Materials for electrification of everything: Moving toward sustainability

Kevin Jones, and David Ginley*, Guest Editors

Society is at a unique tipping point in a move from conventional fossil fuel based technologies to renewable sourced electrified technologies which can enable creating a carbon neutral or carbon negative energy economy. Many of the key approaches to achieving this transition in the critical areas of transportation, buildings and manufacturing depend on new materials and new approaches to rapidly increase electrification. This article reviews the overall energy landscape and highlights specific areas where new materials are critical to enabling transitions in energy storage, hydrogen utilization, transportation, buildings and the chemical industry and the articles on these topics that follow. How these transitions can be best integrated and the global societal impact of these transitions is also discussed. The development of new materials is instrumental in accelerating the move to a cleaner electrified society. The "*electrification of everything"* is increasingly important if we are to mitigate the adverse effects of climate change and materials will play a critical role realizing this goal.

Introduction

Fundamentally, society and its technologies are at the tipping point in changing from our historic carbon-based technology to carbon neutral or carbon negative approaches. Many of the key approaches to achieving this transition depend on moving to electrification and offer the potential for a truly sustainable energy system. A key focus of this transition is the move from our current dependence on thermal energy from fossil fuels for transportation, buildings, and chemical industry to electrified technologies that can be driven by renewable electrons and solar thermal energy. In many areas these transformations are taking place very rapidly, enabled by new generations of materials that reduce the cost of renewable electrons and their storage, enhance renewable thermal energy, and extend the range of these technologies' applications. This power generation and storage is coupled to new generations of technologies developed to use renewable electrons, such as the advent of electrified transportation. This issue of *MRS Bulletin* focuses on this trend which some have named the "*electrification of everything"*—with a fundamental assumption that by electrifying everything from transportation to the chemical industry through the use of renewable electrons we can potentially create a carbon-free energy system. The economics of this transition is increasingly compelling. As per the Wall Street Journal:

> You've also come face to face with one of the hottest, and most poorly understood, buzz phrases in energy—the "electrification of everything."
> The concept, most simply put, is that more of the energy we use will come from the electric socket. Instead of having fuels like natural gas or oil or gasoline flow directly into our homes, offices, manufacturing facilities and cars, those fuels—and other sources of energy—will increasingly be converted to electricity first.[2]

As renewable electrons become both more available and more cost competitive with any conventional energy source, the breadth of their potential application significantly increases. This trend is key to enabling this transition. In 2017, the solar industry achieved the US Department of Energy's original SunShot 2020 cost target of $0.06 per kilowatt-hour for utility-scale photovoltaic (PV) solar power three years ahead of schedule, dropping from about $0.28 to $0.06 in 2017. The most recent 700 megawatt (MW) PV facility in Portugal has a bid power cost of $0.013/kWh, which makes this historically one of the lowest costs of electricity.[3] In addition,

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land-based, utility-scale wind is one of the lowest-priced energy sources available today, costing 1–2 cents per kilowatt-hour after the production tax credit in the United States.[4]

Clearly, as the cost of renewable electrons becomes the cheapest form of electrical energy, the electrification of everything is enabled and its overall attractiveness increases significantly. However, many key issues remain, including the magnitude of the challenge required for the generation, distribution, and storage of renewable electrons so 24/7 operation is available globally, to all people. Nonetheless, if sources of reliable abundant renewable electrons can be achieved, this can lead to a paradigm shift across a broad range of energy use areas, from transportation and buildings to industry and new refining methods. But only if technologies are available to make use of renewable electrons. Electric vehicles (EVs) are an example where miles/gallon equivalents are approaching 150 miles per gallon using new battery and motor technologies. Consequently, materials and the technologies in which they are integrated, will play a critical role in meeting the challenge of the electrification of everything.

This issue of *MRS Bulletin* will illustrate both the potential of moving from present hydrocarbon sources of energy to renewable electrons and the materials challenges this transition poses. Clearly, the challenges are area specific and impact a broad swath of society. To better understand where materials could play the most significant role in the electrification of everything, we need to understand the energy use landscape.

