrate) and then the catalyst material (iridium nanocoating in PEM) and then the membrane. This could prevent crossover and conduct ions without energy loss and easier to recycle.	■	■	■	■
6	Liquid deposition of nanocoatings to glass for large areas (6m)	Using deposition techniques efficiently and homogeneous to large areas in e.g. advanced energy efficiënt windows.			■	
7	Single deposition method for Perovskite solar cells	To be developed: one technology or machine to combine the 6 different deposition nanocoating methods for cheaper solarcells			■	
8	Replace titanium in electrolysers and fuel cells	High quality nanocoating to protect less noble metal to save cost and optimization of the expensive material: eliminating the use of titanium in electrolysers to increase production.		■		■
9	Lithium ion graphite battery with silicon	Lithium ion graphite battery with silicon instead of graphite.	■			
10	Low temperature inorganic solid (electrolytes)	Novel multi-element materials made by wet chemical methods or PLD that conduct ions at low temperature, enabling solid-state batteries and solid oxide fuel cells for conductivity at roomtemperature which would make the process cheaper and easier.	■	■		

2. Introduction to nanocoatings

TNO innovation for life

Introduction to nanocoatings (1/3)

- Nanocoatings are structures of which the dimension is smaller than 100 nm (nano), and are applied on a surface (coating). They add a specific property to this surface that would otherwise not be accomplished. Either the layers that are built are thinner than 100 nm, or the particles in the coating that give it its special properties are smaller than 100 nm[1]. Functionalities to add to a product are for instance; stability, protection, self-cleaning or anti-corrosion.
- Innovation on nanocoatings can focus on three different areas:
  - **Materials** – using other type of materials with new or better functionalities or to reduce dependency on scarce materials
  - **Production technologies** – improving deposition techniques to apply high quality homogenous nanocoatings in a way to different sized surfaces with economies of scale
  - **Integration of technologies for industrial applications** – using the nanocoatings by integrating them within a product or devices for improving performance, new functionality or lowering cost
- Developments take place along these areas, but there are barriers to overcome when using nanocoatings besides the technique itself For instance, the perceived risk of nanocoatings due lack of knowledge and conservative sentiment in some industries. Also, the regulations or the lack of regulations on nanocoatings has an impact on investments and has to be taken in to account.

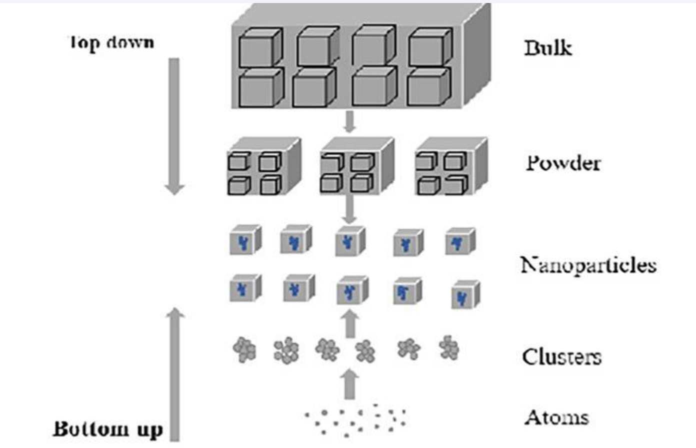
[1] source: (van Lente, H., & van Til, J. I., 2008)

Introduction to nanocoatings (2/3)

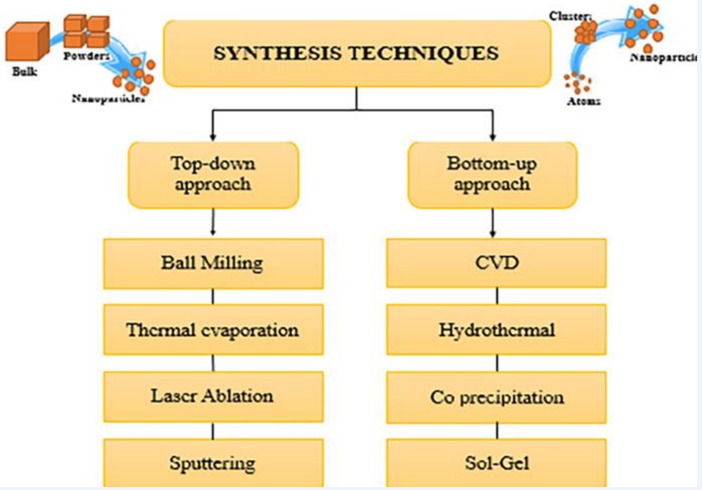
- Innovation is taking place incrementally to improve the state-of-the-art techniques and there are not many new techniques. At the moment, Spatial Atomic Layer Deposition is the newest, most disruptive technique, because it can enable the deposition of high quality nanocoatings homogenously in a cost-effective manner, which is useful for different application areas.
- However, several other deposition technologies remain the method of choice for specific applications, especially for multi-element, slightly thicker and / or large area coatings. As with most technologies, it`s hard to predict up front what the impact of an innovation will be or how a technology develop exactly.
- New developments regarding the application of nanocoatings within energy transition related technologies, and the challenges related to these developments, can point to potential gamechangers. In the scope of this research a gamechanger is described as a *promising* nanocoating related innovation of TRL4-8 that accelerates the energy transition (cheaper/more efficient/less materials or CO2) and is a product that one could potentially invest in. Identifying the most relevant game changers helps to understand how nanocoatings can impact the energy transition and allows to create a portfolio strategy with the future in mind.

Introduction to nanocoatings (3/3)

- Two main approaches are used for the synthesis of nanomaterials: top-down approaches and bottom-up approaches. The “top-down” approach involves the breaking down of large pieces of material to generate the required nanostructures. This method is particularly suitable for making interconnected and integrated structures such as in electronic circuitry.
- In the “bottom-up” approach, single atoms and molecules are assembled into larger nanostructures. This is a very powerful method of creating identical structures with atomic precision, although to date, the man-made materials generated in this way are still much simpler than nature’s complex structures.
- In this report we will mainly talk about bottom up: Spatial ALD, ALD, CVD, PVD, Sol-gel, Hydrothermal synthesis / chemical bath synthesis and electrodeposition* due to the specialization of TNO. We will make a distinction between wet and vacuum techniques due to size constraints of vacuum chambers and the thickness of the wet nanocoatings. This impacts the applications.



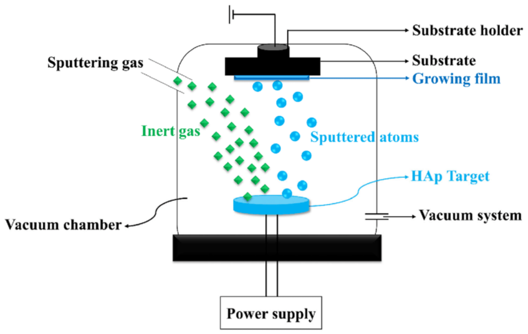
The top-down approach and the bottom-up approach



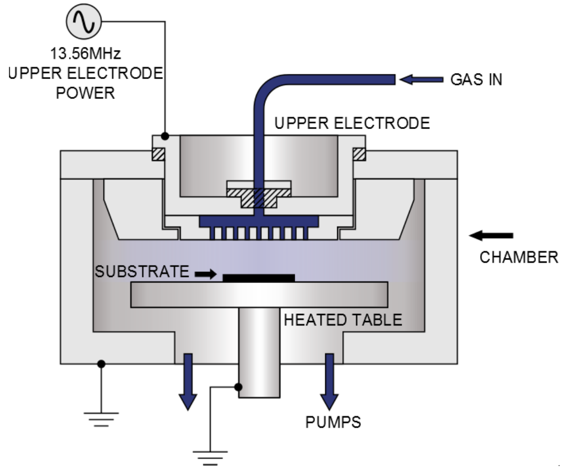
* For an overview of all different production methods:
[Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges - Materials Advances (RSC Publishing) 2021]

Different production technologies (1-3)

