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Final report

Advanced materials for the energy transition

Study to survey the state of knowledge and technology on the application of advanced materials in the various technologies for the production and storage of renewable energies

by:
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On behalf of the German Environment Agency

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Abstract: Advanced Materials (AdMa) for the energy transition

The climate crisis is the burning issue of our time. In order to avert the impending consequences, global efforts are being made in a wide variety of social and scientific fields. This report looks at a small part of these efforts, a technical aspect, namely the question of which AdMa are currently considered in techniques to support the energy transition. AdMa, i.e. materials that are rationally designed to have new or enhanced properties, and/or targeted or enhanced structural features [OECD 2022], are used in all sectors of the energy transition. Questions of energy generation, storage and saving are considered here. This report is based on literature research and contains a general compilation of various AdMa that are used in the energy transition or are being researched for this purpose. From this compilation, ten materials that are considered particularly relevant for various reasons were selected and examined in more detail in relation to their use. The specific question here lies in the conflicting objective that the development of technologies for the energy transition is welcomed, but the use of AdMa may entail possible challenges in view of chemical safety as well as sustainability and circular economy.

Kurzbeschreibung: Neuartige Materialien (AdMa) für die Energiewende

Die Klimakrise ist das brennende Thema unserer Zeit. Um drohende Folgen noch abzuwenden, werden auf den verschiedensten gesellschaftlichen sowie wissenschaftlichen Gebieten globale Anstrengungen unternommen. Dieser Bericht betrachtet einen kleinen Teil dieser Anstrengungen, einen technischen Aspekt, nämlich die Fragestellung, welche AdMa derzeit und zukünftig in Techniken zur Unterstützung der Energiewende eingesetzt werden könnten. AdMa, also Materialien, die bewusst so konzipiert sind, dass sie neue oder verbesserte Eigenschaften und/oder gezielte oder verbesserte strukturelle Merkmale aufweisen [OECD 2022], kommen dabei in allen Sektoren der Energiewende zum Einsatz. Betrachtet werden hier Fragen zur Energiegewinnung, - speicherung und -einsparung. Dieser Bericht beruht auf einer Literatur-Recherche und enthält eine allgemeine Zusammenstellung verschiedener AdMa, die in der Energiewende eingesetzt werden oder in der Erforschung dazu sind. Aus dieser Zusammenstellung wurden zehn Materialien, die aus unterschiedlichen Gründen als besonders relevant betrachtet werden, herausgegriffen und in Bezug auf ihre Verwendung genauer betrachtet. Die konkrete Fragestellung liegt hier im Zielkonflikt, dass der Ausbau von Techniken für die Energiewende begrüßt wird, aber die Verwendung von AdMa mögliche andere Herausforderungen für die Chemikaliensicherheit, Nachhaltigkeit und Kreislaufwirtschaft mit sich bringen könnte.

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Abbreviation	Explanation
AdMa	advanced materials
CIGS	copper indium gallium (di)selenide
CNT	carbon nano tube
GR2M	Graphene related 2D materials
HC	hard carbon
ITO	indium tin oxide
LIB	lithium ion batteries
MOF	metal-organic frameworks
NP	nanoparticle
OECD	Organisation for Economic Co-operation and Development
PVD	physical vapour deposition
QD	quantum dots
SIB	sodium ion batteries
TRL	technology readiness level

Summary

This report deals with the use of advanced materials (AdMa) in the energy transition, i.e. the question of where and to what extent AdMa are considered to be used to achieve the goal of climate neutrality. To do this, a literature search was first carried out and then a selection of materials was examined in more detail.

First of all, the question arises as to how the term "advanced materials" is to be understood in this context. For this report, the OECD's working description was followed, which states that "AdMa are understood as materials that are rationally designed to have new or enhanced properties, and/or targeted or enhanced structural features with the objective to achieve specific or improved functional performance." In addition, Giese et al. provides a list of material groups that fall under this description.

The second term that needs to be narrowed down is the "energy transition". In principle, one can look at the different sectors of electricity, heat and mobility. In addition, one can distinguish between the three cornerstones of energy generation, energy saving and energy storage or transport. For this report, the latter approach was chosen and the AdMa found were assigned accordingly.

The report begins with a brief overview of the current situation regarding energy transistion with the focus on Germany, followed by an overview on AdMa that are used or investigated for use in the techniques for the energy transition. The situation in Europe and in the rest of the word was considered for an estimation of the future use of the AdMa in energy application. A general literature search formed the basis for an analysis of relevant areas of energy transition and how and which AdMa are used or investigated. Results were transferred into a tabular overview, including information on the state of knowledge and technology. From the AdMa found in this way, which are used in the energy transition in various areas or are being researched for this purpose, ten particularly relevant AdMa were selected and examined in more detail. The relevance was determined based on different criteria that were found important in different ways for the ten materials. On the one hand, the prospect of success of the AdMa or the probability that it will actually be introduced onto the market was considered.. Another relevance criterion is problematic properties, such as material risks or high energy consumption. With regard to environmental pollution or recycling, the question would then have to be answered as to how environmental pollution can be avoided. Another relevance criterion was the consideration of whether harmful substances could be substituted by appliying respective AdMa.

Based on these different criteria, ten materials were finally selected: perovskite, quantum dots, CIGS, aerogels, iridium oxide, MOFs, hard carbon, MXenes, graphene and related 2D materials (GR2M) and CNTs. These materials were then examined to determine how they are or can be used in the energy transition and what challenges and implications their use might feature regarding e.g. resources use, hazards for human and environment or demand needed. .

As a result, on the one hand, AdMa have great potential for the use in all cornerstones of the energy transition. They are either already being used or are being researched for this purpose. On a laboratory scale, you can find the best thermal insulation, the highest levels of efficiency, enormous conductivity and synergy effects by combining several AdMa with one another. On the other hand, in some cases, information on potential implications for human health, environment as well as implications for sustainability of the respective AdMa is still rare. In addition, sometimes their application affords the use of known harmful substances or critical materials and challenges for circular economy are foreseeable. There is therefore still a need to carry out

more detailed investigations here, i.e. in order to improve the knowledge base but also to allow further improvement with regard to safety and sustainability of the applications in AdMa in techniques to support energy transition.

Zusammenfassung

Dieser Bericht beschäftigt sich mit dem Einsatz neuartiger Materialien (AdMa) in der Energiewende, also der Frage, an welcher Stelle und inwiefern AdMa nützlich sein könnten, das Ziel der Klimaneutralität zu erreichen. Hierfür wurde zunächst eine Literatur Recherche durchgeführt und anschließend eine Auswahl an Materialien näher betrachtet.

Zunächst stellt sich die Frage, wie der Begriff „neuartige Materialien“ in diesem Zusammenhang zu verstehen ist. Für diesen Bericht wurde sich an die Arbeitsbeschreibung der OECD gehalten, die besagt, „dass man unter AdMa Materialien versteht, die bewusst so konzipiert sind, dass sie neue oder verbesserte Eigenschaften und/oder gezielte oder verbesserte Strukturmerkmale aufweisen, mit dem Ziel, eine bestimmte oder verbesserte Funktionsleistung zu erzielen.“ Darüber hinaus liefert Giese et al. eine Liste von Materialgruppen, die in diese Beschreibung fallen.

Der zweite Begriff, der einzugrenzen ist, ist die „Energiewende“. Hier kann man prinzipiell die verschiedenen Sektoren Strom, Wärme und Verkehr betrachten. Zudem kann man unterscheiden zwischen den drei Eckpfeilern Energiegewinnung, -einsparung und -speicherung bzw. -transport. Für diesen Bericht wurde insbesondere die letztere Betrachtungsweise gewählt und gefundene AdMa entsprechend zugeordnet.

Der Bericht beginnt mit einem kurzen Überblick über die aktuelle Situation der Energiewende mit dem Fokus aufDeutschland, gefolgt von einem Überblick über AdMa, die in der Energiewende verwendet oder untersucht werden. Die Situation in Europa und im Rest der Welt wurde berücksichtigt, um eine Einschätzung der zukünftigen Nutzung von AdMa in Energieanwendungen zu geben. Eine allgemeine Literaturrecherche bildete die Grundlage für eine Analyse der relevanten Bereiche der Energiewende, gefolgt von einer tabellarischen Übersicht über den Stand des Wissens und der Technik. Aus den auf diese Weise gefundenen AdMa, die in der Energiewende in den verschiedenen Bereichen eingesetzt oder dafür erforscht werden, wurden zehn besonders relevante AdMa herausgegriffen und näher untersucht. Die Relevanz wurde dabei an unterschiedlichen Kriterien festgemacht, die für die zehn Materialien in unterschiedlicher Weise bedeutend waren. Betrachtet wurde zum einen die Erfolgsaussicht, des AdMas bzw. die Wahrscheinlichkeit, dass es tatsächlich in den Markt eingeführt wird. Ein anderes Relevanzkriterium sind problematische Eigenschaften, wie stoffliche Risiken oder auch ein hoher Energieverbrauch. Ein weiteres Relevanzkriterium stellte die Betrachtung dar, ob schädliche Stoffe substituiert werden könnten.

Auf Grundlage dieser verschiedenenKriterien wurden schließlich zehn Materialien ausgewählt: Perowskit, Quantum Dots, CIGS, Aerogele, Iridium Oxid, MOFs, Hard Carbon, MXene, Graphen und verwandte 2D Materialien (GR2M) und CNTs. Diese Materialien wurden nun daraufhin betrachtet, welche Anwendung sie in der Energiewende haben oder haben könnten und welche Herausforderungen und Auswirkungen sie hinsichtlich z.B. Ressourcennutzung, Gefährdungen für die menschliche Umwelt und Gesundheit oder dem benötigten Bedarf darstellen.

Als Ergebnis findet man auf der einen Seite großes Potential von AdMa in der Nutzung für alle Eckpfeiler der Energiewende. Entweder werden sie hier bereits eingesetzt, oder sind dafür in der Erforschung. Im Labormaßstab lassen sich durch die Kombination mehrerer AdMa miteinander beste Wärmedämmung, höchste Wirkungsgrade, enorme Leitfähigkeit und Synergieeffekte erzielen. Andererseits sind Informationen über Risiken der jeweiligen AdMa in manchen Fällen noch wenig verfügbar und darüber hinaus erfordert ihre Anwendung mitunter den Einsatz bekannter Schadstoffe. Darüber hinaus können ihre Anwendungen die Verwendung bekannter schädlicher Stoffe oder kritischer Materialien erfordern. Zudem sind

Herausforderungen für die Kreislaufwirtschaft absehbar. Hier besteht daher noch Bedarf an detaillierteren Untersuchungen, um einerseits die Wissensbasis zu verbessern, andererseits aber auch um weitere Verbesserungen hinsichtlich der Sicherheit und Nachhaltigkeit von Anwendungen mit AdMa in Techniken zur Unterstützung der Energiewende zu ermöglichen.

1 Introduction

Objective of this study was to provide the current state of knowledge and technology on advanced materials (AdMa) in technologies of relevance for the energy transition. In addition to that, for selected AdMa, challenges and concerns regardings human health and environmental safety as well as sustainability issues should be highlighted and the expected demand in the coming years should beestimated. The report provides a systematic overview of the application of AdMa in the generation, saving, and storage of energy, including in the transport sector. Based on criteria for potential market introduction, existing challenges in the use of materials, high energy consumption, environmental protection, and overall life-cycle assessment, ten materials were selected and analyzed in more detail. For this study, scientific literature and publicly accessible publications were used. It must be explicitly stated that this report does not claim to be exhaustive due to the multitude of sources, but it reflects the essential developments in this field from the authors' perspective.

1.1 Energy transition with the focus on Germany

The term energy transition was introduced as early as the 1980s. Today, the topic is more relevant than ever. With the Green Deal (2019), the EU has formulated ambitious goals for the energy transition. The EU's goal here is to be climate neutral by 2050. Germany wants to be climate neutral by 2045 and by 2030 Germany has committed itself to reducing the CO_2 emissions by 65% compared to 1990 (BMWK 2024). To achieve this, the amount of renewable energies gained is to be increased. From a global perspective, the energy transition was formulated as a political objective in 2016 with the Paris Climate Agreement and the UN's "Sustainable Development Goals" (Goal 7: Affordable and Clean Energy) (United Nations).

The topic of energy transition includes three main areas: Energy saving, i.e. the reduction of energy consumption, e.g. through greater efficiency, energy generation, i.e. the switch to mainly renewable energy sources, such as wind power, solar energy, hydropower, geothermal energy or energy obtained from renewable raw materials. And finally, it includes energy storage, i.e. infrastructure issues in terms of storage and transport of energy and heat, including in the context of electromobility, are also part of the energy transition.

In the energy transition one can distinguish between three main areas: electricity generation, heat generation and the transport sector. The public debate usually focuses on electricity generation, but energy consumption in the other sectors is considerable (IEA 2025). The transport sector in particular plays a major role here (see Fig. 1).

If we first look at electricity generation, renewable energies already have a significant influence. Here one can distinguish between wind energy, solar energy, energy through the use of biomass, hydropower and geothermal energy. Wind energy is the source of electricity in Germany, with the largest share, followed by brown coal and photovoltaics (see Fig. 2). The supply from wind and sun is heavily dependent on the weather, season and time of day.