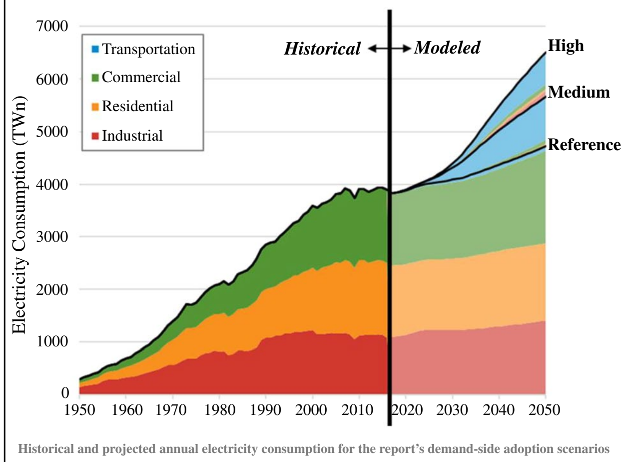


Figure 2. Worldwide forecast of electricity needs by sector. Based on three scenarios the current reference use then medium growth and high growth scenarios. *Source* IEA (2020) World Energy Outlook. [6]

From **Figure 1**, the greatest opportunities for impact upon electrification are in transportation and industry followed by the buildings sectors. **Figure 2** shows the forecast of the growth in electrical consumption.

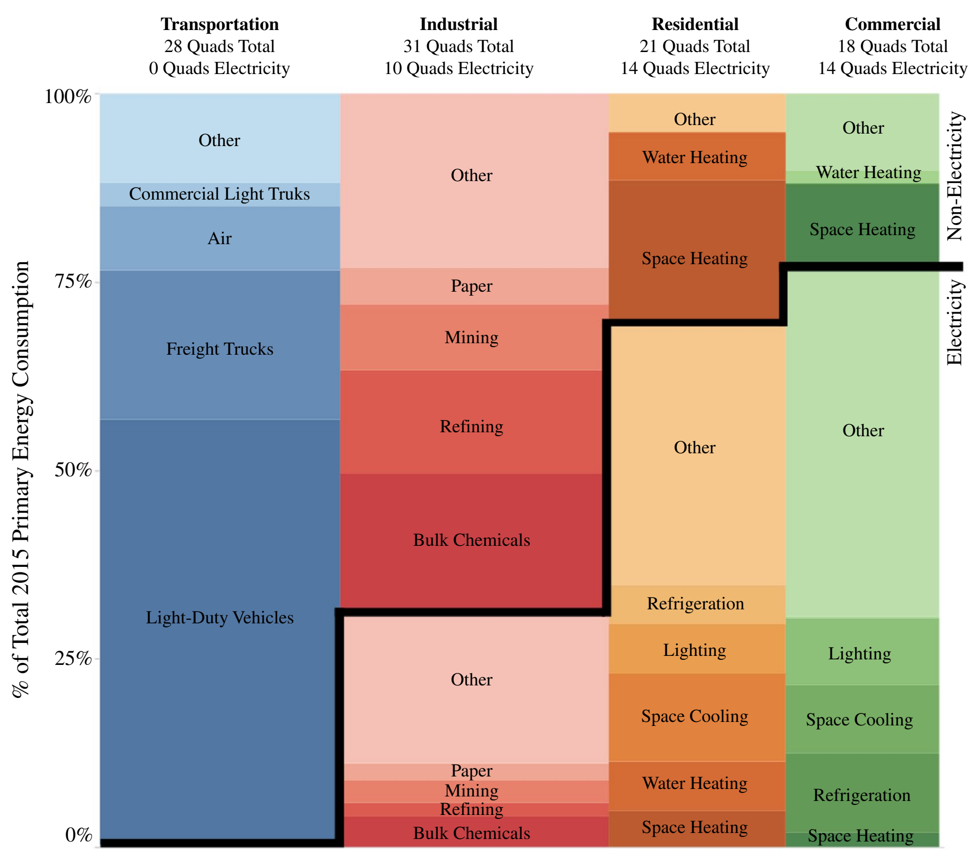


Figure 1. The breakdown of primary energy consumption by area. The solid black line shows the breakdown between electricity use and non-electric energy consumption.[5]

Integration of energy systems

There is clearly a need for thousands of additional terawatt-hours (TWh) of electricity to meet the demand of the transition to electrification. To impact the climate and to be economical, the transition to electrification must take place rapidly and be powered by electricity available 24/7 and demonstrate a high level of energy systems integration. Despite the rapid reduction in the cost of renewables the overall supply of renewable electrons is at present limited worldwide. The demand for power continues to increase at a little over 2% per year according to the IRENA report 2021.[7] 2.8TW of renewable energy is currently installed (for a generation capacity or 400 TWh or roughly 10.4% of global electricity production).[8]

Overall, this transformation is motivated by the continuing issues associated with climate change, but ultimately it must make current practical economic sense as well. Moving increasingly to electrification is one of the fastest ways to reduce CO_2 emissions and recent cost reductions in renewable energy have enabled a rapid growth of renewables worldwide, which is starting to offset production by other means.[9] This will require better interconnections for bidirectional electrical flow, new models for on demand electricity delivery and the ability to handle vastly more sources and syncs for renewable electrons. This must ultimately be driven by much more sophisticated models and controls from the nanoscale to the very large scale (**Figure 3**).