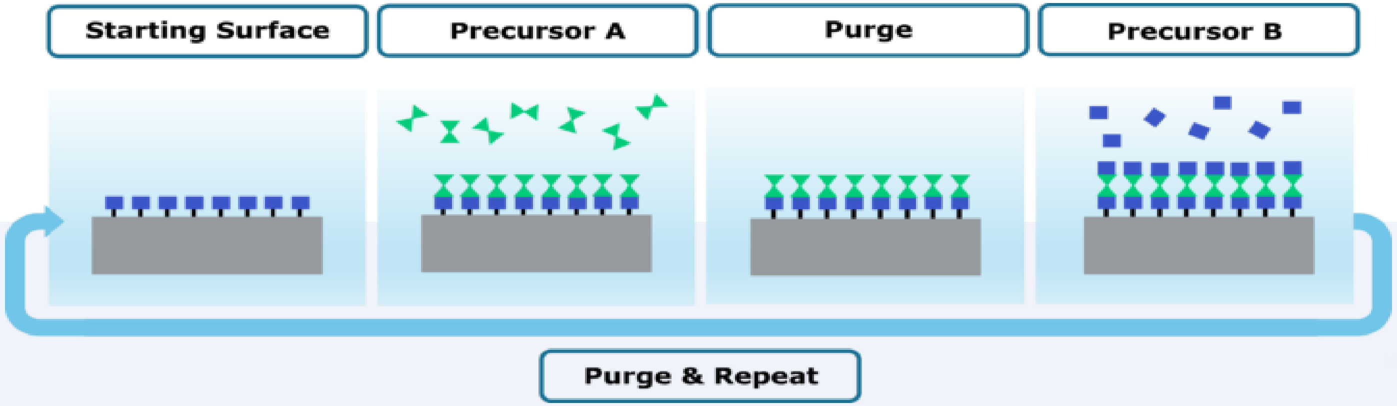
Deposition method	Description
Physical Vapor Deposition (PVD) (incl. sputtering)	Closed chamber (vacuum) with a block of the desired material (known as a 'target'). By electrical discharge, laser pulse or other methods a high energy pulse is given to the target, the material is ablated and ends up on the substrate
Chemical Vapor Deposition (CVD)	Closed chamber (vacuum) with reactive gases (chemicals) to grow high quality materials
'classic' Atomic Layer Deposition (ALD)	Closed chamber (vacuum) with reactive gases to grow high quality materials. Several cycles to fill and empty the chamber with chemicals are used to grow materials down to the atomic scale (hence the name)



PVD



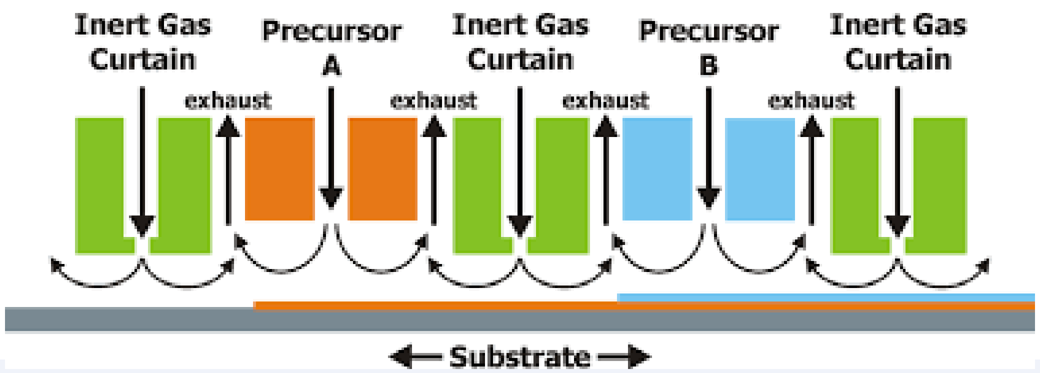
CVD



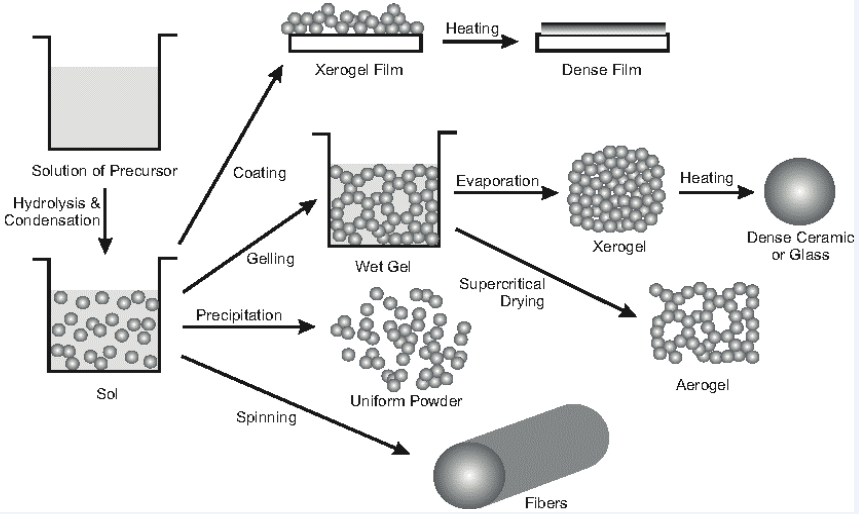
ALD

Different production technologies (2-3)

Deposition method	Description
Spatial Atomic Layer Deposition	Similar to ALD, but because of innovative hardware, the process can be done much faster (‘rotating chamber’ concept)
Chemical solution deposition (also known as sol-gel)*	Chemicals are stabilized in a liquid, which is coated on a substrate by an application technique (e.g. dip-, spray coating). Often requires a thermal step to remove solvent. Can be applied to m2 large scale with stable results.



Spatial ALD



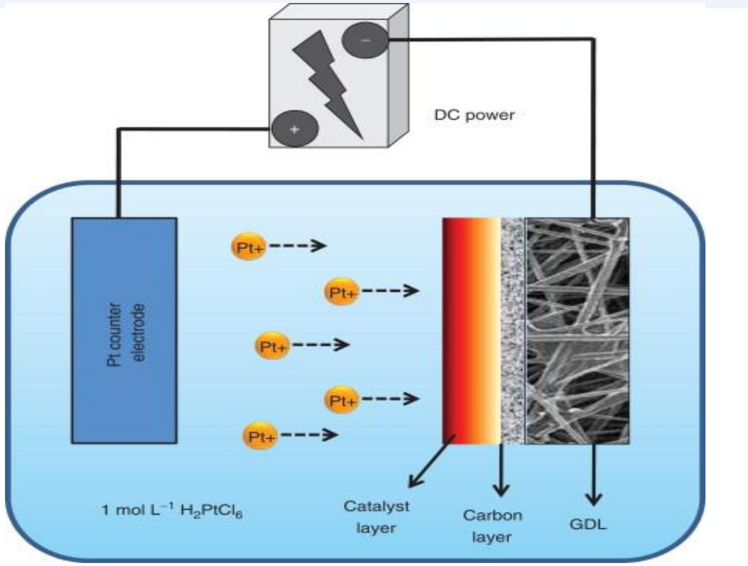
Sol-gel

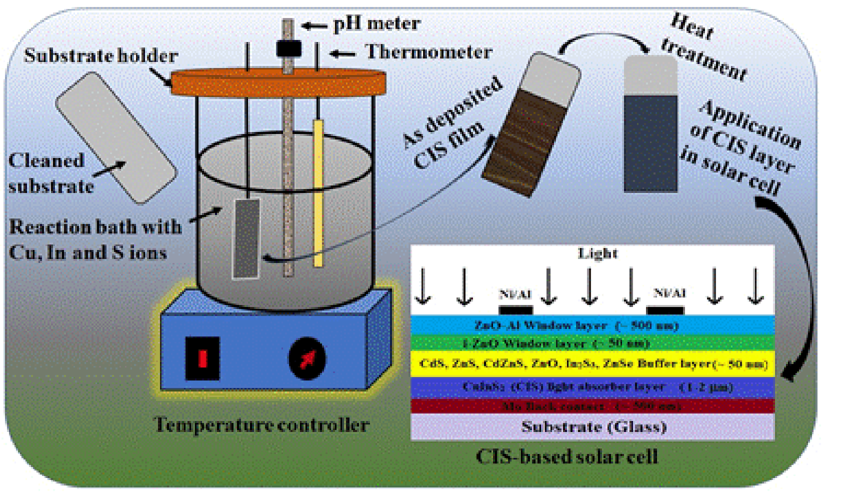
* *Includes application methods like spin-coating, dip-coating, spray-coating, slot-dye coating, ink-jet printing, Doctor blade coating, etc.*

Different production technologies (3-3)

Deposition method	Description
Electrodeposition	A conductive substrate is submerged in a liquid with chemicals, followed by application of a current. This can grow materials from solution with high control over thickness. Can be done at very small (centimeter-scale) to very large scale (meter-scale).
Hydrothermal synthesis / chemical bath synthesis	A substrate is submerged in a liquid with chemicals, within a closed pressure vessel. By controlling composition, time and temperature, structured materials can be grown on the substrate. Typically done at lab scale.