With wind energy, one renewable energy source currently has the largest share of the electricity mix in Germany. However, if the government's goals are to be achieved, further massive expansion or further development is necessary. Further developments here are moving in the direction of finding digital solutions, for example, the best location, and optimizing the materials used so that more efficient energy generation is possible (Wenske et al. 2018).

If we look at the government's goals for the expansion of renewable energy sources, the expansion of wind energy is currently behind schedule, while the expansion of solar energy is currently in line with the goals (Zeit Online 2024). Figure 2 shows a current overview of the composition of energy sources for electricity generation in Germany. However, smaller power plants are not required to be reported, which leads to an underestimation of solar energy generation and electricity generation from biomass (Zeit Online 2024). The combination of wind and solar energy is crucial and should be balanced, as both forms of energy reach their maximum production at different times (see Fig. 3). One problem is the lack of or limited storage options. In general, wind power plants are more likely to be found in the north and solar power plants in the south of Germany. The federal government's goals state that the electricity grid should be completely converted to renewable energies by 2035 (BMWK 2024).

In the field of photovoltaics, other markets such as China, the USA, and Japan have developed more dynamically than the German market in recent years. The main reason for this growth was the significantly reduced prices for solar panels. While Germany was leading in the production of electricity from photovoltaics until 2015, it has now ceded this position to China. Between 2020 and 2023, average global growth rates of 40% were achieved, with China accounting for 60% of this growth. Even if growth slows to an annual rate of 20%, the newly installed capacity in 2030 will reach 1 TW, which roughly corresponds to the total installed capacity of 2022 (Quatschning 2024). The transport transition relies on electric cars instead of cars using gasoline. Since the average lifespan of a car is 10 years, no new cars with combustion engines are to be registered from 2035 onwards in order to be climate neutral by 2045 (Bundesregierung 2024). However, little progress has been made in recent years and energy consumption remains at a high level, as can be seen in Figure 1.

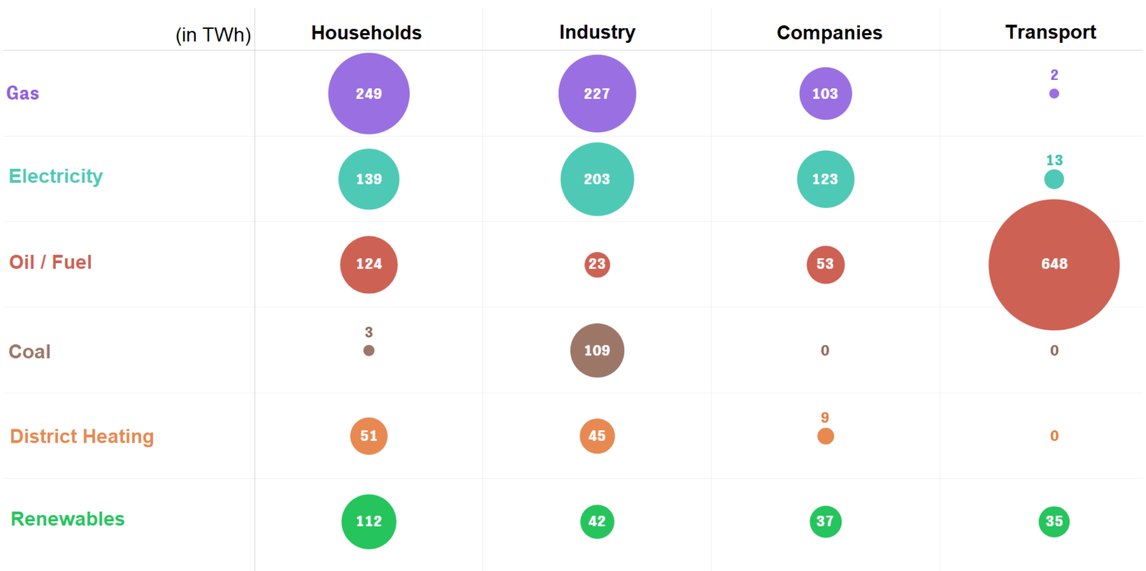
The world's dominant market for electric mobility is China, with a share of 57% of all newly registered battery-powered vehicles worldwide in 2023. Europe follows with 22%, and the USA with 13%. Although Germany is the largest sales market in Europe in terms of volume, it only had below-average growth of 11% in 2023. Due to the still low prevalence of fully electric cars in Europe and Germany, the share of these vehicles among all registered vehicles remains relatively low, at around 15% for fully and partially electrified vehicles in 2024. In China, this share is over 35% (CAM 2024).

Natural gas currently still plays a major role in the heat transition. Almost a third of Germany's energy needs are covered by it (Statistisches Bundesamt 2024). Here, a distinction can be made between households that use natural gas for heating and industrial applications. Although heat pumps are now the most common energy source in new buildings, the building sector with its existing buildings is rather slow. Here, longer-term considerations must be made than in the other two sectors.

If we look at all sectors of the energy transition together, we can see only a small change over the last 30 years. In the electricity sector, however, renewable energies now account for a large share. In addition, the nuclear phase-out in Germany was completed in April 2023. This initially led to higher numbers of electricity imports, although most of these came from renewable sources. In Germany itself, there is a lack of sufficient energy storage for a complete switch to renewable energy sources, particularly wind and solar energy, which reach their maximum production depending on the weather. In the building sector, heat pumps are the most common heat source in new buildings, accounting for more than 50%, but only minor changes can be observed in both the housing stock and the transport sector. Subsidies and political decisions also have a major influence. For example, the feed-in tariff for solar energy fell in 2012, after which its expansion collapsed, and subsidies for electric cars expired in August 2023, which led to a decline in new registrations.

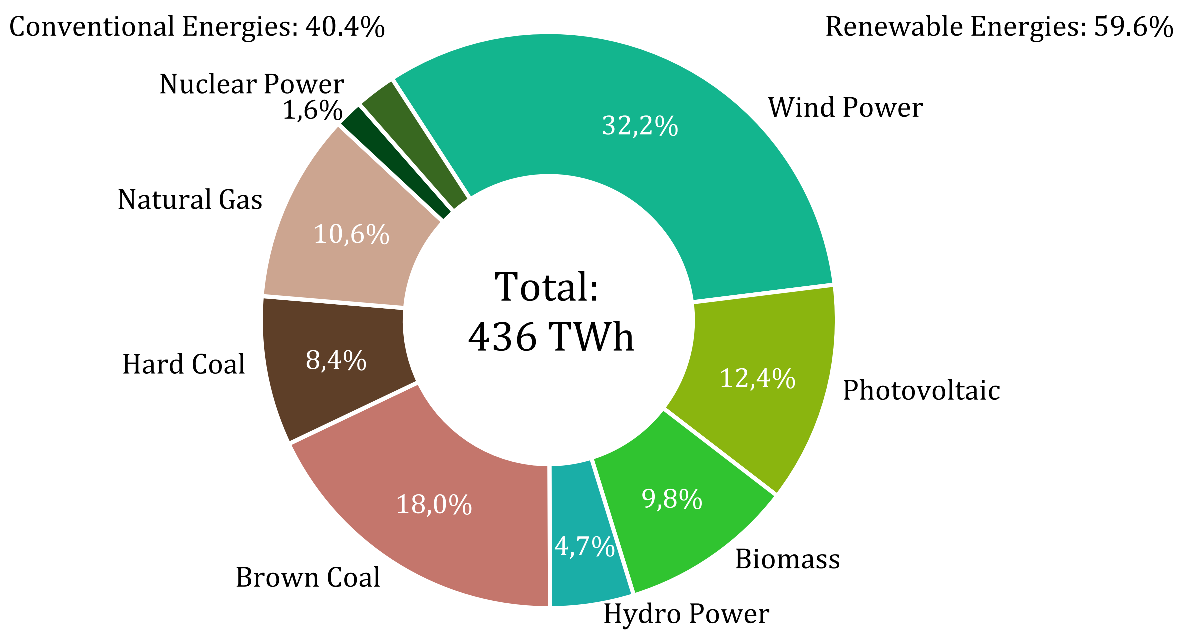
Various raw materials play a crucial role in the technical implementation of the energy, heat and mobility transition. These include copper, cobalt, nickel, lithium, neodymium, dysprosium and graphite (Gielen et al. 2021) in particular, but other raw materials are also used (see Fig. 4). Their mining and use sometimes poses great risks to the environment. In addition, there is sometimes a high level of land use during mining or high energy consumption during extraction. Social or economic aspects, such as political dependencies or the availability of raw materials, also play a role. This is one of the reasons why there is an effort to replace critical raw materials by AdMa. The AdMa used are partly made of these raw materials themselves but have other advantages due to their special properties. Furthermore, the use of AdMa in the energy transition is expected to result in, among other things, greater efficiency and/or greater longevity. They are present, for example, in solar panels for energy generation, in thermal insulation for energy saving, in the production of energy sources such as hydrogen for energy storage. These materials represent an improvement through new properties, but also possible new risks for people and the environment due to dangerous material properties or may imply new challenges regarding sustainability. Possible exposure should not be ignored, nor should be End of Life considerations, e.g. recyclability.

Figure 1: Energy consumption by sectors in Germany in 2022



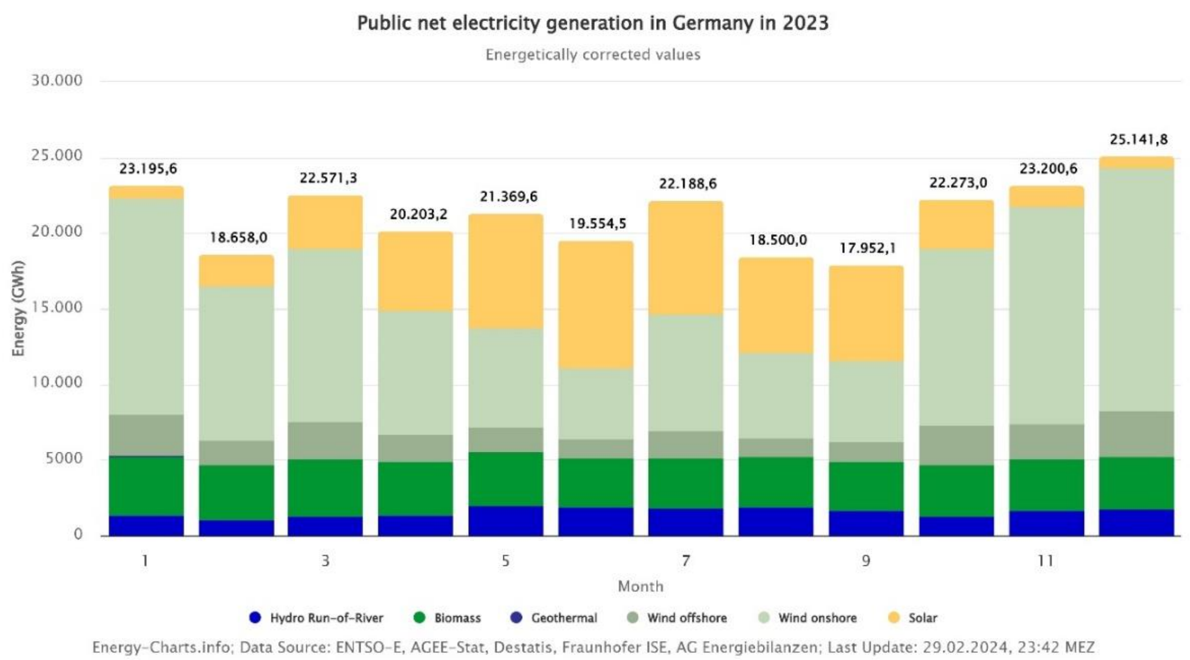
Source: adapted from (Zeit Online 2024)

Figure 2: Current composition of energy sources for electricity generation in Germany 2023



Source: adapted from (Strom-Report 2024a)

Figure 3: Distribution of electricity generation from renewable energies in 2023 broken down by month



Source: Burger 2024

Figure 4: Material compositions of current technologies in 2022

Technology		Steel	Al	Cu	Pb	Zn	Ni	Ag	Si	Sn	In	Ga	Se	Cd	As	Nd	Dy	Pt	Ti	Va	Li	Mn	Co
Photovoltaic	PERC	x	x	x	x			x	x	x													
	SHJ	x	x	x	x			x	x	x	x												
	CIGS	x	x	x						x	x	x	x	x									
	III-V/Si	x	x	x				x	x	x	x	x			x								
Wind	EESG	x	x	x																			
	PMSG-MS	x	x	x	x											x	x						
	PMSG-DD	x	x	x	x											x	x						
Power-heat coupling	GuD	x	x	x																			
Heat pump	Air-Water	x	x	x																			
Gas condensing boiler		x	x	x		x																	
Solar thermal power	Collectors	x	x	x																			
Fuel cell	PEMFC	x		x														x	x				
Power-to-X	AEL	x	x	x			x																
Batteries	VRF	x	x	x																x			
	NMC Li-Ion	x	x	x			x														x	x	x
Heat accumulator	Liquid	x																					
Transmission system	AC	x	x																				
	DC	x		x	x																		
Renovation	Isolation	x				x																	

Source: adapted from (Senkpiel et al. 2022)

1.2 Advanced materials for the energy transition

AdMa are materials that have been rationally designed in such a way that their properties are improved compared to the use of conventional materials. This rough description covers a wide range of materials that can be understood as advanced depending on their application. The time factor also plays a role here. What is advanced today maybe not in the future. Initially, the term “AdMa” was used synonymously with nanomaterials, but over the years it has become increasingly clear that AdMa should not only be limited to nanomaterials, which according to the definition recommendation of the European Commission have a dimension of up to 100 nm and only contain solids (Commission Recommendation 2022). Rather, a description of AdMa should be based on the functionality of the materials. With regard to nanomaterials, it has long been known that materials on this scale have different properties than the same material on a larger scale. However, the transition is fluid and 100 nm as a discrete limit is rather arbitrary. Thus, the term AdMa includes not only certain nanomaterials but also materials whose properties have additional complexity or improvement. In terms of chemical safety and risks to humans and the environment, similar considerations must be made here as with nanomaterials. The term AdMa is therefore an extension and also includes part of the group of nanomaterials. The description of AdMa is therefore also based on physical properties that affect not only the elemental composition and size of the material.