Overall, if significant penetration of renewables occurs worldwide and there are enough terawatts of renewable electrons, then society can shift to a nearly carbon-free, sustainable energy economy. The challenge is ensuring the energy from renewable electrons is available when needed and then prioritizing where we will use them and how to integrate this use in a fair and equitable way globally. To do this we need to look more closely at the challenge of mitigating the intermittent nature of many renewable sources.

This will be covered in more detail in the article by Arent et al.[10]

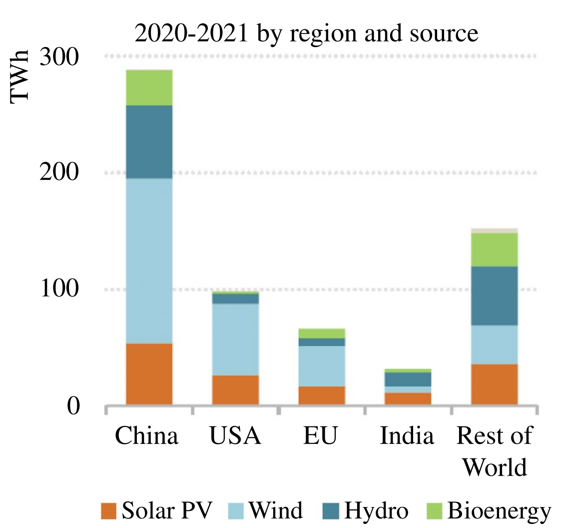


Figure 3. The breakdown in the sources of renewable electrons by geographic area. *Source* International Renewable Energy Agency.[7]

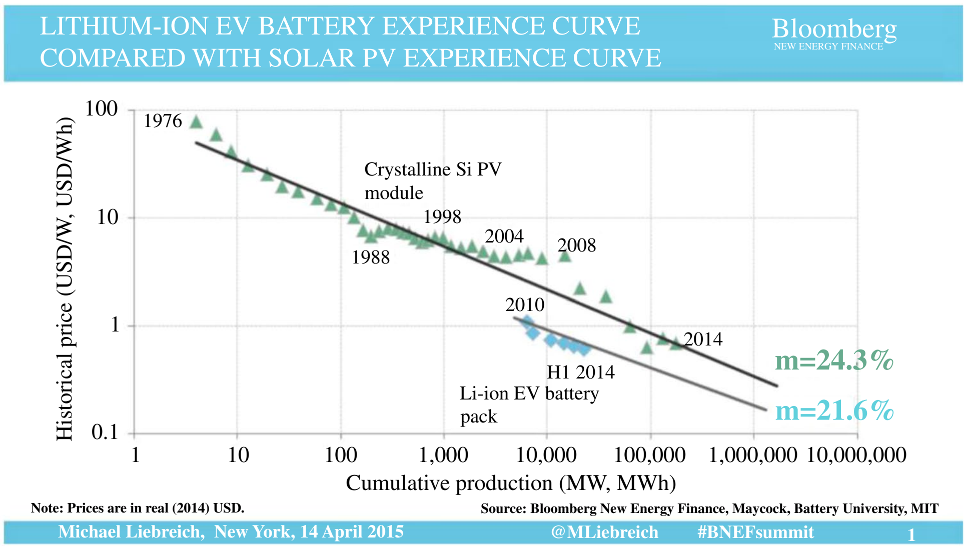
Materials for electrical energy storage

As previously discussed, given the variable nature of many renewable electron sources, there is an increasing need for low-cost, carbon-free energy storage to achieve grid integration with 24/7 performance. As the demands for electrification increase, so does the necessity for storage. Storage can take many forms. Currently the most utilized electrical energy storage systems are pumped hydroelectric. This technology is about 1/3 the current cost of lithium-ion batteries. However, it is limited in its distribution going forward since it requires two large water reservoirs to be constructed close together but at different heights. For more flexible electricity storage the approaches maybe thermal storage in the form of molten salts, batteries (Li-ion and flow batteries), electromechanical storage such as flywheels or creating energy carriers such as hydrogen from water. The amount of energy storage required in the future is significant. Recent estimates suggest that to achieve 90% renewables by 2035 will require 1 TWh of storage to mitigate the intermittency issue worldwide.[11,12] Ideally this could be readily achieved at \$0.02/Wh but many experts believe that even at \$0.1 or \$0.15 dollars per watt hour there would be enough penetration to impact the overall renewables market. **Figure 4** shows the effective learning curves for both silicon solar cells and Li-ion battery technology. Interestingly, the slopes are very comparable and the data seem to track similarly indicating with increased market penetration, storage cost can be significantly reduced toward the \$0.02/Wh goal, thereby enabling high penetration renewables. The articles in this issue will discuss recent advances in energy storage.