Electro deposition





Hydrothermal synthesis / chemical bath synthesis

Thickness, (production)cost, quality

Deposition method	Type	Thickness	Quality*	Cost	Special requirement
Chemical vapor deposition (CVD)	Vacuum	Low - Medium	++	Medium	Material restrictions (chamber contamination)
‘classic’ Atomic Layer Deposition (ALD)	Vacuum	Low	+++	Very high	Material restrictions (chamber contamination)
Spatial Atomic Layer Deposition (Spatial ALD)	Vacuum	Low - Medium	+++	High	Material restrictions (chamber contamination)
Physical vapor deposition (PVD) (incl. sputtering)	Vacuum	Low - Medium	++	High	Not suitable for porous / high surface area materials
Electrodeposition	Wet	Low - high	++	Low	Liquid compatibility, conductive substrate
Hydrothermal synthesis / chemical bath synthesis	Wet	Low - Medium	+	Medium	Liquid compatibility
Chemical solution deposition / sol-gel	Wet	Low – high	++	Low	Liquid compatibility

**Quality implies superior control of thickness, preventing pin-holes (shunts) and ensuring coating homogeneity*

Key Strengths

Deposition method	Key Strengths
Chemical vapor deposition (CVD)	Highly conformal films on irregularly shaped surfaces. The coatings can be deposited with very low porosity levels and with high purity.
‘classic’ Atomic Layer Deposition (ALD)	Ensuring fully closed coatings, coating of porous materials
Spatial Atomic Layer Deposition (Spatial ALD)	Ensuring fully closed coatings, coating of porous materials, relatively high speed
Physical vapor deposition (PVD) (incl. sputtering)	Ease of application for complex materials, high speed process
Electrodeposition	Ensuring fully closed layers, high material utilization, high speed process
Hydrothermal synthesis / chemical bath synthesis	Possibility to structure (complex) materials, low temperature requirements
Chemical solution deposition / sol-gel	Flexible and very precise material composition, suitable to make (very) complex materials*. There`s (high) speed of application and scalability, high speed process

** Inorganic materials such as cathodes for Li-ion batteries, e.g. LFP, NMC, or electrocatalysts AEM electrolyzers such as double-perovskites*

Key Challenges

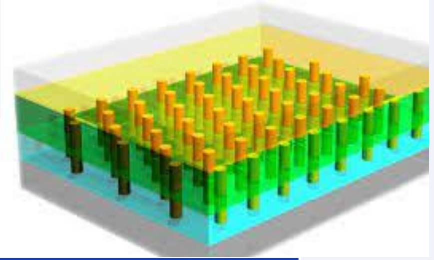
Deposition method	Key Challenge
Chemical vapor deposition (CVD)	Reduce costs, material utilization, process development for multi-element materials*
‘classic’ Atomic Layer Deposition (ALD)	Scalability, cost, process speed, material utilization, process development for multi-element materials*
Spatial Atomic Layer Deposition (Spatial ALD)	Further scalability, material utilization, process development for multi-element materials*
Physical vapor deposition (PVD) (incl. sputtering)	Reduce production costs, not suitable for porous materials
Electrodeposition	Process development needed for non-metallic materials; process development needed for multi-element materials*
Hydrothermal synthesis / chemical bath synthesis	Research to enable more materials to be made, scalability, process speed (batch process), process development for multi-element materials*
Chemical solution deposition / sol-gel	Liquid compatibility, temperature or UV required, coating quality. There is less control on the thickness of the thin film with sol-gel.

** Inorganic materials such as cathodes for Li-ion batteries, e.g. LFP, NMC, or electrocatalysts AEM electrolyzers such as double-perovskites*

Indepth technology comparison (1-2)

Deposition method	Mechanism	Requires	Yields	Pros	Drawbacks	Known for
Chemical vapor deposition (CVD)	Vapor (slightly different gas) controlled chemical reaction	Tailored chemicals, vacuum chamber	High quality thin film nanocoatings <100 nm	Cost effective, scalable	Expensive, low material utilization, limited coating thickness	Photovoltaic production (amorphous silicon)
'classic' Atomic Layer Deposition (ALD)	Gas phase controlled chemical reaction	Tailored chemicals, vacuum chamber, static gas seals	High quality nano-coatings with superior thickness control <100nm	Very high quality, excellent for porous and structures, fully closed coating	Very expensive, low material utilization, very time consuming, not scalable, limited coating thickness	Academic research, semicon industry, and photovoltaics production
Spatial Atomic Layer Deposition	Gas phase controlled chemical reaction	Tailored chemicals, tailored vacuum chamber with dynamic gas seals	High quality nano-coatings with superior thickness control <100nm	Very high quality, excellent for porous structures, fully closed coating	Limited scalability (thus far), possible substrate limitations because of rotary design, limited coating thickness	SparkNano (batteries, electrolyzers, displays)
Physical Vapor Deposition (PVD) (incl. sputtering)	Electrical discharge or electrical heating	Solid material ('target'), vacuum chamber, electricity	High quality nano-coatings with broad size range 10->1000nm	Excellent thickness control, scalable	Expensive, only for planar structures ('line of sight deposition')	Many applications in electronics, conductive glass for photo voltaic

Nanopillars Promise
Cheap, Efficient, Flexible
Photo Voltaic



Indepth technology comparison (2-2)

Deposition method	Mechanism	Requires	Yields	Pros	Drawbacks	Mostly known for
Electro deposition	Redox reaction from liquids	Conductive substrate, liquid with metal salt, electricity	Nano-coatings with broad size range 10 nm - 100 µm	High throughput and fast, low cost, thickness control, fully closed coating, high material utilization	Liquid compatibility substrate, limited homogeneity over larger surfaces, conductive substrate	Metal finish and anti-corrosive coatings (e.g. metal parts, car chassis)
Hydrothermal synthesis / chemical bath synthesis	Pressure and temperature controlled chemical reaction	Closed, (pressurized) vessel, liquid with metal salt	Nano-coatings with structured features (e.g. nano pillars see picture)	Crystalline materials at low temperature, low cost, structured materials	Substrate needs to be submerged, hostile conditions in vessel, poor thickness control, low material utilization, time consuming batch process	Production of nano-particles and pigments
Chemical solution deposition (also known as sol-gel)*	Liquid phase controlled chemical reaction	Metal salt, stabilizers, solvent	Nano-coatings with broad size range 10 nm - 100 µm	High throughput and fast, low cost, high material utilization, allow patterning	Some require temperature step, liquid compatibility substrate, limited thickness control	Glass coatings, printed circuit boards, paints, inks

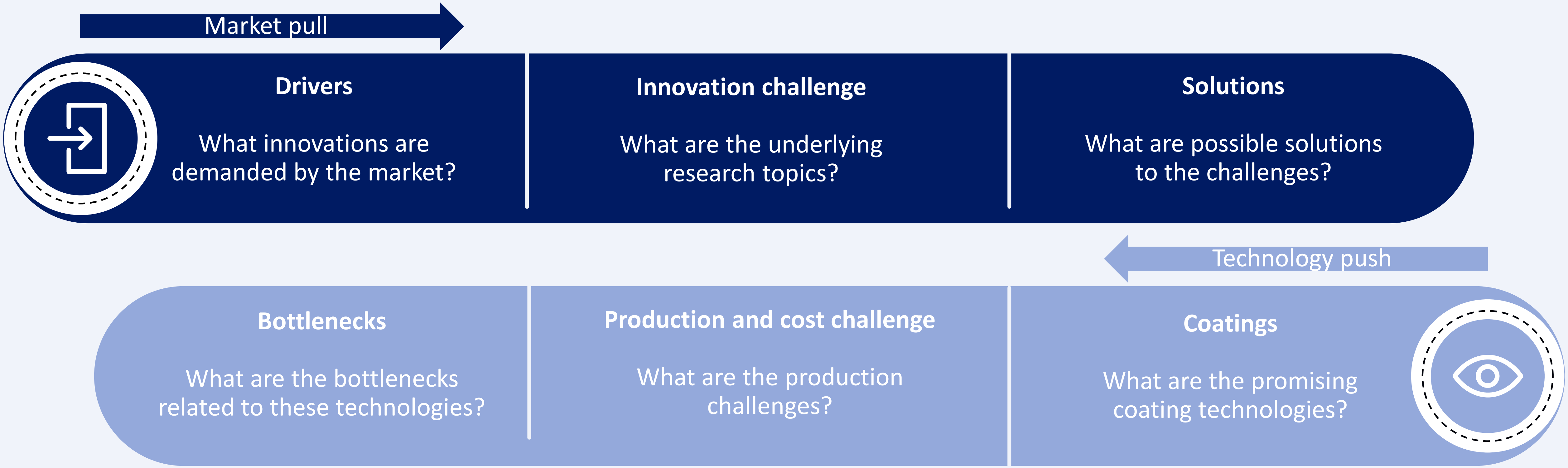
* Includes application methods like spin-coating, dip-coating, spray-coating, slot-dye coating, ink-jet printing, Doctor blade coating, etc.