The term AdMa is also used differently in different contexts. In order to create clarity here, the OECD developed a working description, which is also used in this report ("Working Description on Advanced Materials (WD AdMa)" according to ENV/CBC/MONO(2022)29 of 16 January 2023 (OECD 2022)):

“**Advanced Materials: Working Description**

AdMa are understood as materials that are rationally designed to have

- new or enhanced properties, and/or
- targeted or enhanced structural features

with the objective to achieve specific or improved functional performance. This includes both new emerging manufactured materials, and materials that are manufactured from traditional materials. This also includes materials from innovative manufacturing processes that enable the creation of targeted structures from starting materials, such as bottom-up approaches. It is acknowledged that what are currently considered as AdMa will change with time.”

Annex A of the OECD working description gives examples of various AdMa based on the categorization proposal by Giese et al. (Giese et al. 2020) into biopolymers, composites, porous materials, metamaterials, particle systems, advanced fibres, advanced polymers, advanced alloys and smart nanomaterials. The list is not exhaustive.

Not all of the material groups considered as AdMa are equally relevant to questions of the energy transition. There is little in the literature on the application of biological materials, for example. Other materials are more likely to be used in energy production than in energy conservation, or vice versa. This report examines which AdMa are relevant for which energy transition technologies.

The use of AdMa can result in new risks for humans and the environment (Monikh et al. 2023), for example in the case of the environmental impact of AdMa with dangerous properties or in the case of AdMa in consumer products with a potential direct exposure to consumers. In the context of sustainability, it is important to assess the ecological footprint of AdMa or the products in which they are used in order to be able to assess their actual benefit for the overall green transition. Descriptions of the AdMa categories as proposed by Giese et al. and short estimates of their potential risks can be found in Giese et al. 2020 or in the factsheets according to Oekopol (Drapalik et al. 2020).

A side note:

There is currently a discussion about the extent to which materials should be described as "advanced", "innovative", "emerging" or similar. See, for example, the " Roadmap Safe and Sustainable Advanced and Innovative Materials 2024-2030" of the NanoSafety Cluster (Cassee et al. 2024). This report deliberately does not address this current discussion and adheres to the OECD's working description on AdMa. However, it must be noted that not all materials mentioned in the report are strictly covered by what is understood to be an AdMa e.g. within the OECD, but their use in energy transition might considered as advanced due to their functionalities or features (e.g. CNT) or that they come along with emerging challenges, e.g. with regard to End of Life considerations (e.g. carbon fibres) or Life Cycle Assessement.

2 Methodological approach

The aim of this report was to obtain a systematic overview of relevant AdMa in the energy transition based on a literature search. The question addressed here is which AdMa are and can be used in the energy transition. However, it is important to consider which of these materials actually have a chance of being used on a large scale and that these materials can also pose risks to the environment and humans. Based on different criteria ten AdMa were therefore examined in more detail.

In order to find out which AdMa are or could be used in the energy transition in future, a literature search was carried out. The approach here was from the general to the specific. The search platforms used were primarily the Web of Science and Google Scholar. A systematic research on AdMa of relevance for the energy transition can be approached from two views, one from the perspective of the material and the other from the perspective of the application. Both perspectives were considered and combined for the search.

Search terms were accordingly starting from "advanced materials" AND "energy transition", going to terms such as "advanced materials" AND "solar energy", "advanced materials" AND "wind energy", "advanced materials" AND "biomass", "advanced materials" AND "hydropower", "advanced materials" AND "geothermal energy". The search was then further specified to include more specific components of the energy sources such as "advanced materials" AND "solar cells"; "advanced materials" AND "wind turbines", advanced materials" AND "generator" for energy generation from renewable sources. For energy saving, the combination was then with terms such as "(thermal) insulation", "(increasing) efficiency", "energy saving" and for energy storage, a combination with terms such as "storage", "batteries", "hydrogen (production)". Instead of the term "advanced materials", the terms from the OECD Working Description in Annex A were used, i.e. "Biopolymers" AND "Energy Transition"; "Biolpolymers" AND "Solar Energy" etc. then "Composites" AND "Energy transition"; "Composites" AND "solar energy" etc. up to "smart nanomaterials" AND "energy savings".

For further research, review articles, publications marked as "hot papers" and "highly cited papers" were used. Publications that were no older than 10 years were considered in particular. When reviewing these publications, the publications cited therein that were relevant to the topic were also considered. This approach revealed materials that were of further interest. Based on these the search was generally refined, for example to "Perovskite" AND "application" or "properties", "structure", "advantages", "synthesis" or "lifecycle", "hazards", "risks", "sustainable", "SSbD", "substitution" or search terms adapted to the most common application. In the example of perovskites, which are often used in solar cells, e.g. "perovskite" AND "quantum yield"; "efficiency" was used.

Of additional relevance was the technological readiness of the identified AdMa in their respective applications. The classic application of TRLs 1-9 is difficult here because the descriptions on technical maturity in the found literature are sometimes not clear enough or rather vague. To avoid misunderstandings, some TRLs were merged and called "under research", "in development" and "market readiness".

"Under research" here means TRL 1-3, i.e. the description of the idea or concept, numerical simulations and initial experiments in the laboratory. The second stage, "in development", means TRL 4-6, i.e. the first test setups in the laboratory, the development of the first prototypes and the testing of prototypes in the real environment. The third stage, "market readiness", means TRL 7-9, i.e. from the use of the first prototypes, the market launch to regular use and serial production.

Depending on the state of development of the application of the material in the energy transition, the search was moved away from the Web of Science. Now, for example, the websites of research institutions (Fraunhofer, Max Planck, DFG, etc.) were searched for current research projects on the topic, and conventional search engines and statistical overviews from the German Federal Statistical office or market research consulting service (Furion analytics Research and Consulting LLP™ 2024) were used to assess market readiness and to find companies that are already bringing products onto the market.

Using this methodological approach, around 700 websites and publications were found. After reading the abstracts, the sources suitable for the research question could be filtered out. Based on this literature research, a systematic overview of AdMa relevant to the technologies of the energy transition was created. It has to be noted that this report does not claim to provide a complete list of all AdMa that are or could be used in energy transition. Based on the systematic overview, ten AdMa considered particularly relevant were selected for more detailed analysis.

3 Results

3.1 AdMa in technologies relevant for the energy transition

As the cornerstones of the energy transition, questions of energy generation, energy saving, and energy storage must be considered. AdMa are used here at various points. The use of AdMa in the following areas of energy transition is explicitly addressed in this report:

- Energy generation
  - Wind energy
  - Photovoltaics
  - Hydropower
  - Solar thermal energy
  - Geothermal energy
- Energy saving
  - Thermal insulation
  - Increasing efficiency
- Energy storage and transportation
  - Batteries
  - Hydrogen

3.1.1 Energy generation

3.1.1.1 Wind energy

Wind energy is the most important source of energy and electricity in Germany. At the beginning of 2023, 29,982 wind turbines were installed. In 2023, 138.6 TWh of electricity was generated by wind power (Strom-Report 2024b). A rapid expansion of wind energy as the most important renewable energy source in Germany is crucial for the energy transition. Not only the sheer number of new wind turbines is of interest here, but also, for example, a larger span of rotor blades is necessary, or a greater height. The mechanical stress on the material is the main challenge for wind turbines. Weather influences place special demands on the material due to the large forces that occur. Withstanding precipitation, solar radiation or storms is already difficult for onshore systems. This is even more true for offshore systems. Added to this are waves, the influence of salt water and the more complicated maintenance of the systems. The rotor blades, supporting structures and foundations are particularly stressed (Dashtkar et al. 2019).

This is where innovative building materials come into play, and so do AdMa. These are used in lightweight construction with high-strength steels to optimize component stress. Fibers and 2D materials with enhanced functionalities are still being in development for the use in composite materials. Composites made of carbon and glass fibers are used in the manufacture of wind turbines for some time but brought into attention recently due to the challenges they pose in the context of the recycling of dismantled wind turbines. Reinfored composites on the one hand lead to weight reduction and on the other hand to greater structural strength.

When expanding wind power, it is not just the number of new wind turbines that is crucial, but also their size. In modern wind turbines, especially in the offshore sector, rotor blades reach lengths of up to 120m. These large dimensions pose new challenges for the material for all parts of the wind turbine. High-strength steels are also used here (Zhang et al. 2019). AdMa are also used here in the sense of new alloys. Microalloys with titanium and niobium are particularly worth mentioning (Schroeder et al. 2023). These are used, for example, in the foundations of wind turbines. Low-transformation temperature alloys used in weld joints in high-strength steels are also discussed as AdMa (Igwemezie et al. 2022). Wind blades are usually manufactured as structures containing several materials, here typically glass, carbon fibers or hybrid fabrics are used (Hiremath et al. 2020). These materials are combined with wood, to meet the challenges of lightweight (Rubino et al. 2020). Here the recycling of the material is a critical challenge (Rani et al. 2021), (Blade2024).

High-performance paint-based coatings mixed with nanoparticles are used on the rotor blades themselves. These coatings protect wind turbines from environmental influences. This is particularly necessary in the offshore sector. Ice-free, hydrophobic and actively heatable surfaces (Zhang et al. 2023) are used here as thin layers in the nanometer range. Hard material protective coatings applied by PVD (physical vapour deposition) are used in bearings and drive units to reduce friction and as wear protection (Seyfert et al. 2022).

3.1.1.2 Photovoltaics

In 2023, 1581 GW electricity were produced with photovoltaic worldwide, of which 81.4 TW were produced in Germany (Quatschning 2024) which account for 12% of the electricity generated in Germany. An increase to 215 GW until 2030 and 400 GW until 2040 is prescribed by national law (EEG 2023 – Gesetz für den Ausbau erneubarer Energien) (Wirth 2024). At the beginning of 2024, 3.7 million solar systems have been installed in Germany (Strom-Report 2024c). In photovoltaics, improvements with the help of AdMa offer a lot of potential.

Thin layers in particular (i.e. in the nanometer range) are already being used in solar cells. There are different ways for the application of these thin films (Hossain et al. 2023). AdMa help to reduce the reduction in performance through the recombination of charge carriers and to reduce losses due to reflection, absorption or shading.

A relevant example is PERC cells (passivated emitter and rear cell). Here, the back is provided with a thin dielectric layer that is first perforated by laser and then aluminum is vapor-deposited onto it. This clever use of materials leads to point-by-point contact with the wafer and the subsequent reflection of light waves that have passed through the wafer on the back. This leads to the renewed formation of charge carriers and thus the increase in the efficiency of the solar cells. Another form of solar cell that uses thin layers is HJT (heterojunction technology) solar cells. Their structure consists of an n-doped Si wafer on the inside, which has thin layers of doped and intrinsic amorphous Si on both sides. In addition, the outermost layer is an ITO (indium tin oxide) layer, i.e. a transparent conductive layer made of indium tin oxide. This structure enables high light output and good passivation properties. This makes it possible to achieve efficiencies of more than 24% and lower temperature coefficients. The production of these solar cells requires less energy and fewer production steps compared to PERC cells.

Another thin-film type is TOPCon cells. Here the back consists of a thin tunnel oxide, while the middle consists of a highly doped polycrystalline Si layer. This prevents the recombination of the charge carriers at the contact.

Perovskite solar cells are currently being discussed a lot. Perovskites are hybrid materials made of organic and inorganic materials. Perovskite solar cells consist of many thin layers. In a simple perovskite absorber, sunlight releases electrons from the bound state. In the electronically excited state, holes remain. Electrons and holes are removed from different sides of the absorber using selective membranes made of metal halide. Efficiencies of these simple solar cells are 25%. One advantage here is that the entire spectral range of visible light is used.

A tandem cell now combines the positive properties of the conventional Si solar cell by applying thin perovskite layers. Light up to the near infrared range (NIR: about 800nm to 2500nm) penetrates the perovskite layer and is converted into electricity there. Efficiencies of up to 30% can be achieved here. Efficiencies of up to 40% are theoretically possible. A disadvantage here, however, is the comparatively shorter service life (Seyfert et al. 2022); for a further discussion see 2.3.1.1.