This will be covered in more detail in the article by T.M. Gür.[13]

Renewable Hydrogen Generation

One way to mitigate the costs and complexity of storage is to employ a chemical energy carrier. Thus, in addition to storing renewable electrons, one could use those electrons to create hydrogen. Having abundant renewable hydrogen is enabling for many areas, including energy storage, transportation, and industry. The specific energy (Wh/kg) of hydrogen combined with fuel cells is up to four times greater than Li-ion batteries.[14] At present there is an increasing political and industrial interest in the availability of hydrogen. It offers ways to decarbonize a range of sectors, including long-haul transport, chemical and iron and steel production, where it is proving difficult to meaningfully reduce emissions. Despite very ambitious international climate goals, global energy-related CO_2 emissions reached an all-time high in 2018. Outdoor air pollution also remains a pressing problem, with around 3 million people dying prematurely each year. All of these are strong motivators for switching many of these areas to renewable hydrogen. Historically, hydrogen has been derived primarily from fossil resources. As a consequence hydrogen use and storage is already at industrial scale around the world (approximately 80 million tons, as shown in **Figure 5**), but its current methods of production are responsible for annual



BNEF says li-ion batteries are on the same trajectory as solar PV. | (BNEF)

Figure 4. The decrease in Solar cell and Li-ion battery costs as production increases. *Source* Bloomberg New Energy Finance, Maycock, Battery University, MIIT.[13]

CO_2 emissions equivalent to those of Indonesia and the United Kingdom combined.[15]

Thus, we must move to producing hydrogen by renewable approaches. Fortunately, the use of renewables for hydrogen production is increasing by almost 26 MW per year for electrolysis but it remains much less than 1% of all the hydrogen produced.[16] Despite the fact that the amount of electrically generated hydrogen is currently very small, the applications space is large including among others chemicals, metals, electronics and glass-making industries.

There are a number of approaches to facilitate the production of hydrogen by carbon-free means, including electrolyzers, thermal, and nuclear approaches. Within these approaches there are options as well. For example, in electrolyzers there are solid oxide electrolysis cells, which operate at high temperatures, polymer membrane electrolysis cells which operate at low temperatures, and alkaline electrolysis cells. Note that many of these approaches require steam which can be made by thermal means. In the thermal area, approaches include solar-thermal-chemical