3. Four promising applications

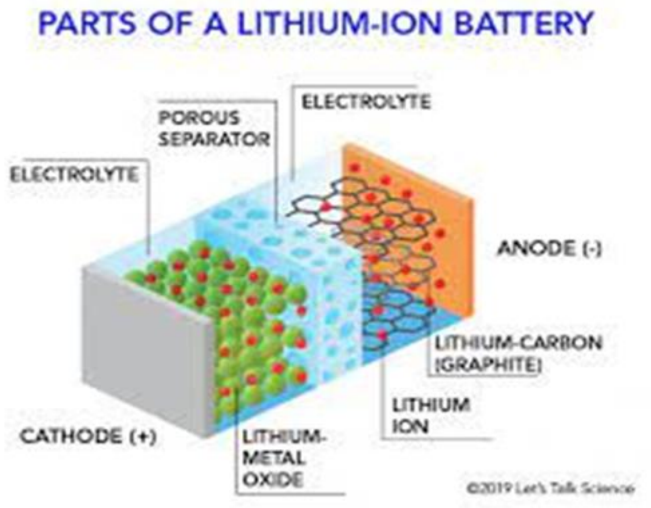
TNO innovation for life

Explanation

- The next slides will present the promising areas of innovation in relation to nanocoatings. We have asked seven TNO experts to mention potential gamechangers in 5 interviews (see the long list of nominations in the appendix) in technology area's batteries, photovoltaics, electrolysers and fuel cells. The input is structured following the storyline below.



Batteries



Introduction to batteries
- A way of storing energy (single use or multiple uses after recharging)

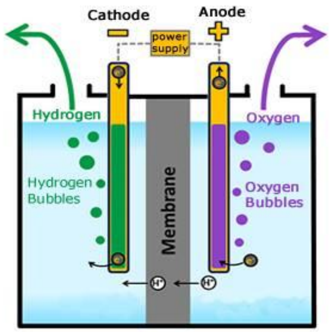
- Most popular are lithium ion batteries: they have a very high power & energy density, performance and lifetime. When searching for an alternative to lithium ion batteries the challenge is to find more abundant and economically feasible battery materials without compromising performance.
- CRM Materials used: graphite (anode) and metal oxides (cathode). The anode material graphite has a layered structure that hosts lithium ions. Cathodes generally consist of layered transition-metal oxides that also host lithium ions. Electrochemical redox reactions that take place in anode and cathode let us store/harvest electrochemical energy. Electrolytes allow the lithium ion migration between anodes and cathodes.
- In conventional lithium-ion batteries, and electrolyte is an organic solvent & lithium salt mixture that is dipped in a polymeric membrane (separator).
- Most core materials are critical raw materials (CRM) and similar to electrolysers. These technologies can be in resource competition.

Context around the use of nanocoatings
- Nanocoating for batteries are available, but not very popular due to tradeoffs. We can use them to improve stability (to replace CRM with alternatives), performance or lifetime of batteries.
- The tradeoffs are limiting the interest in coatings. Batteries with a different (less CRM) consistency such as silicone anode, are less stable, have a lower lifetime, and higher degradation. See the next slide for more information.

Nanocoating solutions for battery challenges

Driver	Innovation challenge	Solution	Bottleneck (performance, etc.)	Production and cost challenge	Coatings
Next generation cathode materials with less CRM	Replacement of the critical raw materials in batteries to reduce the cost of batteries and to become less dependent on scarce materials (and their political producers) while preserving energy density.	Use less lithium to produce batteries. Replacement of for instance lithium cobalt oxide to nickel manganese aluminum due to cost and availability.	There`s material and nanocoating technology development required to bring the solution to TRL6 without drawbacks. The new components lead to batteries with lower lifetime, less stability. In the future when a nanocoating for stability is developed; a low cost needs to be achieved to compete with contemporary battery materials.	The technology (Spatial ALD) still needs to be upscaled to make the production of new batteries cheaper.	Spatial ALD is the most promising technique. The application of thinfilms on batteries to extend lifetime will get a boost by Spatial ALD because the coatingprocess requires minimal material and no vacuum, and the coatings are very equal and thin.
Next generation anode materials with less CRM and lower costs	To improve the energy density and to become less dependent on scarce materials (and their political producers).	Lower the use of CRM by replacing of graphite with silicon in contemporary (lithium ion graphite) batteries.	Replacement leads to batteries with lower lifetime, less stability. Batteries are powering bigger machines that are used to certain battery performance, output and stability. A thinfilm-nanocoating could improve stability.	The nanocoating technology still needs to be upscaled to make the production of more energy dense batteries cheaper.	Silicon lithium ion battery with silicon anodes is mainly made by chemical vapor deposition or sputtering. Spatial ALD can be used to deposit a protective layer on silicon anode, which can improve the battery stability and lifetime.