3.1.1.3 Hydropower

With 20.4 TWh, hydropower accounted for 4.7% of German electricity generation (Strom-Report 2024a). In Germany, this technology is therefore less relevant than wind power or solar energy, but in the North Europe or in the Alpine region this amount is much higher with values between from 50 % up to 90 % of the electricity generation. Nevertheless, there is still the possibility of making the systems more efficient. Developments in wind power also benefit hydropower. For example, high-strength alloys are used in turbines, which can significantly reduce wear. Microalloys with titanium and niobium are also used here (Schroeder et al. 2023).

3.1.1.4 Solar thermal energy

Solar thermal energy does not use the photoelectric effect as in photovoltaics, but the heat radiation from the sun. Single-layer metal ceramic coating materials consisting of e.g. Al, Ni, SiO_2, Si_3N_4 or Al_2O_3 are used here in optically effective layers made of ceramic material (Sing et al. 2024). This layer acts like an optical filter. Incoming light is let in, but the layer is not transparent for heat radiation. This means that radiation is reflected and does not penetrate to the outside.

AdMa like nanostructured materials are also used on the heat transfer pipe. Here they ensure the absorption of visible light and the inhibition of the radiation of heat. Efficiency levels here are 20-30%.

3.1.1.5 Geothermal energy

Geothermal energy does not play a large role in electricity generation in Germany (less than 1 %). In contrast, ca. 12 % of renewable heat in Germany is produced by geothermal or environmental heat with a relative increase of 18 % annually (Adam 2024). Worldwide leading countries in geothermal power generation are USA, and Indonesia (Huttrer 2021). A high percentage of 27 % of electric production and 65 % of primary energy production was reported for Iceland (Government of Iceland 2025), The use of AdMa is not reported in this field to our best knowledge.

3.1.2 Energy saving

3.1.2.1 Thermal insulation

There are not just questions about energy generation from renewable energy sources that are relevant to the energy transition. Questions about energy saving are just as crucial. In addition to social questions, such as the expansion of public transport or similar, there are also questions about the technical implementation of energy saving, e.g. in the area of thermal insulation. AdMa are also used here.

Functional nano-coatings on glass panes are used to insulate buildings and vehicles against heat loss (Kim et al. 2020). These ensure efficient heat and sun protection and thus reduce energy requirements. Material savings are also possible with building-integrated photovoltaics [von Adrenne].

Switchable glazing which have already been in development for a while also offers new possibilities. Transparent, electrically conductive thin indium tin oxide (ITO) layers are applied here. These layers enable dynamic changes in the properties of the glazing. For example, so-called electrochromic glass can be dimmed, which means it offers adapted sun and heat protection.

The use of AdMa in classic thermal insulation can be found in research in the form of highly porous materials such as cellulose nanofiber aerogels made of (ZrP/RGO) nanosheets or also through polymer-based metamaterials (Chai et al. 2022).

3.1.3 Energy storage and transportation

3.1.3.1 Batteries

A cross-sectional issue in the energy transition is the storage of energy obtained from renewable energy sources. This applies to both electricity and heat. On the one hand, classic batteries are suitable for storing electricity, but the topic of hydrogen is also on everyone's lips.

When it comes to batteries, and electromobility as a major application, there are various developments in which AdMa are used.

Fiber-reinforced aerogels (Bausch et al. 2023), nanocarriers (Ahn et al. 2022) are investigated to stabilise batteries against thermal runaways and also thin films (Ondrejka et al. 2023) play a role to improve various battery components of lithium-ion batteries (LIB). In classic batteries, one can counteract reduced performance, fires and premature failure by applying physical vapour deposition (PVD) for producing thin films of metal oxide, metal chalgogenides and carbon-based materials. Carbon-based coatings on current collector contact foils lead to a reduction in contact resistance, an increase in current carrying capacity and an increase in corrosion protection. Al coatings on plastic foils are being discussed as current conductors.

Solid-state electrolyte materials consisting of ultrathin membranes are also being used in solid-state batteries, which, for example, leads to an increase in ion storage capacity (Wang et al. 2022). Different Li-containing materials like perovskite, mixed phosphide, sulfide or halogenides are used. New anion-framework based superionic conductors (e.g. fluoride, mixed anions, and high entropy materials) are discussed. Porous substrates or optimized preparation methods have led to high-areal-capacity solid-state electrodes to increase the energy density significantly, to shorten the charging time, and to increase the number of charging cycles. These high-performance batteries are found in electronic devices as well as in electric cars, for example. The use of Li batteries is state-of-the-art here.

However, since lithium is only present in small quantities in the earth's crust and its mining is associated with high environmental risks, sodium-ion batteries (SIB - Sodium Ion Batteries) have been developed. This is a very recent development: SIBs were launched on the market in 2023 and at the end of 2023 the first electric car with a SIBs battery even came onto the (Chinese) market. In this case, sodium replaces lithium, but is an element that is much more common in the earth's crust. One disadvantage here, however, is that the voltage depends heavily on the state of charge. The main hope of substituting Li with Na is that it will reduce environmental impact, but also reduce costs due to the higher occurrence of Na in the earth's crust. From a political point of view, regional independence is also hoped for.

Materials are now being replaced in SIBs compared to LIBs. HC (hard carbon) is promising as an anode material, or CoreShell Carbon with deliberately designed pore structures and surface functionalization. Precious metals in electrocatalysts can be replaced by MPEA (multi principal element alloys). These have promising catalytic activity and long-term stability.

3.1.3.2 Hydrogen

Hydrogen is considered the energy storage medium of the future. For hydrogen, value chain considerations from production to transport, storage and use are of special importance.

Green hydrogen is produced by electrolysis from water using renewable energy sources. Bipolar plates made of stainless steel are now used here, instead of graphite as was previously the case (Wang et al. 2003). These are where H_2O is converted into H_2 and O_2.. In addition, a coating applied by PVD can be used to protect surfaces from corrosion and reduce contact resistance.

Hydrogen is used to store unused energy. It can be used for reconversion to electricity or as a fuel. For transport of hydrogen in the natural gas network, it can be converted into synthetic methane with CO_2 and fed into the natural gas network. So far, only low levels of efficiency have been achieved. Advantages are expected from catalytically active nanoscale surfaces. For example, research is being carried out on a nanoscale lanthanum nickelate ($LaNiO_3$) surface as a catalyst (Seyfert et al. 2022).

The transport of H_2 is critical in systems designed for natural gas (mostly methane - CH_4). Since H_2 molecules are very small, they can penetrate the surfaces. This leads to embrittlement, cracking or fractures. One solution here is coating with MAX phase materials applied by PVD. MAX phases are nanolaminar layer stacks made of ternary nitrides and carbides, e.g. Ti_2AlN (M stands for early transition metals; A stands for elements of group A in the periodic table; X stands for C or N) (Groener et al. 2020). This coating provides a combination of metallic properties (machinability / conductivity) and ceramic properties (high melting point / rigidity). Another possibility is to use high-strength steels with an alloy containing titanium and niobium. In fact, this problem only affects some pipelines. Around 95% of the network is suitable for H_2. However, converting the natural gas network to H_2 also creates other problems. Many components that are not designed for H_2 must be replaced, such as all components for measuring, controlling and regulating, gas meters in the house, all seals in the network, boilers and consumption systems.

AdMa are used not only in pipelines, but also for hydrogen storage. Combining glass capillaries and carbon fibres in a polymer matrix can lead to a lightweight composite material (Beck and Prewitz 2024).

3.2 Systematic overview

In the energy transition, different AdMa are used in different areas of application. The following tables provide an overview of different AdMa that were found during the literature research, sorted by area of application. The "State" column indicates the status of development of A: "Under research", which means approximately TRL 1-3, B: "in development", which corresponds approximately to TRL 4-6, and C: "market readiness", which is equivalent to approximately TRL 7-9 (see section 2).

Table 1: AdMa for energy generation

Type of energy generation	Component	AdMa	State	Remark	Source
Wind energy	Coating of blades	Cu2(OH)3NO3	A	Preventing the icing of wind turbines through a combination of different nano-coatings. Hydrophobic coatings are used in combination with actively heatable layers Cu2(OH)3NO3 is discussed in a slice-like structure on copper foil, as it shows superhydrophobic properties.	(Zhang et al. 2023, Liu et al. 2024)
Wind energy	Bearig of blades	NBBS (nanostructured bainitic bearing steel: Includes C, Mn, Cr, Mo, Ni, Cu, W, N)	C	Nanostructured bainitic bearing steel: enhanced mechanical properties like hardness, toughness, wear resistance	(Zhang et al. 2019)
Wind energy	Blades	polymer composites, e.g. Al_2O_3, ZrO_2, or CeO_2 nanoparticles-reinforced epoxy coatings	C	strength, durability, flexibility, ease of fabrication, low cost, protection against erosion by rain and solid particles	(Bera et al. 2023)
Wind energy	Coating of blades	hybrid-coating GPTMS-MTEOS-GrOx-PFAS (glycidoxy propyltrimethoxy silane -methyltriethoxysilane - Graphne oxide - per- and polyfluoroalkyl substances)	B	Anti-corrosion coating	(Dashtkar et al. 2019)
Wind energy	Blades	Graphene	C	Graphene is strong, high stiffness, extremely light, high thermal conductivity, can carry heat; So, hybrid composites	(Dashtkar et al. 2019)

Type of energy generation	Component	AdMa	State	Remark	Source
				are built which are strong, tough, thin and light.	
Wind energy	Blades	FKV (fiber-plastic composites), AFK (aramid fiber-reinforced plastic);	C	Rotor blades of wind turbines (high strength, rigidity and weight saving); Commonly used in rotor blades: Material savings enable the construction of large, lightweight rotor blades	(Kraus and Trappe 2021, Raj et al. 2023)
Wind energy	Turbines	Ceramic fibers in nano laminar matrix	A	Turbines, heat resistance up to more than 1000°C	
Wind energy	Coating of blades	SiO_2	A	coating prepared by sol–gel method: Hydrophobic coating, erosion-, corrosion- and abrasion-resistant coatings; as substitute for environmentally unfriendly Cr surface	(Dou et al. 2016)
Wind energy	Coating of blades	CNTs (carbon nano tube)	A	better deicing, better mechanical properties	(Boncel et al. 2018)
Wind energy	Blades	Ti- / Nb- alloys	A	Corrosion resistance, high-strength steels	(Schroeder et al. 2023)
Wind energy	Foundation	HSLA steels: Nb or Ti as microalloys (Includes: C, Si, Mn, Cr, Mo, Al, Nb, Ti, N)	A	microalloyed high strength low-alloyed (HSLA) steels: increase in the strength of high-strength fne-grained structural steels	(Schroeder et al. 2023)
Wind energy	In weld seams for high strength steels	Low-transformation temperature welding additives for structural steels (different compositions of C, Mn, Si, Mo, Cr, Ni)	C	High strength steels are needed, when wind blades have bigger dimensions. Also, the weld seams	(Igwemezie et al. 2022)

Type of energy generation	Component	AdMa	State	Remark	Source
				need to be optimized then.	
Wind energy	Wind turbine blades	Carbon fiber (CF) or glass fiber (GF) carbon/glass (hybrid) fiber-reinforced polymer composites (FRPCs)	C	high strength and high stiffness, longevity, wear resistance, resistance to corrosion and fire, lightweight	(Rani et al. 2021, Hiremath et al. 2020, Rubino et al. 2020)
Wind energy	Wind turbine blades	CNTs	B	mechanical properties, ice resistance (antiicing and deicing)	(Boncel 2018)
Wind energy	Coating of bearings & drive units	PVD-coating of e.g. Ti, Zr, Cr or Al based nitrides or carbides	C	Nano coating, thin film coating hard material protective coatings in bearings and drive units to reduce friction / protect against wear	(Seyfert et al. 2022)
Hydropower	Turbines	MMC (metal matrix composites: Ti, Nb); Matrix: plastic	A	Turbines of hydroelectric power plants (high strength, rigidity and heat resistance)	(Schroeder et al. 2023)
Solar energy	Nanostructured surface of the solar cell	CdTe	C	NPs / Nanostructured surface, Improving the light absorption of thin-film solar cells / saving material	(Song et al. 2022)
Solar energy	Hemispherical structuring of the surface of the solar cell	ITO (indium tin oxide), PMMA (polymethylmethacrylate), P3HT:PCBM ([6,6]-Phenyl-C61Buttersäuremethylester), Al	A	Hemispherical structuring of the surface; Improving the light absorption of thin-film solar cells by optimizing the shape of the surface (numerical calculation)	(Hah et al. 2024)
Solar energy	Light absorbing layers of the solar cell	Perovskite (general: ABX_3; e.g. $CH_3NH_3PbI_3$)	C	Very high efficiencies, in combination with	(Snaith et al. 2018, Eperon et