PEM electrolyser



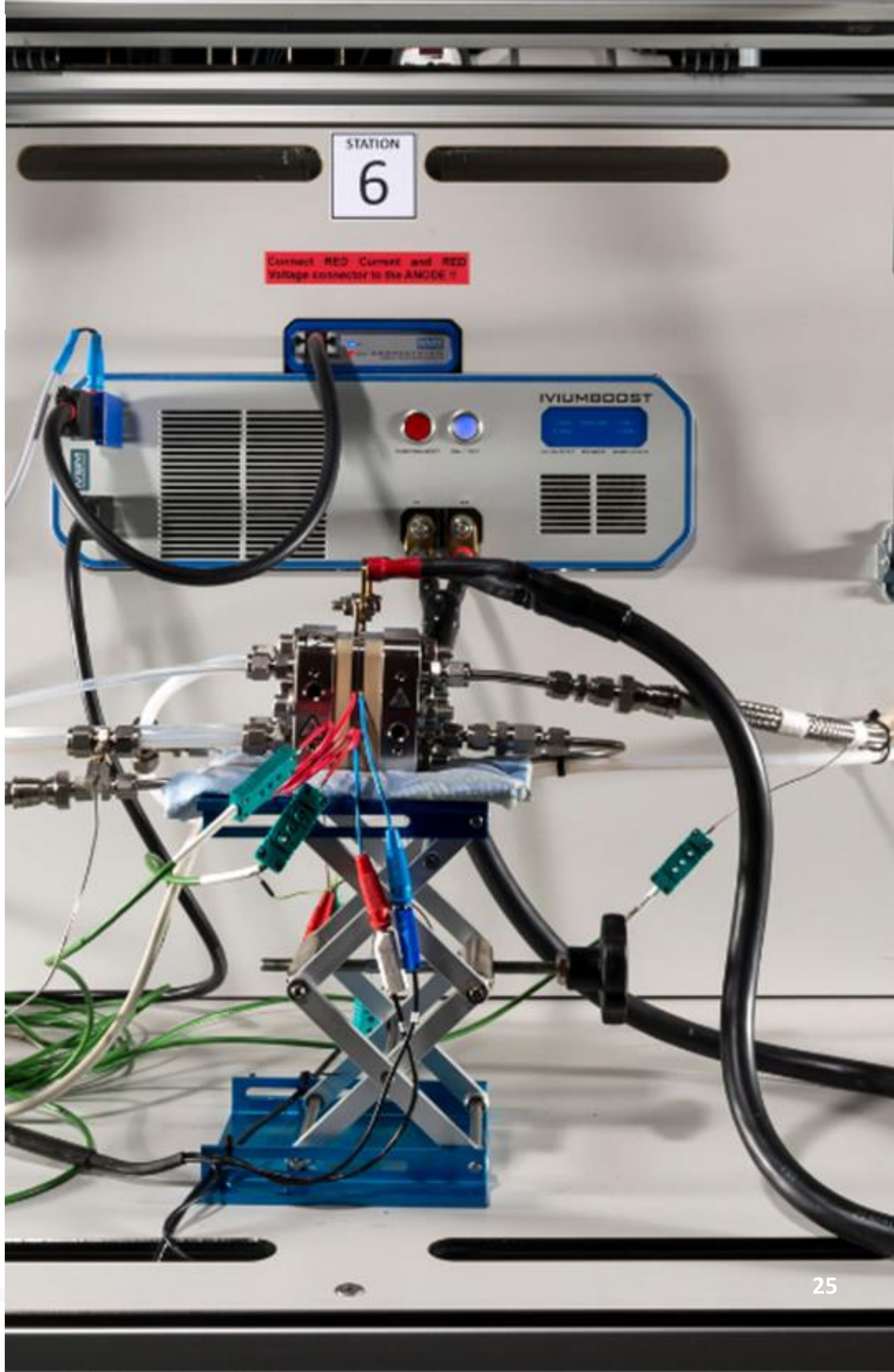
Electrolysers

Introduction to electrolysers

- Allows you to use electricity to split molecules. Also called electrolysis; to use electricity to split water in oxygen & hydrogen. Most popular types of electrolysers are: PEM (proton electron membrane), AEM (alkaline electrode membrane), Liquid Alkaline, High temperature ceramic or CO2 electrolyser.
- PEM contains CRM: titanium, iridium, platinum and is more expensive than alkaline but has advantages for green energy. The electrochemical conversion to hydrogen is faster in acidic media than in alkaline media because the hydrogen reaction is easier (no chemical bonds broken). Also it can be run at higher pressure for the same output
- For the green energy transition we need a cheaper sunpowered PEM electrolyer and a durable AEM which can withstand an intermittent energy supply (when there’s no sun, there`s no energy). Most core materials are CRM and similar to batteries; therefore they can be in resource competition.

Context around the use of nanocoatings

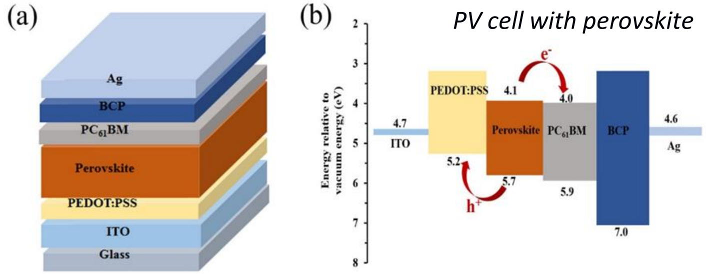
- To reduce the use of CRM (iridium, platinum and titanium) and reduce gas crossover in the electrolyser allowing thinner membranes to reduce energy losses.



Nanocoating solutions for electrolyser challenges

Driver	Innovation challenge in electrolyser	Solution	Bottleneck (performance, etc.)	Production and cost challenge	Coatings
Continuous production of electrolysers to fulfill demand. Currently we produce PEM's in batches.	Reduce the cost of electrolyser components and housing (less CRM) while maintaining the electrolyser durability. We need to find new materials or alternatives to the current consistency of PEM; due to difficulty to produce and high cost.	Replace titanium in electrolysers	The currently used titanium in electrolysers is very stable and is difficult to surpass with new combinations even though the new combinations will be cheaper. The new materials used to make low cost electrolysers are less stable, and less durable or have unwanted side effects. Non-titanium materials can be used in to replace titanium if a suitable nanocoating is applied as a divide to prevent unwanted side effects.	The new materials used to make low cost electrolysers are less stable, and less durable or have unwanted side effects. Non-titanium materials can be used in to replace titanium if a suitable nanocoating is applied as a divide to prevent unwanted side effects.	Chemical vapor deposition (CVD), Physical vapor deposition (PLD) (incl. sputtering), Chemical solution deposition / sol-gel, Electrodeposition.
Low cost electrolysers for high scale (>MW)	Reducing critical raw materials to reduce the cost of electrolysers and increase production by becoming less dependent on scarce materials (and their political producers).	Reduce Iridium or platinum in electrolysers	Material and nanocoating technology development required, lifetime (material stability) is the key problem to replace platinum and iridium.	Spatial ALD is the applied technology. Spatial ALD is not yet available at large scale and remains costly.	To add a catalyst membrane nanocoating in an electrolyser will prevent degradation and drive the oxygen evolution more efficiently. This will also impact batteries and fuel cells due to a similar catalyst layer and degradation issues.
Thinner polymer electrolyte membranes with thin films gas barriers for energy efficient electrolysers	Putting thin films on polymers is difficult due to different properties: rigid high heat film versus flexible low heat resistance polymer. With the current technologies the polymer disintegrates. High temperature materials cannot be made on a low-temperature compatible device.	Low temperature inorganic solid (electrolytes) for conductivity at room temperature	Developments in low temperature inorganic solid (electrolytes) would make the electrolysis process cheaper and easier, but it is very difficult to achieve; there are processing issues.	Material and nanocoating technology development required, multi-element materials (different demands and melting temperatures) combined with low temperature working restictions	Chemical vapor deposition (CVD), Physical vapor deposition (PLD) (incl. sputtering), and (S)ALD are the used technologies.
Energy optimization electrolysers	For optimization we need to try to prevent energy losses due to thick membrane, but a too thin membrane is a security risk (hydrogen and oxygen crossovers can explode). A gas barrier/ nanocoating could prevent crossover and conduct ions without energy loss. A monolithic device is a complete set of layers and connections on a single substrate rather than separate elements to form a functional unit.	A single piece device. This consists out of: a gas barrier, PTL (porous transport substrate), the catalyst material (iridium nanocoating in PEM) and the membrane.	The components are there but should brought together. A monolithic device could prevent crossover (causes explosions) and conduct ions without energy loss and easier to recycle. It`s a one piece devide which has an assemblage and energy optimization benefit.	Nanocoating processing development required. It can be seen ast the holy grail for many technologies such as batteries, PV, membranes of fuel cells and electrolysers. It will take 5-10 years before this innovation has TRL9.	Spatial ALD and Physical vapor deposition (PLD) because of low-temperature requirements of substrate

Photovoltaics



PV cell with perovskite

Introduction to photovoltaics

- The technology applies the photovoltaic effect to convert solar energy into voltage and current, thus electrical power. A photovoltaic module consists of multiple solar cells. 95% of all solar cells in the market are made of crystalline silicon (cSi).
- First generation photovoltaics (cSi): uses energy intensive manufacturing process which creates a lot of CO2. The green transition could improve the CO2 output. It`s a slower manufacturing process but profits a lot from high economies of scale. Photovoltaic quality of silicon is cheap to use.
- Second generation photovoltaics: thin film cadmium photovoltaics, less CRM, less machines and CO2 needed. There is less production scale due to lack of R&D and investments.
- Emerging generation photovoltaics : The manufacturing uses low <100 degrees temperatures. The difficulty is to deposit these cell structures on flexible substrates to cover for example houses and cars. Several technologies make use of nanoscale thin film materials, in particular, dye-sensitized solar cells (DSSCs), quantum dot PVs, nanocomposite PVs and graphene-based PVs.

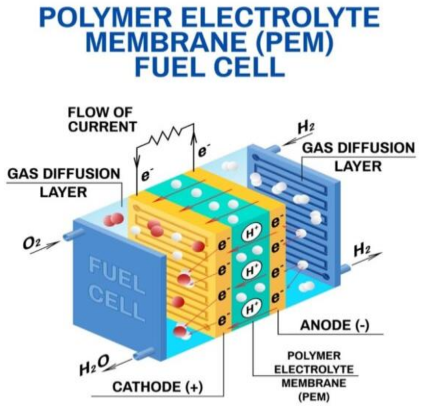
Context around the use of nanocoatings

- New (flexible) thin films at a nanoscale (nanocoatings) could improve the performance, stability and lifetime of the photovoltaics by improving conversion efficiency. Nanocoatings can add functionalities such as self-cleaning, or enable application to flexible/curved objects or integration with e.g. windows.