Type of energy generation	Component	AdMa	State	Remark	Source
				Si solar cells, but moisture-sensitive	al. 2017, Xiao et al. 2022)
Solar energy	Light absorbing layers of perovskite solar cell	Graphene and MoS_2	A	Improvement of the performance of perovskite solar cells: protection against atmospheric degradation for moisture-sensitive perovskite	(Pescetelli et al. 2022)
Solar energy	Light absorbing layers of the solar cell	Quantum dots (semiconducting nanocrystals; e.g. InGaAs, CdSe, GaInP/InP, PQD (perovskite quantum dots), CQD (carbon quantum dots))	B	Adjustable absorption range, thus better utilization of the light spectrum, Light absorption over a wider wavelength and under different lighting conditions, increasing efficiency	(Liu et al. 2022 a, Semalti et al. 2020)
Solar energy	Light absorbing layers of the solar cell	CIGS (general: $CuInxGa_{(1-x)}Se_2$; e.g. $CuInGaSe_2$)	C	High absorption coefficient due to direct band gap, bendable, thin, Improving the light absorption of thin-film solar cells / Material savings / Without coating: Dust reduces the efficiency of solar cells / CIGS: Hydrophobic anti-dust coating increases efficiency by 20%	(Alarifi et al. 2023, Seyfert et al. 2022, Song et al. 2022, Jošt et al. 2022, Rahman et al. 2024)
Solar energy	Light absorbing layers of the solar cell	MoS_2	A	Performance improvement of perovskite solar cells	(Pescetelli et al. 2022)
Solar energy	Coating of the solar cell	ZnO:Al / Al/ZnO:Al/i-ZnO/CdS /CIGS/Pt	A	Nano-coating: Increasing conductivity / increasing charge carrier transport	(Uddin et al. 2024)

Type of energy generation	Component	AdMa	State	Remark	Source
				speed / increasing energy conversion efficiency	
Solar energy	Coating of the solar cell	TCOs (Transparent conductive oxides)	A	Nano-coating: Improving the light absorption	(Fortunato et al 2007)
Solar energy	Light absorbing layers of the solar cell	Al-/ PEDOT- / ITO-Layer (Aluminum, Poly-3,4-ethylendioxythiophen, indium tin oxide)	A	Application in organic photovoltaics	(Jahnel et al. 2015)
Solar energy	As thin films in HJT-Solar cells	ITO	C	As thin films in HJT-Solar cells (Hetero-junction) outside on both sides: transparent conductive ITO layer	(Chang et al. 2022)
Solar energy	Selective membranes in solar cell	$FAPbI_3$, $CH_3NH_3PbI_3$	A	Selective membranes made of metal halide, entire spectral range of visible light is used, promising efficiency, stability, and scalability $FAPbI_3$ with Ni foil/NiFeOOH electrocatalyst	(Song et al. 2022, Hansora et al. 2024) [European Perovskite Initiative 2019]
Solar energy	Coating of solar cell	TiO_2 NPs with thin film SnO_2 (amorphous, crystalline or nano-crystalline)	A	Nano coating / thin film: Increasing the efficiency and UV stability of perovskite solar cells through oxide double layer, improving heat transfer	(Tavakoli et al. 2018)
Solar energy	Transparent electrode, junction layer	Graphene foil	A	Improve light absorption, improve efficiency	(Das et al. 2018), Mahmoudi et al. 2018)
Solar energy	Solar cell	Dielectric thin film layers, e.g. SiN_x or SiON	C	Back with thin dielectric layer, laser perforated, Al vapor-deposited	(Seyfert et al. 2022, Bonilla et al. 2017)

Type of energy generation	Component	AdMa	State	Remark	Source
				Point-by-point contact with wafer Reflection of light waves that have passed through the wafer on the back Renewed formation of charge carriers Increase in efficiency	
Solar energy	Solar cell	Metamaterials, e.g. nanoscopically perforated metallic films; long hydrocarbons chains ($C_{16}H_{34}$) in SiO_2 aerogel microparticles		improving the absorption range of solar cells to the entire visible range; cooling of the solar cells	(Wang et al. 2012; Lee et al. 2022)
Solar energy	Solar cell	P_3HT:PCBM	A	Improving the efficiency of conventional bulk HTJ solar cells	(Ghosekar and Patil 2021)
Solar thermal energy	Absorbing medium	CNT	A	Increasing efficiency and improving thermal conductivity through applications of CNT nanofluids in energy harvesting systems / solar collectors	(Sidik et al. 2017, Kumar S. et al. 2018)
Solar thermal energy	Optically effective layers in solar collector	Ceramics, e.g. Al_2O_3, Si_3N_4	B	Multi thin films of ceramic	(Sing et al. 2024)
Solar thermal energy	Solar thermal absorber	Graphene (structured graphene metamaterial)	A	Improvement of heat transfer, research on special applications	(Lin 2020)

In this table AdMa that are used or investigated for the use in methods for energy generation are listed.

Table 2: AdMa for energy saving

Type of energy saving	Component	AdMa	State	Remark	Source
Thermal isolation	Insulation material in walls	Aerogel e.g. with silicic acid ($H_{2n}{}^{+}2Si_nO_{3n+1}$)	C	Highly porous structure with low thermal conductivity, thermal insulating properties dendritic branching, often silicates, based on silicic acid, highly porous, low thermal conductivity	(Li et al. 2020, Schubert et al. 2023)
Thermal isolation	Insulation material	Al_2O_3-SiO_2 aerogel doped with CNTs	A	low thermal conductivity wiht improved mechanical performance	(Jiang et al. 2022)
Thermal isolation	Insulation material in walls	Biopolymer-based aerogels	A	Highly porous, low thermal conductivity, thermal insulating properties	(Zhao et al. 2018)
Thermal isolation	Insulation material in walls	Graphene based aerogels	A	Lightest material, elastic, flexible, heat-resistant, conductive, compressible and absorbent; no sol-gel synthesis needed	(Riaz et al. 2017, Wu et al. 2023)
Thermal isolation	Insulation material in walls	Cellulose/carbon nanofiber aerogels - hierarchical graphene-confined zirconium phosphate (ZrP/RGO) nanosheets	C	low thermal conductivity, thermal insulating	(Gan and Gang. 2020, Wang et al. 2020, Li et al. 2021)
Thermal isolation	Transparent wood with shielding effect	Antimony-doped zinc oxide nanoparticles	A	Transparent wood with shielding effect against infrared heat and ultraviolet through the incorporation of modified antimony-doped tin oxide nanoparticles	(Qiu et al. 2019)

Type of energy saving	Component	AdMa	State	Remark	Source
Thermal isolation	Functional nano-coatings on glass	Nanoparticle-polymer composite, containing, e.g. metal oxides, Ag nanowiresx	C	Insulation of buildings and vehicles against heat loss	(Kim et al. 2020)
Protection against radiation	Glass	TCO (transparent conductive oxides)	C	Electrochemically switchable glasses; functional nano-coatings on glass panes: glass can be darkened to provide insulation against radiation.	(Wang et al. 2016)
Protection against radiation	Electrochemically switchable glasses	ITO/polymers	C	Electrochemically switchable glasses; Glass can be darkened	(Xu et al. 2004)
Protection against radiation	Coating of the glass	NPs-polymer composite, e.g.VO_2-PVDF	A	Smart windows / stimuli-responsive optical properties of architectural glass	(Kim et al. 2020)
Thermal insulation	Insulation in walls	polymer-based metamaterials	A	Regulation ofheat transfer between indoor and outdoor	(Chai et al. 2022)
Protection against radiation	Smart glasses: electrode	graphene	A	Electrochemically switchable glasses; Glass can be darkened	(Bakacak et al. 2024)

In this table AdMa that are used or investigated for the use in methods for energy saving are listed

Table 3: AdMa for energy storage and transportation

Type of energy storage	Component	AdMa	State	Remark	Source
Batteries	Conductive ink, in (micro) supercapacitors, batteries	MXene (general Mn+1XnTx, with Mn+1 a transition metal, Xn: C or N and Tx groups to seal the surface, e.g. O, F or OH groups) e.g. Ti3C2Tx,	A	high conductivity combined with a hydrophilic surface, good biocompatibility	(Najam et al. 2022, Verma et al. 2023; Murali et al. 2022, Anasori et al. 2017)
Batteries	Electrode	MXene / MOF hybrids	A	increase in the stability and conductivity, facilitated rapid electron and ion transfer	(Yang et al. 2023)
Batteries	Electrode	TiO2 QDs on thin MXene-layer	A	Improving the energy density and service life of Li-ion batteries	(Xu et al. 2022)
Batteries	Electrode, additive (regulator)	Graphene	A	Improving energy density and lifetime in Li-ion batteries	(El-Kady et al. 2016), (Fang et al. 2019)
Batteries	Additive (regulator)	Graphene	A	Improving energy density and lifetime in Li-ion batteries	(Fang et al. 2018)
Batteries	Seperator	Metal doped MCM-41	A	Mesoporous material: Catalyzer	(Zhao et al. 2022)
Batteries	Electrode	Porous Materials, fiber-reinforced aerogels derived from cellulose and silicate wool	A	In Li-ion batteries improving energy density, Coating is improving the uptake of Li-ions into the cathodes, increasing the service life, preventing the formation of dendrites	(Bausch et al. 2023)
Batteries	Electrodes and solid-state electrolytes	High-Entropy Materials	A	Replacement of rare earths	(Chen et al. 2021 a)

Type of energy storage	Component	AdMa	State	Remark	Source
Batteries	Electrode	Polyvinylidenfluorid (PVDF)	A	As electrode components and separator/electrolyte materials in lithium-ion batteries (LiBs) (List of typical synthetic polymers in [2020 Costa])	(Costa et al. 2020)
Batteries	anode	HC (Hard Carbon)	A	Improving the efficiency of SIBs	(Wu et al. 2024, Chen et al. 2021b)
Batteries	eSeperator	e.g. MOFs, quantum dots, MXenes	A	improved theoretical specific energy, promising battery for the next generation	(Mori et al. 2023)
Batteries	Electrodes (cathodes)	e.g. disordered rock salt (DRX)	C	The main point is the replacement of Li by Na in batteries, but other materials can also be replaced. In the market since 2023.	(Jones et al. 2024)
Batteries	electrodes	MPEA (multi principal element alloys)	C	Replacement of rare metals	(Yuwono et al. 2023)
Supercapacitor	? electrodes	NiS2 microflowers with NiS2 nanoparticles	A	Improved specific capacity, improved rate performance	(Dai et al. 2020)
Supercapacitor	support for the active electrode material (sandwich fiber)	CNTs	A	Improved specivic capacity, better mechanical performance	(Choi et al. 2016)
Supercapacitor	Electrodes	graphene and GR2M	A	better capacity, mechanical flexibility	(Ke et al. 2016)
Gas Pipelines	wall	Ti- and Nb-microstructured alloys	A	High strenght	(Schroeder et al. 2023)
Fuel cell	H_2 Catalyst	Au und Pt-NPs	A	Combination of plasmonic (Au) and catalytic (Pt) metal nanoparticles for	(Herran et al. 2023)

Type of energy storage	Component	AdMa	State	Remark	Source
				the production of H_2 from formic acid using sunlight	
Fuel Cell	H_2 Catalyst	IrO_2	A	Nano-coating by PVD with highly active iridium oxide	(Sachse et al. 2020)
Fuel Cell	anode material in PEMEL (polymer electrolyte membrane electrolyser) cells	IrO_2	A	Stability in acids	(Marschei-der-Weidemann et al. 2021)
Fuel Cell	H_2 Catalyst	Lanthan nickelat ($LaNiO_3$)	A	Nanoscale surface doubling of O_2 production Alternating layers of lanthanum oxide / nickel oxide with Ni oxide as anode	(Seyfert et al. 2022)
Fuel Cell	H_2 Catalyst	Pd/PdAu- coating	A	Thin film catalysts; Higher performance	(Hlawenka and Hartmann 2022)
Fuel Cell	Electrode material	IMA (intermetallic alloys), Ni and Ga	A	Low-pressure methanol synthesis with intermetallic Ni-Ga catalysts shows high methanol yield	(Lee et al. 2023, Sharafut-dinov et al. 2014, Studt et al. 2014)
Gas storage	Matrix for H_2 storage	MOF-5 ($C_{24}H_{12}O_{13}Zn_4$)	A	Gas storage: storage of H_2 (also natural gas, CO_2); Research on special applications	(Kampou-raki et al. 2019)
Gas storage	Pressure vessle	Ti- / Nb- alloys	A	Resistance of pressure vessels is increased	(Schroeder et al. 2023)

In this table AdMa that are used or investigated for the use in methods for energy storage and transportation are listed.

3.3 10 relevant AdMa used in techniques for the energy transition

As seen from table 1 – 3, a multitude of AdMa are or may be applied in techniques supporting the energy transition. The identified AdMa feature different aspects of relevance. _Therefore, a more detailed analysis of ten considered as relevant AdMa used in techniques for the energy transition was carried out. The first question that arises here is which relevance criteria should be used to select them. The following criteria were used to select the ten AdMa:

- Prospects for success: commercialization potential / scalability / expected tonnage
- Problematic properties: highest risks for people and the environment / recyclability / energy consumption
- SSbD (Save and Sustainable by Design): materials with special potential to replace harmful substances or critical raw materials.