Nanocoating solutions for photovoltaic challenges

Driver	Innovation challenge	Solution	Bottleneck (performance, etc.)	Production and cost challenge	Coatings
High performance PV cells (perovskite -cSi)	The combination of thin films perovskite with silicon leads to a 5-7% (absolute) better conversion efficiency. The challenge is to find trade off among high PCE, production machinery and provide warranty on long term stability of the product.	Perovskite on top of commercial silicon (PERC) or new tech (TOPCON and HTJ) already demonstrate high efficiency. Generally you need 6 layers and multiple different machines to make perovskite with silicon PV. A way could be to have a reduced number of machine ideally 1) that would combine all the different application techniques and nanocoating depositions. This would make the production of perovskite PV ideal and massively cheaper.	To control the stability of the perovskite thin film. Deposition of perovskite stack still requires various (4-5) different processing techniques (sputtering, evaporators, slot die, ALD, screen printing.) Limiting the number of deposition techniques would bring a reduction of initial investment.	Scaling up from centimeters to meters of material to coat with nanocoating production technologies. To deposit nanocoatings efficient, cheap and homogeneous to large areas is barely demonstrated (for instance OXFORD PV is trying that).	There are different techniques possible to deposit for instance the perovskite layer, but at this stage it is not yet clear which technique will be most successful.
High performance PV cells (perovskite based technology via R2R production)	Roll to Roll (R2R) deposition of perovskite and/or hybrid or all-perovskite tandems can lead to high efficiency, high production volumes and low costs (CAPEX and LCOE).	Using controllable deposition methods via solution processing (slot die, inkjet printing and screen printing) combined with dry processing (sputtering or Spatial ALD) to obtain homogeneous coatings over large areas is currently the main research area.	The large areas deposition of various layers on flexible substrates needs to be improved to homogeneity of liquid and dry nanocoating deposition.	Scaling up from centimeters to meters of material to coat with nanocoating production technologies. To deposit such layers efficiently, cheap and homogeneous to large areas with liquid coating is challenging.	There are different techniques possible to deposit for instance the perovskite layer, but at this stage it is not yet clear which technique will be most successful.
Nanocaoting for flat glass for energy efficient windows	Liquid deposition of homogeneous, <10nm precision nanocoatings for large areas.	Replacement of sputtering process for JUMBO glass with liquid deposition methods for energy-efficient window coatings.	The availability of large enough machinery (6m+) for large areas deposition of nanocoatings on glass for liquid nanocoating	The investment costs to scale up the machinery is a hurdle since the market does not exist yet.	Does not yet exist yet for instance on JUMBO glass.

Fuel cells



Introduction to fuel cells

- A way of storing energy and giving out electricity similar to a battery
- It`s an energy converter, but unlike a battery, it`s also a reactor and needs a constant fuel supply to operate.
- Low temperature polymer electrolyte membrane (PEM) fuels cells are the most popular because of their simplicity, reaction times and low operating temperatures, but depend on platinum. In the case of PEM fuel cells, the fuel needed is hydrogen. PEM fuel cells need an oxidiser such as oxygen to convert the chemical energy stored in hydrogen to electricity. The prevalence of hydrogen as fuel can be seen as a barrier because hydrogen is hard to transport and we need a lot of electrolysers to produce hydrogen, while the CRM are limited.
- High temparture fuel cels are also called solid oxide. They`ve higher energy conversion efficiencies but a bigger set up is required, which makes it difficult to use it in nonstationary applications.
- Materials used: steel, copper, aluminium, polymer membrane and metallic or graphite bipolar plates and a catalyst layer from carbon supported platinum particles.

Context around the use of nanocoatings

- A nanocoating could improve the fuel cell lifetime and performance, lowering degradation rates and offering less expensive materials.

Nanocoating solutions for fuel cell challenges

Driver	Innovation challenge	Solution	Bottleneck (performance, etc.)	Production and cost challenge	Coatings
Fast and affordable hydrogen transport with a durable infrastructure.	To develop a nanocoating to protect steel from the demanding properties of hydrogen	Protective steel nanocoating for hydrogen.	A method has to be developed that coats in a conclusive whole, without gaps over thousands of meters. A retrofit and cost-effective nanocoating is required.	This nanocoating would have a lot of impact, only small scale demonstration has been shown by e.g. Fraunhofer (Germany).	Wet chemical
Material utilization issues and costs due to high demand.	To improve the reclaiming of platinum in fuel cells and to use abundant (multi-element) material. Also, to lower degradation.	Replacement of carbon-supported platinum, which is nowadays the most popular catalyst in Polymer Electrolyte Membrane Fuel Cells (PEMFCs).	Some fuel cell manufacturers already claim they can recover over 90% of the platinum from a used fuel cell and reapply it in a new unit. A nanocoating that would aim at competing with platinum should offer similar life cycle aspects. Deposition of a nanocoating functioning as a catalyst layer on the polymer membrane of a fuel cell is difficult because the different heat resistance of the materials (copper, platinum and polymers).	A nanocoating that would aim at competing with platinum should offer higher electrocatalytic activity and/or stability, and would be preferably cheaper than platinum. Challenges for fuel cell module cost are the manufacturing and production processes: due to the amount of product lines and the scale of the production lines we experience no effects of scale. Low amounts equals high production costs per single unit for fuel cells and electrolysers.	Electrodeposition, PLD, Wet chemical

Players in the market

On request of Invest-NL we will also mention some important marketplayers per technology. This is not a conclusive list, but more top of mind.

Nanocoatings

- **EU** SALD (NL), AkzoNobel (NL) Lamoral, (NL) Lusoco(NL), VSParticle (NL), Kalpana (NL), Sparknano (NL), Beneq (Fin)
- **Outside EU** ForgeNano (US), Nfinite nanotech (US)

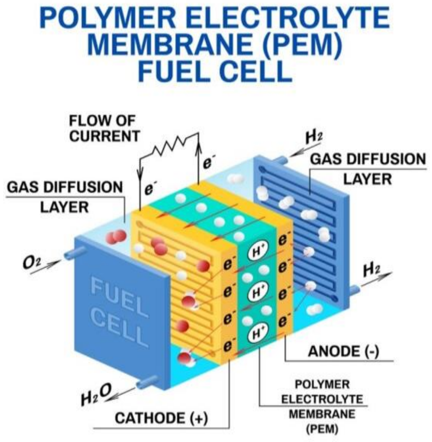
Batteries

- **EU** Delft IMP (NL), Lion Volt (NL), LeydenJar (NL), SparkNano (NL), Solithor (BE), Umicore (BE), ELEO* (NL) (*no NC technology), BasqueVolt (ES), Solvay (BE), Scania (SE).
- **Outside EU** SolidPower (USA) – with BMW and Ford

Photovoltaics and energy efficient windows

- **EU** Ablynx, Solar Botanic Ltd., Covestro (former DSM)
- Dutch SME/start-up: Rads Global, Kriya Materials, ClimAd Technologies.
- Solar panels NL: HyET Solar, Kameleon Solar, Solarge
- **Outside EU** Large glass companies (performing sputtering of silver coatings for HR++ windows): Saint Gobain, NSG Pilkington, Guardian, AGC, Scheuten (former Dutch SME, recently bought by Glas Trösch)

Players in the market



Fuelcells

- **EU** IRD Fuel Cell Technology A/S, W. L. Gore & Associates, Du Pont de Chemours and Company, Giner Inc., Greenerity GmbH, Advent BASF, Fuel Cell Technology (SE), PowerCell (SE) .
- **Outside EU** HyPlat Ltd.(SA), The 3M Company (US), Wuhan WUT New Energy Co. (CH). Johnson-Mattey (UK) Advance reproductions corporation, Z-medica, LLC, InMat, Inc., APS material, Inc., Rogue Valley Micro and Advanced Nanoproducts

Electrolysers

- **EU** Sparknano (NL), Bosch (DE), Magneto (NL), Umicore (BE), John Cockerill (BE), Enapter (DE), Chemours (NL/USA), Solvay (BE), Siemens (DE), Bekaert (BE), Topsoe (DK), SunGrow (DE), Permascand (SE), Alleima (SE).
- **Outside EU:** Johnson-Mattey (UK), Ames Goldsmith Ceimig (UK), Mott (US), Toho Titanium (JP)

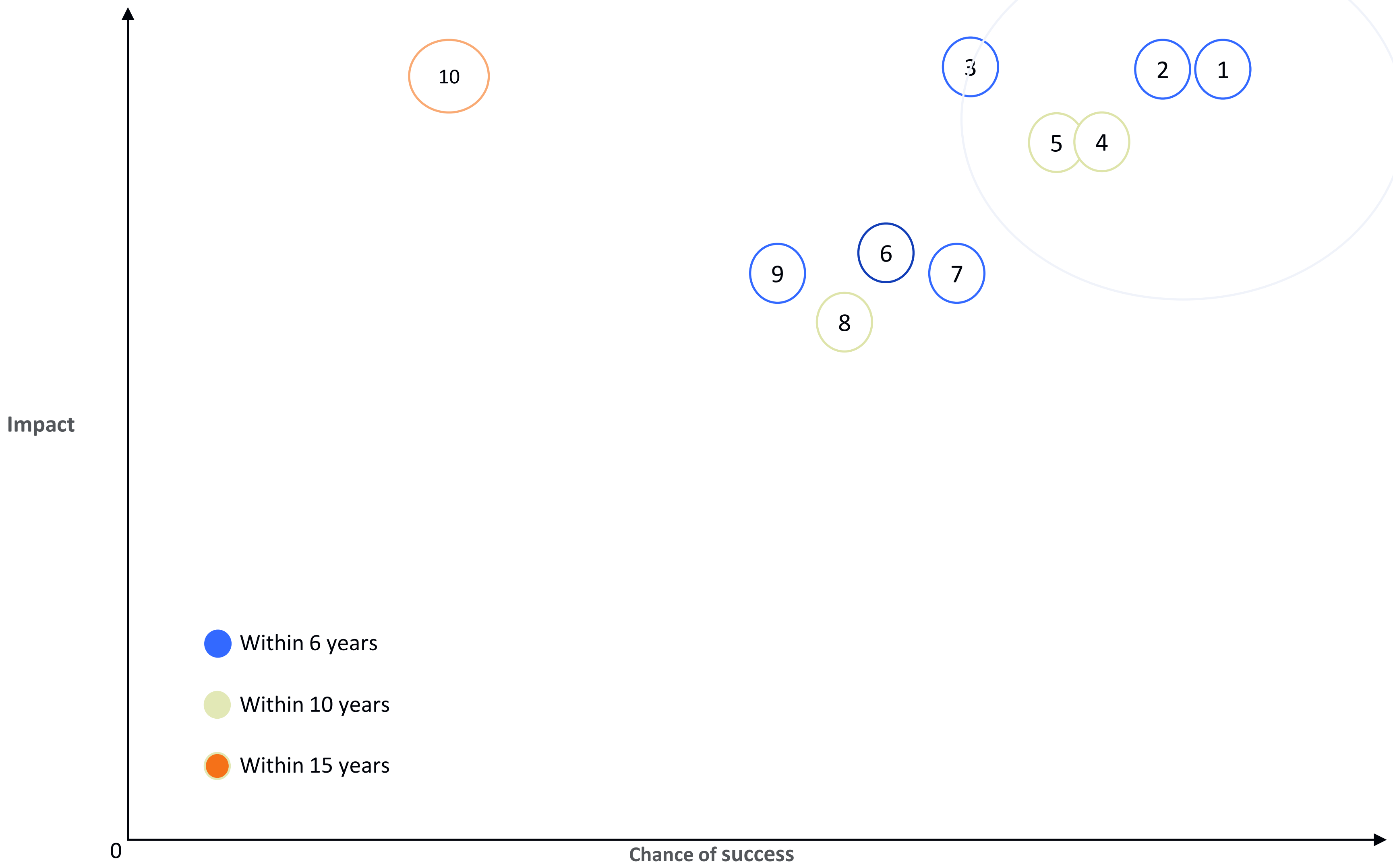
4. Promising nanocoating innovations

TNO innovation for life

Promising nanocoating innovations based on expert interviews

Topics	Description	Batteries	Elektrolysers	PV	Fuel Cells
Spatial ALD deposition	Application of Spatial Atomic Layer Deposition (coating at atomic level) to apply nanocoating to objects; its cheaper due using to less material and better performance and creates closed surface coatings.	■	■	■	■
Reduce Iridium or platinum in electrolysers	Increase material utilization by Spatial ALD nanocoating to reduce PGM to save cost and optimization of the expensive material: reducing the use of Iridium or platinum in electrolysers to increase production..		■		■
Replacing or reducing CRM in battery cathodes	Replacing lithium cobalt oxide to nickel manganese aluminum or replace graphite with silicon in contemporary (Lithium ion graphite batteries) due to cost and availability, but the new components lead to batteries with lower lifetime. The solutions could be new additives in the liquid electrolytes to form a newly optimized artificial interface between these materials.	■			
Protective steel NC for hydrogen transportpipes	Nanocoating to prevent steel degradation when transporting hydrogen (e.g. long distance distribution pipelines). This would be wet chemical coatings (scalable and cost effective) based on polymer and ceramic fillers		■		■
Monolithic device	A combined device to be made with combination of deposition methods: gas barrier, PTL (porous transport substrate) and then the catalyst material (iridium nanocoating in PEM) and then the membrane. This could prevent crossover and conduct ions without energy loss and easier to recycle.	■	■	■	■
Liquid deposition of nanocoatings to glass for large areas	Using deposition techniques efficiently and homogeneous to large areas in e.g. advanced windows.			■	
Single deposition method for Perovskite solar cells	To be developed: one technology or machine to combine the 6 different deposition nanocoating methods for cheaper solarcells			■	
Replace titanium in electrolysers and fuel cells	High quality nanocoating to protect less noble metal to save cost and optimization of the expensive material: eliminating the use of titanium in electrolysers to increase production.		■		■
Lithium ion graphite battery with silicon	Lithium ion graphite battery with silicon instead of graphite.	■			
Low temperature inorganic solid (electrolytes)	Novel multi-element materials made by wet chemical methods or PLD that conduct ions at low temperature, enabling solid-state batteries and solid oxide fuel cells for conductivity at roomtemperature which would make the process cheaper and easier.	■	■		

OVERVIEW PROMISING NANOCOATING INNOVATIONS: TOP 10



1	Spatial ALD deposition
2	Reduce Iridium or platinum in electrolysers
3	Nanocoating interface for stability (and replacing or reducing CRM) in batteries
4	Protective steel nanocoating for hydrogen
5	Monolithic device
6	Liquid deposition of nanocoatings for energy efficient window coatings for large areas
7	Solar with Perovskite deposition machine
8	Replace titanium in electrolysers
9	Lithium ion graphite battery with silicon
10	Low temperature inorganic solid (electrolytes)

Conclusions

This report aims to answer: “What are the most relevant nanocoating innovations within batteries, photovoltaics, electrolysers and fuel cells?”

Nanocoating is an enabling technology that often works and develops in tandem with related innovations around materials, new products or production processes. These aim to create functions or integration of technologies which have a higher performance, lower cost, or to reduce the dependency on scarce materials. Often nanocoating research (for batteries, solar panels, electrolysers and fuel cells) builds on existing research and innovations are not disruptive but incremental.

The core result is the conclusion that currently there are no production and deposition methods comparable in impact, success and relevance to Spatial ALD. As far as the experts are aware, neither are there any production and deposition methods currently being developed that can compare. This is concluded based on desk research, 5 interviews with 7 experts and a collective workshop.

Conclusions

For all known nanocoating production methods a summarization is made on performance, quality (thickness and homogeneity) of the coating, ease of production, costs and CRM (Critical Raw Materials) use in chapter 2. Also, in this chapter 2 the main challenges of these production technologies and their possible solutions are shown, as well as advantages and drawbacks of the applications of these production methods.

Per interview a technology was discussed: Batteries, electrolysers, photovoltaics, fuellcells and nanocoatings. In chapter 3 we show an overview per technology and the gamechangers nominated.

During the interviews, 17 gamechangers were nominated in total and ranked by the experts. Due to the limited existence of production and deposition innovations we expanded the gamechangers to promising nanocoating related innovations. During the workshop one more gamechanger was discussed and added to the detailed list.

These 18 gamechangers or also called ‘promising nanocoating related innovations’, were ranked on the criteria of impact, time to market and chance of success

Conclusions

This resulted in a visualized top 10 of promising nanocoating related innovations. Of the top 5, only Spatial ALD is a nanocoating deposition method, the others are innovative applications of nanocoatings. The others are interesting in terms of time to market, impact, chance of success and mostly need upscaling. The top 10 can be found in the chapter conclusions.