Objective of this analysis was to provide a systematic overview including information on chemical safety and sustainability of the selected AdMa. The analysis should carry out how plausible the potential application of the selected AdMa actually is for the respective technologies. In addition, the following questions should be addressed for the selected AdMa:

- (anticipated) demand in Europe for these materials by applications: current, by 2035, by 2050,
- starting and process materials used for the manufacturing of the AdMafor and intermediates in the production that can be considered as substance of concern[1],
- manufacturing processes used, their scalability and energy intensity,
- existing indications of potential hazards from the AdMa to the environment and human health,
- available information on challenges that may arise by the AdMa for the circular economy, for resource conservation or for other environmental footprints

Based on the literature research and the above mentioned criteria, 10 materials were selected that are relevant for different areas of the energy transition (Table 4).

Table 4: The 10 selected AdMa and their application area as well as the criteria based on which they were selected for the closer analysis

Material	Application	Criterion
Perovskites	solar cells for energy generation	High commercialization potential; market launch, but problematic substances
Quantum Dots	solar cells for energy generation	High potential to reach higher efficiencies, but problematic substances

[1] Substance of concern according to Article 2 of the EU Ecodesign for Sustainable Products Regulation 2024/1781

Material	Application	Criterion
CIGS	thin-film solar cells for energy generation	Already introduced to the market; high efficiencies but problematic substances
Aerogels	thermal insulation for energy saving	Already introduced to the market; high efficiency, but energy-intensive manufacturing process
Iridium oxide	fuel cells for H2 production for energy storage and transportation	Critical raw material, currently no alternative
MOFs	gas (H_2) storage for energy storage and transportation	Material with high potential to be used in energy transition, but sensitive and chemically unstable
Hard Carbon	solid state batteries for energy storage	Material with high potential to be used in energy transition, but energy-intensive manufacturing process and low efficiency
MXenes	batteries and superconductors for energy storage	Material with high potential to be used in energy transition, high conductivity, hazard not understood yet
Graphene Related 2D Materials	multi-use material here with focus on batteries for energy storage	Material with high potential to be used in energy transition also in combination with other AdMa
CNTs (	as multi-use material for all sectors of the energy transition as well in batteries as in thermal insulation or for the stability of wind blades	Already introduced to the market or high potential to be used in many sectors of the energy transition, also in combination with other AdMa, but potentially problematic due to the fibrous morphology

Estimation of current demand in Europe

To estimate the current demand of the selected AdMa REACH registrations were used and be shown it table 5. However, such estimation based on the tonnage should be handeled with care, as not the full amount of the materials will be used for the presented techniques. In addition, information on hazard classification based on CLP entries are provided. For all of the investigated AdMa increase in demand is assumed based on the expectation of their growing relevance in the respective technologies.

Table 5: The tonnage according to REACH entry and the hazard classification according to CLP entries

Material / Precursor	tonnage according to the REACH registration	CLP entries
Perovskite / Lead di(acetate)	10 – 100 t	irritating, serious health hazard, environment
Perovskite/ Tin dichloride	100 – 1000 t	corrosion, irritating, serious health hazard
Quantum dots/ Cadmium sulphide	10 -100 t	irritating, serious health hazard, environment
Qunatum dots / Cadmium selenide	1 -10t	environment, serious health hazard, toxic
Copper Indium-Gallium Selenide (CIGS)	no REACH registration	toxic, serious health hazard, environment
Aerogels /Silicone dioxide	1 000 000 – 10 000 000 t (nanostructured and not nanostructured)	not classified as hazardous substances, except (organosilyl) oxymodified: health hazard
Iridium oxide	no REACH registration	oxidizing, irritating
MOFs, as example HKUST-1	no REACH registration	toxic, environment
MOFs, as example ZIF-8	no REACh registration	corrosive, irritating
Hard Carbon	no REACH registration	carbon: flammable, health hazard
MXene, group of components	no REACH registration	not classified, but titanium nitride as chemical: serious health hazard, flammable
Graphene	10 – 100 t	irritating, health hazard
Graphene oxide	10 – 100 t	health hazard
Single Walled Carbon Nanotubes	10 – 100 t	not classified
Mulit Walled Carbon Nanotubes	1 000 – 10 000 t	rigid MWCNT: serious health hazard, health hazard tangled MWCNT: health hazard

Tonnage were retrieived from https://echa.europa.eu/de/information-on-chemicals/registered-substances/, CLP entries were retrieved from: https://echa.europa.eu/de/information-on-chemicals/cl-inventory-database; from 17.12.2024;

It must be noted that materials or chemicals which are manufactured in or imported to Europe with a tonnage of less then 1t/a do not need a registration under REACH. No classification under CLP does not necessarily mean, that there is no hazard. One reason for no classification can be that the data situation does not allow a classification of the materials. Furthermore, it has to be considered that a further functionalisation of commercial materials, which is typical for AdMa, can lead to another classification. One example is given in Table 5 for aerogels (silicon dioxide), another example are hydrophobic MXene for composite materials, which lead to a classification as “serious health, hazard, corrosive and environment”.

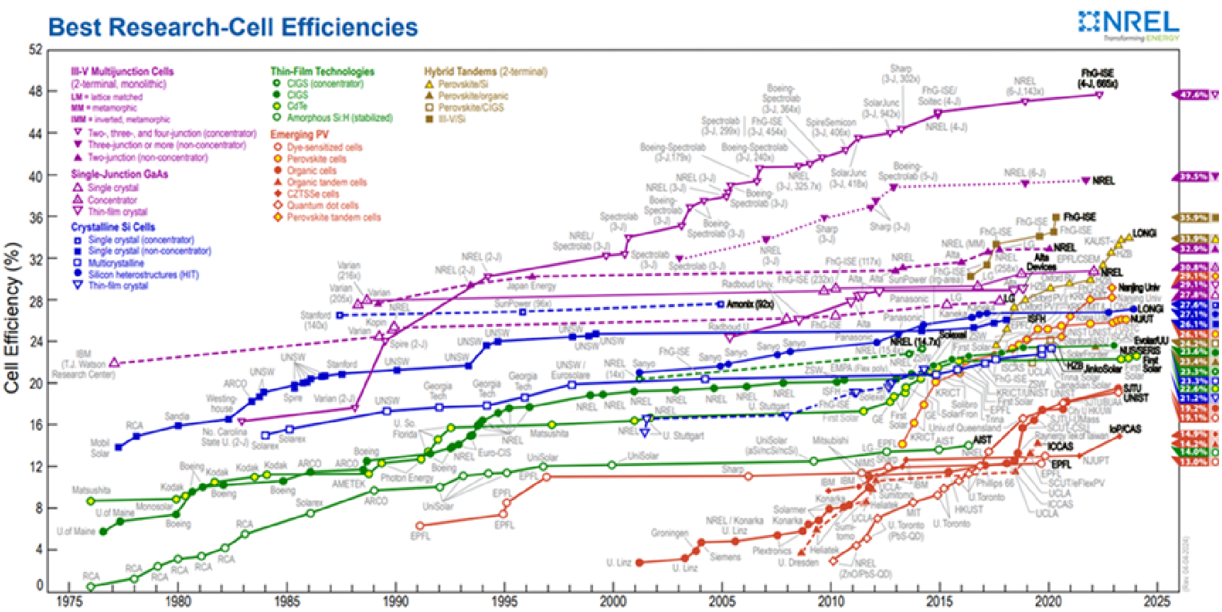
In the following, for each of these materials a short overview on structure, functionality and application within techniques for the energy transition is given, also highlighting potential disadvantages and challenges.

3.3.1 AdMa used in energy generation

AdMa are used in energy generation for example to increase the efficiency of solar cells (Figure 5) or to increase the durability of wind power plants. Here a closer look is taken at three materials that are used in solar cells. In general, it is found that the use of new materials enables very high efficiencies and a better yield of the light spectrum but can also have a significant impact on the environment due to material risks. This is the case as they often contain lead, cadmium or tellurium. Even though such toxic materials are regulated, for example, under EU legislation, their use might imply an increase in environmental and occupational exposure and thus, appropriate measures are needed. What is particularly critical here is that solar cells with AdMa are often more sensitive to environmental influences than conventional silicon solar cells which impacts their lifespan. As a strategy to protect the functionality but also the environment during use phase, hazardous substances are encapsulated, but this in turn could lead to increase challenges for a meaningful recycling.

Another point is economic dependency. Single-junction silicon cells currently dominate the market. Many of these solar cells are produced in China. The use of AdMa is also often based on creating tandem cells with silicon.

Figure 5: Efficiencies of solar cells in research over the years

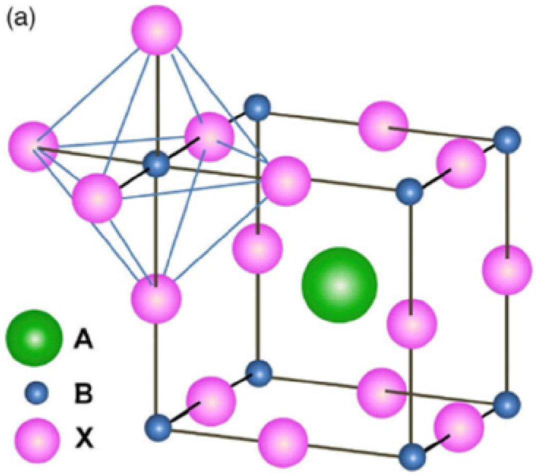


Source: National Renewable Energy Laboratory 2024

3.3.1.1 Perovskites

Perovskites are synthetic materials whose structure is modeled on the natural occurring mineral perovskite, which is why they got their name. Chemically, perovskites can be described by the molecular formula ABX_3. It stands for organic or inorganic cations (e.g. $CH_3NH_3^+$, $NHCHNH_3^+$ or Cs^+), B for metal cations (e.g. Pb_2^+ or Sn_2^+) and X for halogen anions (e.g. Cl^-, Br^- or I^-). The resulting lattice structure is shown in Fig. 6 [according toPark 2015].

Figure 6: General crystal structure of perovskite with A: organic or inorganic cations, B: metal cations and X: halogen anions



Source: Park 2015

Perovskites are used in tandem solar cells. The structure is such that, in addition to other layers, an upper perovskite layer is applied to a lower silicon layer. Perovskites can be designed in such a way that they have a high efficiency for high-energy photons, while silicon has a higher quantum yield for lower-energy photons (Snaith et al. 2018). In the combination of the tandem cell, the light first hits the upper perovskite layer and then the silicon cell below. This means that a larger part of the light spectrum can be used, which leads to an increase in the efficiency of the solar cell. The UV range of the light is particularly addressed here.

The enormously high efficiency is the great advantage of perovskite solar cells. In 2023, the company LONGI reported on perovskite-based solar cells with a laboratory efficiency of 33.9%, theoretical efficiencies of up to 42 % are even possible (Eperon et al. 2017). There are approaches to reach this theoretical limit by combining perovskite with other materials (Hu et al. 2024).

A disadvantage of perovskite solar cells is their short lifespan compared to conventional solar cells. Perovskite solar cells are sensitive to weather influences such as heat, moisture and light. They decompose faster than conventional silicon solar cells. The solar cells with the highest efficiencies have so far only been tested in the laboratory and are on the order of postage stamps.

If you look at the market for perovskite solar cells, they are currently in the market launch phase. The company Oxford PV has started series production of perovskite cells as tandem solar cells, whose solar cells, according to the company, have efficiencies of more than 29.5%. These solar cells should be available to end users by the end of 2024 [nature podcast / oxfordpv.com (Snaith Group)]. To avoid economic dependence, there is also research into all-perovskite cells, as a tandem of two different perovskites (Xiao et al. 2022). It must be noted that "long-term stability is still one of the key issues that impedes rapid commerzialization…" (Correa-Baena et al. 2017).

In the literature it is discussed that third-genereation solar cells (e.g. perovskite, quantum dots) can reach a percentage of ca. 45 % in the year 2030, and herewith the same as crystalline Si (Maalouf et al. 2023). In the same study based on literature study, the environmental impact of the perovskite was described as the highest among the most popular systems currently being discussed due to high amount of energy consumption despite the high efficiency.

One of the greatest problems is the toxicity of lead which is used in perovskite. Efforts were performed to substitute lead by tin, however with a great loss of efficiency. A further study showed for tin-based perovskite toxicity due to acdification. Therefore, other substances like germanium, antimony and bismuth are discussed for substituting lead. (Galagan 2021). However, germanium and antimon and their compounds show toxic properties as well (European Chemical Agency 2025). Futhermore germanium, antimon and bismuth are considered as critical raw materials in the EU (Regulation (EU) 2024/1252) To reduce chemical riskduring use phase an encapsulation of the lead is discussed (Galagan 2021).

3.3.1.2 Quantum Dots

Quantum dots are currently subject of a lot of discussions. In 2023, Bawendi, Brus and Yekimov were awarded the Nobel Prize in Chemistry "for the discovery and development of quantum dots" (Nobel Prize 2023). These nanomaterials are nanometer-sized semiconductors whose electrons exhibit quantum effects. Typical examples are InGaAs, CdSe, GaInP/InP. The size of quantum dots is between 2nm and 10nm. The crucial thing here, however, is that changing the size of the particles changes their properties. The quantum dots absorb and emit light. This depends not only on their size, but also on their shape and composition. By changing these properties, the properties of the quantum dots can be influenced or quantum dots can be designed so that they are adapted to the respective question.

Quantum dots are used in solar cells. In addition to research on perovskite quantum dots (PQD) with efficiencies of around 25% (Liu et al. 2022), which then contain environmentally harmful cesium or lead, there is also research on carbon quantum dots (CQD), which are less toxic compared to PQDs (Navarro-Ruiz et al. 2020). Some components of QD under investigation like indium, arsenic or gallium are considered as critical raw materials in the EU (Regulation (EU) 2024/1252).

The advantages of quantum dots in solar cells are primarily that their properties can be adjusted. For example, it is possible to design QDs so that they absorb light from the NIR/IR range (above 800nm), which is in the direction of research into nocturnal solar cells. In addition, such QD solar cells also extend the spectral range in which solar cells function, and are therefore complementary not only to silicon, but even to perovskites, which potentially enables a significant increase in the efficiency of solar cells through better utilization of the light spectrum in a tandem cell.

As before, however, there are disadvantages here, as such materials comprise components such as lead, cadmium or cesium, which are cytotoxic or carcinogenic and can also accumulate in plants or fruits such as oranges (Liu et al. 2022). Indium, arsenic, gallium and their compounds show toxic properties as well (European Chemical Agency 2025). In addition, the environmental toxicity of QD is challenging. These substances are regulated, for example, under RoHS (Restrictions of Hazardous Substances).

QD are mainly used in light-emitting diodes, field-effect transistors and photodiodes for optoelectronic devices. They are used in high-end dispays. Therefore, the mass production of quantum dots devices via a roll-to-roll process is state of the art (Lee et al. 2020). In the same reference it was stated, that predictions of the use of QD in solar cell are not available. They are still in development, the highest potential is seen in the flexible, portable PV market. Like for perovskite, the limited stability is the greatest disadvantage which hinders the commercializationSimilarly to perovskites, encapsulation during use phase is discussed as best solution for this problem. Due to their low conversion efficiency compared to perovskite-based cells QD based devices have the longest energy payback time (Maalouf et al. 2023).

3.3.1.3 CIGS (Copper indium gallium (di)selenide)

CIGS (copper indium gallium diselenide) can generally be represented by the formula Cu(InxGa1-x)Se2. CIGS are mixed crystals made of semiconductor materials. Indium and gallium are present here.

Typical applications for CIGS are as thin-film solar cells. The structure of the crystals creates absorbers with a direct band gap, which leads to a high absorption coefficient. It is possible to work with very thin layers of the material and thus create flexible thin-film solar cells. A typical structure of a solar cell here is substrate/Mo/CIGS/CdS/i-ZnO/Al-ZnO/MgF_2, with cadmium sulfide (CdS) acting as a buffer layer and the upper MgF2 layer serving to suppress reflections. The higher band gap is created by the combination of indium and gallium (Ramanujam et al. 2020).

The efficiencies of such solar cells are very high. Theoretically, around 30% can be calculated (Bhattarai et al. 2023). For CIGS / perovskite tandem cells, the theoretic efficiencies are even higher (Islam et al. 2023) and at least 24% can be proven in the laboratory (Jošt et al. 2022). Combinations with other materials like with Sb_2S_3 lead to an increase in these values (Rahman et al. 2024).

The advantages of CIGS solar cells are that they can be made very thin. This means that less material is needed. It also makes it possible to produce solar cells that are flexible and have a higher efficiency than conventional solar cells. This flexibility opens up other possibilities for the construction industry than rigid, thicker solar cells.

CIGS cells contain some harmful elements like indium, copper and gallium (European Chemical Agency 2025). Gallium meets the criteria of the critical raw materials, copper is included in the list as strategic raw material (Regulation (EU) 2024/1252).

Nevertheless, CIGS solar cells have already been introduced to the market and are available in series production. They are priced competitively with conventional silicon solar cells and are sold by various companies.

It is expected that the marked CIGS solar cells increase parallel to the the whole market of solar cells with a percentage of 5 % to 10 %. The life cycle energy demand and global warming potential is close to the convential Si cell, whereas the energy pay back time is shorter due to higher efficiency (Maalouf et al. 2023). Like for the other advanced solar cells the use of harmful elements and of critical raw materials is a problem.

3.3.2 AdMa used for Energy saving

Energy saving should not be neglected when considering the energy transition. AdMa can also be used here, e.g. ITO or GR2DM as thin coatings on switchable glass to reduce solar radiation or aerogels as insulation material. Here, the latter is examined in more detail.

3.3.2.1 Aerogels

Aerogels are highly porous solids. They consist of dendritic branches of particle chains and mostly of empty spaces (Deuber et al. 2017). They are categorised on the basis of their chemical origin (Sonu et al. 2023). Aerogels were actually developed to store gas in these spaces, but their heat-insulating properties enables them to be used as high-performance thermal insulation and noise insulation material. Aerogels are therefore a stable sponge-like network with nanopores.

Due to this property of very low thermal conductivity, very thin layers are sufficient for insulation, which means that only a small amount of material needs to be used. In addition, aerogels have a high temperature stability, which makes them difficult to burn. They are flexible, robust, light and easy to process. They have a high light transmittance, with little material required, which means they can be processed in a space-saving manner.

They are often made from silicate, e.g. with silicic acid ($H_{2n}{}^{+}2Si_nO_{3n+1}$). The components are considered as environmentally friendly and aerogels easily recyclable. However, the manufacturing process is problematic (Kara et al. 2024). In the so-called sol-gel process, the gel is dried under extreme conditions (Schubert et al. 2023), which is very energy-intensive and hydrophobic agents often contain chlorine. Also, biopolymer-based aerogels are being researched (Zhao et al. 2018). Production with supercritical CO_2 is also being researched (Fraunhofer Institut für Umwelt-, Sicherheits- und Energietechnik 202). It is expected that these both approaches have a better environmental footprint than the established ones (Kara et al. 2024).

The fibrous structure of aerogels can also be problematic with respect to safety as they can potentially lead to inflammation and are suspected of being carcinogenic. This was discussed for carbon-fibres reinforced plastic but can be broaden to all fibreous structures. (Westphal 2024)

There is also research into various combinations of aerogels (Sheng et al. 2023), e.g. with graphene and aerogel fibers (Xia et al. 2022), Ni/graphene and aerogel fibers (Wu et al. 2019), MXene and aerogel fibers (Li et al. 2020). Aerogels have already been introduced to the market in the construction industry. Here they are already used in new buildings and in the renovation of buildings. A global market volume of $1.2 billion (arc 2024) is estimated for 2026.

According to Boccia et al. 2023, the regulation is currently inadequate for aerogels, but safety research is being carried out in the Harmless project [https://www.harmless-project.eu/].

A huge demand on effective insulation systems for buildings can be supposed. Granular aerogels are on the market, but the success is hindered by the high prices compared to conventional systems. As they are not transparent, they can only be used in large facades or other parts without windows. Furthermore, the long-term stability is unclear. Fully transparent monolithic aerogels offer great opportunities, but they are far away form market readiness (Buratti et al. 2021). 95 % of the environmental impact is caused by the raw materials, especially by the silica aerogel synthesis. Main contributor is the drying using isopropanol and electricity. Optimisation of the drying process is therefore necessary for reducing the environmental impact and the costs of aerogels (Pedroso 2023).

3.3.3 AdMa used for Energy storage

Energy storage is the bottleneck in the energy transition. Renewable energy is produced depending on the day or the season and therefore has to be temporarily stored. Batteries are used in particular for this purpose, but hydrogen is also traded as an energy storage medium. AdMa can be used in both areas.

3.3.3.1 Iridium oxide

The chemical formula for Iridium oxide is IrO_2. At temperatures higher than 1200°C the structure changes to IrO_3. Large deposits of iridium oxide are found in South Africa, the Urals, North and South America, Tasmania, Borneo and Japan. IrO_2 is a harmful substance which can cause severy eye damage and skin irritation (European Chemical Agency 2025).

Application in the energy storage: Iridium oxide is used in hydrogen production in fuel cells and is used as an anode material in PEMEL cells (Marscheider-Weidemann et al. 2021). Due to its stability in acids, there is currently no alternative to iridium oxide, which is why it is classified as a critical raw material for the energy transition (Smolinka et al. 2018, EU-CRM 2023). The big bottleneck for this material is the shortage of raw material and the low production volume of 7-8 t per year maximum (Cowley 2022).

Recently, a literature survey was published discussing different scenarios for Ir the next years until 2050 (Clapp et al. 2023). It was assumed that 20 % of the annual supply of Ir (1.5 t per year) can be used for the water electrolysis. Recycling rates between 80 % and 100 % can be reached after 2035. In 2020, a rate of 70 % was reached. In a conservative scenario a capacity of ca. 470 GW by 2050 can be reached with hydrogen electrolysis using Ir electrodes, in a more optimistic scenario ca. 130 GW by 2030 and ca. 1.3 TW by 2050.For these scenarios recycling rates of 100 % are assumed. Reasons are the development and optimization of the electrodes. In a further study it was shown that reduction of the metal amount is the key to decrease the environmental impact independent on the metals used, e.g. Pt, Ni (Zhao et al. 2020).

3.3.3.2 MOFs (metal organic frameworks)

Metal organic frameworks (MOF) are microporous solids that have a sponge-like structure. They generally consist of a framework of inorganic metal ions and compounds of organic linkers. The size of the resulting pores depends on the material used and can therefore be variably adjusted. In this way, a large internal surface is created.

MOFs are used in the energy transition as gas storage. Their empty spaces can be filled with gases, e.g. hydrogen in MOF-5 with the structure $C_{24}H_{12}O_{13}Zn_4$. These are cubes with Zn_4O nodes and linkers made of terephthalate.

A particular advantage is the possibility of individually constructing the framework of MOFs adapted to the intended use (Kampouraki et al. 2019). In addition, they are possible to be produced in different forms of appearance, e.g. they can be ground into powder

However, MOFs are sensitive to moisture and chemically unstable. They have a limited storage capacity and low electrical conductivity. Their production requires a lot of energy, as meaningful storage capacities can only be generated under extreme conditions, which require a complex synthesis. In addition, long diffusion paths of the hydrogen mean that time is a factor to consider.

MOFs have not yet been introduced to the market as hydrogen storage, but are being researched. It is estimated that the global market volume will be around $8 billion by 2030 [(arc 2024). For the mass production of 2500 t costs between $ 10 and $ 60 per kg were discussed depending on the type of MOF and the production method (Wright 2024). The synthesis of MOFs combines the environmental challenges of organic chemistry like a huge use of problematic solvents with the hazards of inorganic chemistry like toxic metal ions (Julien et al. 2017). A possible greener solution is the use of mechanochemical methods to produce MOFs (Alic 2024). High production costs and the upscaling of this method for the mass production are however challenging (Wright 2024). Efforts for overcoming these problems are ongoing (Gugin 2024),

3.3.3.3 Hard Carbon

Sodium-ion batteries (SIBs) are currently being discussed a lot because they are being considered as a replacement for lithium-ion batteries. Sodium has similar properties to lithium, but in contrast, is available in large quantities in the earth's crust. SIBs do not require critical raw materials and are therefore considered a sustainable and inexpensive alternative to LIBs, but have so far been less powerful. Nevertheless, they were launched on the market in 2023 and are already included in the first electric cars (Pohontsch 2023). In order to achieve an increase in performance, suitable active materials for the anode are being sought. Graphite is the standard active material in LIBs. However, this cannot be used in SIBs, because it cannot be incorporated in the graphite structure due to the larger sodium ion.

Hard carbons are non-graphitizable carbons. They form an amorphous carbon material without an exact crystal structure. Their microstructure is curved graphene platelets that form strongly twisted structures as basic units (Chen et al. 2021). This structure creates numerous nanopores, which is associated with the ability to store sodium.

HCs can be obtained by sintering resin, biowaste and coal, among others (Duo et al. 2018). This process is energy intensive due to high temperatures (over 1000°C) needed for this (Chen et al. 2021). Their acquisition costs are low, they are widely available and have optimal overall performance. Therefore, HCs are considered the most promising candidates for anode materials in SIBs.

The main bottleneck for the efficiency is the insufficient initial Coulombic efficiency (ICE), as the Na storage abilities of HCs are closely related to the degree of graphitization, structural hybridization, and state of surface/defect (Yang 2023). To improve the performance pre-sodiation by thermal decomposition of $NaBH_4$ are discussed (Oh et al. 2023).

An analysis of patents and existing production capacities shows the early phase of market development. Therefore, robust predictions about the market development are not possible (Liu et al. 2022b). In this early stage, no manufacturing processes for mass production are established. In the cited literature survey, it was concluded, that “HC is currently the most advanced and promising anode option for SIBs” despite the acutal uncertainties about the future of the HC mass production.