With this top 10, this report provides an overview of the new developments in batteries, solar panels, electrolysers and fuel cells that can be realized by the use of nanocoatings and indicates the potential of various nanocoating technologies.

Which nanocoating production technique is chosen for the production process depends on the goal and the factors of costs, the scale of the coated surface, necessary thickness and quality of the coating, properties and material. This report tries to give information for those factors to help the reader notice impactful innovation, e.g., when those factors change, or a key challenge is solved.

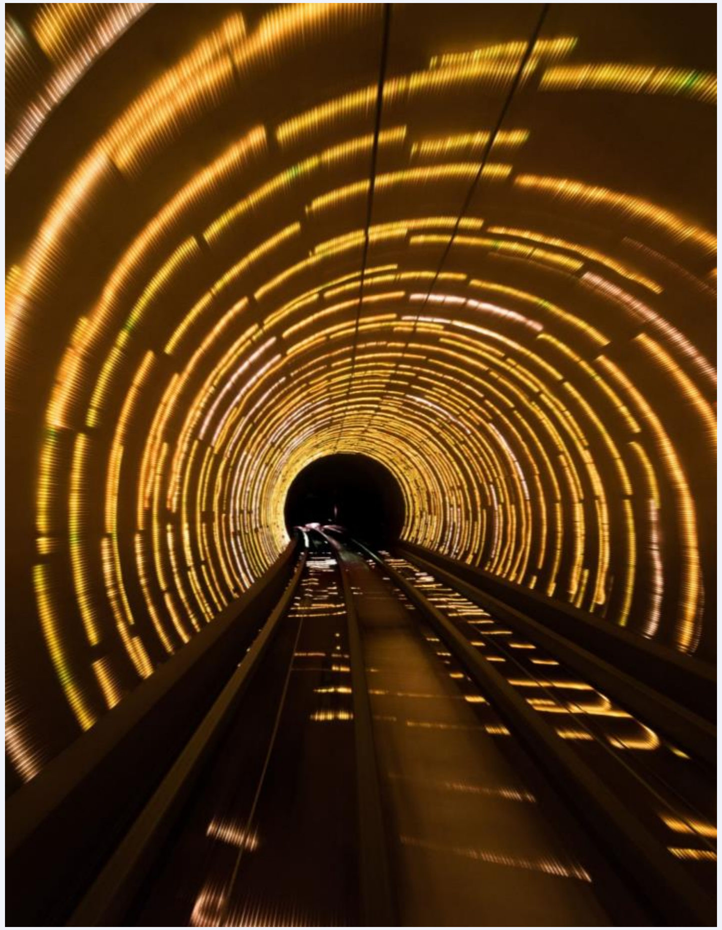
For more information on the total of 18 gamechangers and our approach, see the Appendix.

Next Steps & recommendations

Spatial ALD is currently the innovation with the biggest impact, success and relevance. However, further scalability of the technology is yet to be shown.

There is a great demand for scalable homogenous high-quality coating technology, offering opportunities in the energy domain, such as large scale (flexible) photovoltaics and energy efficient windows, as well as safe and efficient distribution of hydrogen through underground pipelines.

We can conclude that developments in scalable homogenous high-quality coating technologies are therefore crucial to bring the transition towards sustainable energy sources a step closer.



Appendix

TNO innovation for life

Approach

1. Kick off with Invest-NL
2. Desk research and preparation of the interviews
3. A round of 5 interviews to gain insight into the impact and state-of-the-art of nanocoatings in four application domains. These interviews were held online by the TNO Strategic Business Analysis department with seven TNO experts.
4. Processing the interviews and preparation of the workshop
5. Impact assessment of the game changers through a workshop with the seven TNO experts
6. Creating draft report
7. Sharing the draft report and collect feedback Invest-NL
8. Processing the feedback of Invest-NL
9. Internal review
10. Final draft send to Invest-NL
11. Optional: feedback is received and processed
12. Both parties agree to final report

Detailed gamechangers

Interview	Name	Gamechanger	Chance of succes	Amount of impact in the market	Time estimated to relevance
Nano coatings 1	*Spatial ALD deposition*	Application of Spatial Atomic Layer Deposition (coating at atomic level) to apply nanocoating to objects; its cheaper due using to less material and better performance and creates closed surface coatings.	1 (Some upscaling issue`s)	Very high (1)	1 Year
Nano coatings 2	*Energy optimizing window NC*	Advanced coating on windows, SMART windows to regulate sun in&outflow and to make buildings more energy efficient.	1 (Very high chance)	High (2)	<5 Years
Nano coatings 3	*Transparant solar panels*	Transparant solar panels: to use as windows on houses and cars.	1 (Very high chance)	High (3)	5-10 Years
Nano coatings 4	*Anti reflection NC on solarpanels*	Anti reflection coating on solarpanels. Easy to apply, cheap material and increased performance of the solarpanel by 6%.	1 (already there)	High on market(4)	0 years
Fuelcells 5	*Protective NC for hydrogen distribution*	Nanocoating to prevent steel degradation when transporting hydrogen (e.g. long distance distribution pipelines).	3 production & upscaling	High (2)	<10 Years

Detailed gamechangers

Interview	Name	Gamechanger	Chance of succes	Amount of impact in the market	Time estimated to relevance
Fuel cell 6	*Catalyst materi al replacing platinum*	A new catalyst materials and/or compounds allowing higher electrocatalytic activity and or stability, increasing conversion efficiency and lower degradation.	8 not very likely	Very high (1)	10-15 years
Batteries 7	*Industry level Spatial ALD*	To expand the use of Spatial ALD to industry level, to coat meters of layers quickly and effectively; in a scale that's not yet feasible now.	2	2	5 years
Batteries 8	*Spatial ALD lifetime improvement batteries*	The application of thinfilms on batteries to extend lifetime will get a boost by Spatial ALD because the coatings require minimal material and no vacuum and the coatings are very equal and thin.	1	5	<5
Batteries 9	*NC interface for stability in batteries*	We`re trying to replace lithium cobalt oxide to nickel manganese aluminum due to cost and availability, but the new components lead to batteries with lower lifetime. The solutions could be thin-film coated cathode materials/cathode layers or new additives in the liquid electrolytes to form a newly optimized artificial interface between these materials. The latter has higher chance.	3	1	<5

Detailed gamechangers

Interview	Name	Gamechanger	Chance of succes	Amount of impact in the market	Time estimated to relevance
Batteries 10	*Improved lithium mining*	Lithium mining done differently by Saltworks to increase the mining speed.	2	8	1-3
Batteries 11	*Lithium ion silicon battery*	Lithium ion graphite battery with silicon instead of graphite.	5	5	1-3
Electrolyser 12	*Reduce titanium in electrolysers*	Optimization of the expensive material: Finding alternatives or reducing the use of titanium in electrolysers to reduce cost and to increase production.	5	2	5-10
Electrolyser 13	*Reduce Iridium or platinum in electrolysers*	Optimization of the expensive material: eliminating the use of Iridium or platinum in electrolysers to reduce cost and to increase production.	3	1	1-6
Electrolyser 14	*Low temperature inorganic solid (electrolytes)*	Developments in low temperature inorganic solid (electrolytes) for conductivity at roomtemperature which would make the process cheaper and easier.	8 (very difficult)	2	10-15

Detailed gamechangers

Interview	Name	Gamechanger	Chance of succes	Amount of impact in the market	Time estimated to relevance
Elyctrolyser 15	*Cathalyst layer in electrolyser*	To add a catalyst membrane nanocoating in a electrolyser to prevent degradations and drive the oxygen evolution more efficiently. This will also impact batteries and fuelcells due to a similar cathalyst layer and degradation issues.	2 catalysts and fabrication are already there, putting the pieces together	2	1-5
Elyctrolyser 16	*Monolithic device*	A combined devide: gass barrier, PTL (porous transport substrate) and then the catalyst material (iridium nanocoating in PEM) and then the membrane. This could prevent crossover and conduct ions without energy loss and easier to recycle.	2 components are there but should brought together	2	5-10
17 Photovoltaics	*Solar Perovskite*	The emergent generation new photovoltaic cells from Perovskite. Combined with silicon is 5-7% better converstion effiency. A machine that would combine all deposition layers in 1 machine would improve the cost & production.	Very high (2)	Very high (1)	1-3
Workshop 18	*Liquid deposition of nanocoatings for energy effienct windows for large areas*	Using techniques efficiently and homogeneous to large areas in e.g. advanced windows.	2	4	1-3yr