3.3.3.4 MXenes

MXenes (early-transition metal carbides) can generally be represented by the structure $M_{n+1}X_nT_x$, such as $Ti_3C_2T_x$, with M_{n+1} a transition metal, X_n: C or N and T_x groups to seal the surface, e.g. O, F or OH groups. These are planar 2D materials or layers that lie on top of each other. 2D nanosheets have a hexagonal crystal structure. The first MXene to be discovered was Ti_3C_2 in 2011 (Lim et al. 2022). The greatest advantage of MXenes is the high conductivity combined with a hydrophilic surface which makes them attractive for batteries. Therefore, MXenes are used for energy storage (Najam et al. 2022). The sensitivity of MXene can be problematic for the use in batteries. MXenes have a high biocompatibility, on the other hand cytotoxic effects on bacterial cells, for example, have already been proven (Vasyukova et al. 2022, Szuplewska et al. 2022). However, the toxicity of MXenes for humans or environmental organisms is not yet fully understood.

Considering potential market relevance, MXenes are still in the research phase (TRL 4) (Mim 2024). A global market volume of $121.5 million is expected for 2027 (arc).

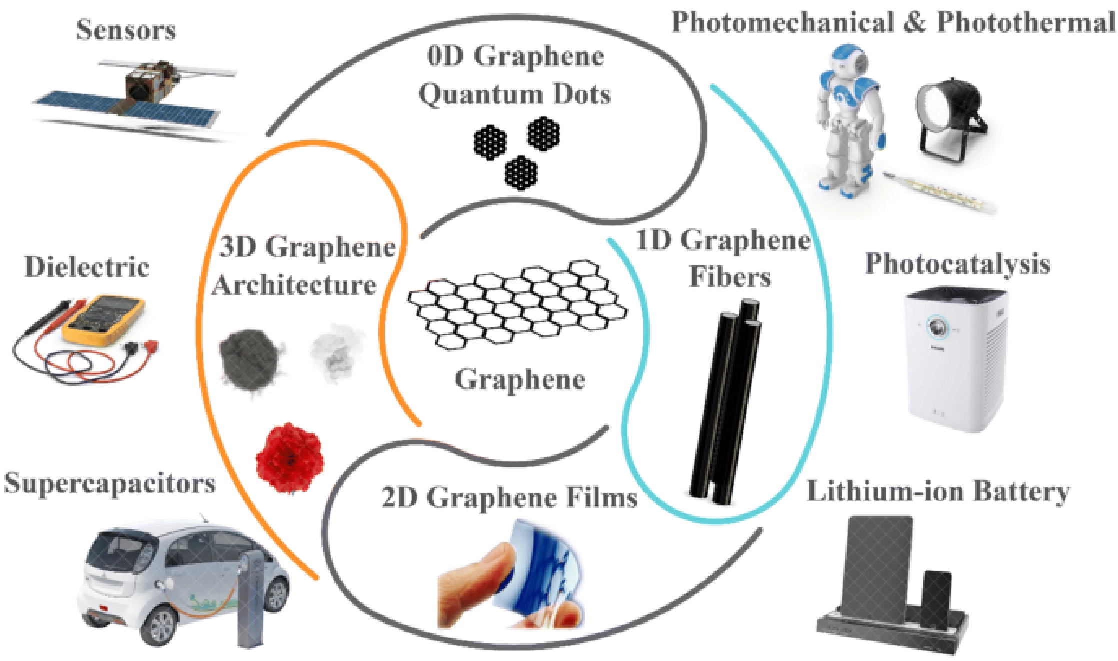
However, combinations of different AdMa are also being researched, such as MXene/MOF hybrid materials (Yang et al. 2023). Here, tailor-made shapes are created with MXenes as a substrate, which lead to an increase in the stability and conductivity of MOFs, as well as facilitated rapid electron and ion transfer.

For the synthesis of MXenes often scarce (and expensive) raw materials and acid-based etching with e.g. concentrated HF or HCl is used. A molten fluoride salt mixture at elevated temperatures of 550°C can be used for etching, too (Salim et al. 2019). Optimization of these etching processes are necessary to establish less toxic and more environment (and equipment) friendly methods (Mim 2024).

3.3.4 Multi-use-materials for energy transition

One of the most discussed AdMa of this time are graphene and graphene related 2D materials (GR2DM) for their superior properties. In big projects like the graphene flagship [https://graphene-flagship.eu/] the potentials and risks (Lalwani et al. 2016) of these materials are discussed. Here applications of GR2DM and CNTs in techniques for the energy transition are described.

Figure 7: The use of graphene in energy applications



Source: Bai et al. 2020

3.3.4.1 Graphene and other graphene-related two-dimensional materials (GR2M)

Graphene and GR2M are materials that are currently receiving a lot of attention due to its outstanding properties.

The properties of graphene and GR2M go from mechanical stiffness, strength, and elasticity to high electrical and thermal conductivity. To differentiate between different members of the GR2M-family, a classification scheme for GR2Ms with three key parameters is used (Fadeel et al. 2018). The number of graphene layers, the average lateral size, and the oxygen-to-carbon (O/C) atomic ratio play a role here.

In this report, we follow the definition of terms for graphen, graphene-related two-dimensional (2D) materials and other 2D materials (ISO 80004-13:2024). Other 2D materials like MoS_2 or BN are not considered. MXenes are discussed in chapter 3.3.3.4. It must be mentioned that in the literature often other terms are used like graphene-based materials, or graphene-family materials. Sometimes the term 'graphene' is used also for functionalized graphene or graphene oxide.

Graphene or other GR2M can also be used in a variety of ways (Figure 7), e.g. in supercapacitors (Ke and Wang 2016, El-Kady et al. 2016), batteries (El-Kady et al. 2016), solar cells (Das et al. 2018, Mahomoudi et al. 2018) or switchable windows for thermal management (Bakacak et al.2024)

Graphene is being investigated in particular in combination with other AdMa for use in the energy transition. Layered materials such as graphene or molybdenum disulfide can improve the performance of perovskite solar cells, for example (Pescetelli et al. 2022). In this combination, the properties of graphene offer advantages. Graphene is hydrophobic, which could provide protection against atmospheric degradation for moisture-sensitive perovskite solar cells.

Graphene is also being studied in combination with aerogels (Riaz et al. 2017, Wu et al. 2023). The resulting material holds the record of being the lightest material in the world. It is elastic, flexible, heat-resistant, conductive, compressible and absorbent. In contrast to silica-based aerogels, no sol-gel synthesis is necessary for its production; freeze-drying is sufficient. This creates a clear advantage in terms of energy requirements. The disadvantage, however, is that the resulting material is more brittle than conventional aerogels. Nevertheless, it is being investigated for the insulation of houses, but also in lighter batteries with higher energy density. It can also be used as an oil absorber for environmental protection.

In 2022, the global graphene demand was estimated in the range of 500 t to 12000 t per year (median 2500 t) with a forecasted increase to 9000 t to 170000 t in 2028 (median 30000 t) (Schmaltz 2024). In the time range between 2022 and 2023, 10.6 % of the graphene related patents applications worldwide were related to energy storage and 2.1 % to energy generation. Herewith, energy storage is one of the most important applications of graphene next to additives for chemicals and polymers. It must be noted that these numbers cannot be correlated straightforward with the tonnage, but it stressed out that the energy sector plays an important role in future application of graphene. For the production of graphene processes using alternative sources than graphite are being developed, because graphite becomes more and more a critical raw material due to its use in batteries (Barkan et al. 2024, Regulation (EU) 2024/1252).

The environmental impact of GR2M is mainly determined by used chemicals and the electrical energy which is needed in the production process (Beloin-Saint-Pierre and Hischier 2021). From the environmental point of view, the use of waste from different sources for the synthesis of GR2M would be the best way, but it is not possible to produce high quality graphene with these starting materials (Munuera et al. 2022). In both references it was stressed out, that it is necessary to carry out life cycle assessments depending on the planned application due to the versatility of the GR2M applications. Therefore, a good example is the assessment of graphene-perovskite (GRAPE) solar panels which shows an environmental footprint that meets the future Europe`s requirements (Pescetelli et al. 2022).

Graphene and GR2M are self-classified as irrating and can cause health hazards (European Chemical Agency 2025). Lin et al. 2024 investigated graphene and other 2D materials (such as MXene) with regard to their effect on the environment and the health of living beings.

They identified hazards (for environment and humans) and found an impact on several lifeforms they investigated (Invertebrates, Vertebrates, Fish, Algae, Plants, Fungi and Bacteria). An impact on human health is shown by found effects on different organs (Skin, Immune System, Liver, Spleen, Kidneys, Pulmonary system, Cardiovascular System, Reproduction, Gastrointestinal System, Central Nervous System). But there is also a mutual interaction between biotransformation, enzymatic degradation and the toxicity of agglomerates. Additionally, the hazard potential for different members of the GR2M family may vary considerably and even the functionalization of GMBs may change the properties and biological behavior (Fadeel et al. 2018).

3.3.4.2 CNT (Carbon Nanotubes)

CNTs comprise a group of materials that are discussed for many sectors of the energy transition, e.g. in thermal insulation (Jiang et al. 2022), in composites for wind blades (Boncel et al. 2018).In the field of energy storage, CNTs are disussed as additives in batteries as the use of CNTs leads to an improvement of the charge density and of the cyclability which leads to a longer lifetime (Fang et al. 2019), and as supercapicators which allow a fast release of energy to compensate for fluctuations in the power grid (Choi et al. 2016).

Carbon nanotubes are essentially tubes made of carbon with diameters between 0.5 nm and 100 nm. Tube walls of CNTs exhibits honeycomb lattice similar to graphene. They can be manufactured with single or multiple walls (Filchakova and Saik. 2021).

Their greatest advantages are their high conductivity, high mechanical strength and chemical stability.

It is expected that the current market of CNTs with a worldwide production of over 5000 t per year will increase in the next 10 years by a factor of 3. In the global market, ca. 10 % of the CNTs are used in the energy sector; the major part of CNTs are used as additves in plastic or in composites (Fortune Business Insights 2024). Carbon nanotubes are classified as irriating and can cause serious health problems, especially for the respitatory system (European Chemical Agency 2025). Due to their rigidity, however, some CNT also fall under the currently much-discussed fiber problem as potentially carcinogenic substances (Federal Institute for Occupational Safety and Health 2023)] A problem for recycling CNTs is that they are often damaged after their use or cannot be separated from the other components without damage. like in composites. Such composites are often mechanically processed by milling. This produces conductive dust which can cause damage to electrical machines and equipment (Quicker and Stockschläder 2021) A viable approach being discussed is chemical recycling with the return of used CNTs (or their end-products) in the production process. (Kim et al. 2023).

4 Conclusion

This report gives a systematic overview on AdMa used in techniques relevant for the energy transition. The rationale for such a systematic overview lies in potential conflicts of objectives between benefits of the application for either energy generation, savings or storage and potential negative effects on environment and human health or drawbacks regarding environmental footprints. As AdMa have not yet been studied much in terms of possible environmental impacts or toxicological consequences, it is of high importance to elucidate which AdMa are of special relevance for the energy transition.

As a first step of conducting such a systematic overview, it has to be clarified how the term AdMa is to be understood. What is advanced today may no longer be so once it has been introduced onto the market. In the discussion about the term, the time factor is therefore a component and is pursued using the "moving target" approach. In order to be able to address the question nevertheless, the OECD's working description (OECD 2022) with the list according to Giese et al. (2020) was used as basis for the presented analysis.

Based on the material groups mentioned in the OECD working description, a literature search was carried out concerning the various cornerstones of the energy transition. Issues of energy generation, saving and storage were investigated. Literature covering AdMa in these areas of energy transition were examined comprehensively, resulting in three tables arranged according to these three main pillars. These tables present the type of energy generation, saving or storage, the technical component the AdMa is used in, the AdMa itself, the state of development as well as specific remarks (e.g. information on the structure and/or functionality). From these lists, 10 materials were selected (perovskites, quantum dots, CIGS, aerogels, iridium oxide, MOFs, hard carbon, MXene, graphene and GR2M and CNTs) for a closer analysis of their relevance in energy transition, including challenges and disadvantages with consequences for environmental safety and human health as well as selected sustainability considerations. The selection of these 10 materials was based on several criteria, like because they have a high probability of commercialization, are made from raw materials, that are harmful to the environment or health or because they are currently in the focus of research. Among these materials are some that are used in solar cells and are particularly promising for increasing efficiency. Furthermore, materials that serve or could serve to save energy were considered, as well as materials that could be used as hydrogen storage for energy transport, or those that could increase the efficiency of batteries. Overall, it can be said that AdMa are used in all three cornerstones of the energy transition, or their use is being researched there. AdMa show particular potential, for example, through high efficiency, good thermal insulation, good conductivity, large surfaces or the possibility of achieving synergistic effects in combination with other AdMa. When researching the literature, however, also potential risks are described as not yet fully understood. Typical problems lie, for example, in materials whose dimensions are similar to pathogenic fibers, or in known to be harmful or raw materials. In order to protect the humans and environment, harmful substances are additionally encapsulated in application, for example, which in turn can lead to recycling problems. The synthesis processes are also sometimes very energy-intensive or use harmful or critical materials. AdMa open up new possibilities in the energy transition, but challenges with regard to safety and sustainability must also be faced in parallel to material innovation. The overview given in this report can serve as source to identify knowledge gaps, research needs or other follow up actions with regard to safety and sustainability for AdMa relevant within the energy transition.

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