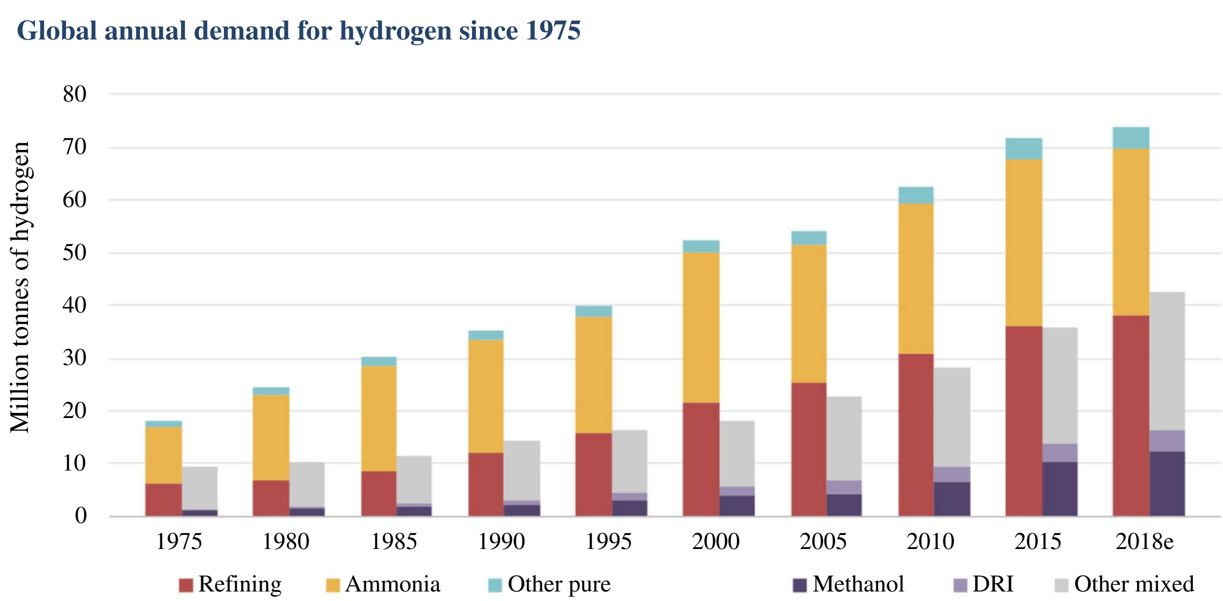


Figure 5. Global hydrogen production since 1975. *DRI* direct reduced iron steel production. Refining, ammonia and “other pure” represent demand for specific applications that require hydrogen with only small levels of additives or contaminants tolerated. Methanol, DRI and “other mixed” represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock. *Source* International Energy Agency.[16]

production of hydrogen by direct reaction (STCH) usually using concentrated solar power, or heat from nuclear reactors, or the use of geothermal sources. Many hybrid electrochemical/thermal systems are being investigated as well not only for hydrogen as an energy carrier but also for NH_3 for the same use. In the cases, above both the heat and electrons can be generated using renewable resources.

Currently hydrogen generated by renewable electrons is not cost competitive with fossil generated hydrogen (not including CO_2 remediation) as shown in **Figure 6**. However, note that if carbon capture utilization and storage (CCUS) is included this substantially affects the hydrogen cost. The cost of producing hydrogen with renewable electrons is close to natural gas with carbon capture. With the current cost reduction trends for producing renewable electrons, this approach may become the most lowest-cost approach to hydrogen production, thus enabling its use as a key component for electrification of everything.

Hydrogen has an even worse problem than renewable electrons in that the infrastructure for hydrogen distribution broadly is almost non-existent. Despite this challenge, hydrogen has the potential to both mitigate load leveling issues and provide alternatives for materials manufacturing. This will be covered in more detail in the Boardman et al.[17] article, which will be featured in the March 2022 issue.

Electrification of transportation

Both pure electric vehicles (EVs) and fuel cell vehicles (FCV) can be zero-carbon, and both depend on renewable electrons to do so (i.e., to charge the batteries or to produce renewable hydrogen). Interestingly, in the former case this can be done on a local household basis using home solar but this is more difficult to accomplish for hydrogen. **Figure 7** shows the rapid adoption of EVs globally. It is of interest that while many of the major auto makers have committed to going 100% electric, including Ford, GM, Honda, Hyundai, Volkswagen, and Mercedes on the 2030–35 timeframe, currently it is actually China and India that are rapidly implementing EVs in part to remediate pollution problems in the large cities.

Figure 8 illustrates the major issue with the kinetics of EV adoption, which is the availability of charging stations. Even as the range of EVs increase toward 1000 km there will need to be many more charging stations than at present and the grid infrastructure must be able to support the large current drawn by multiple EVs charging simultaneously. The same is even more true of hydrogen filling stations for PEM based personal vehicles. There are only a few in California at present and some in Japan. The other potential problem with hydrogen powered personal

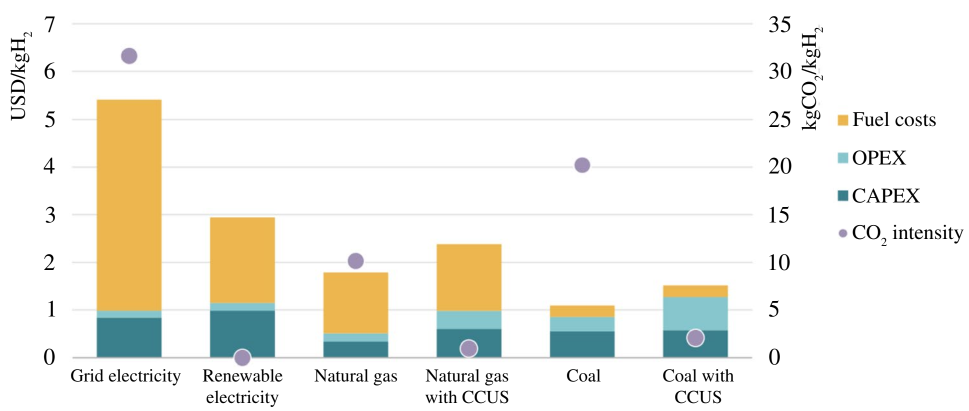


Figure 6. Cost of generating hydrogen in both dollars and CO_2. *Source* International Energy Agency.[16]

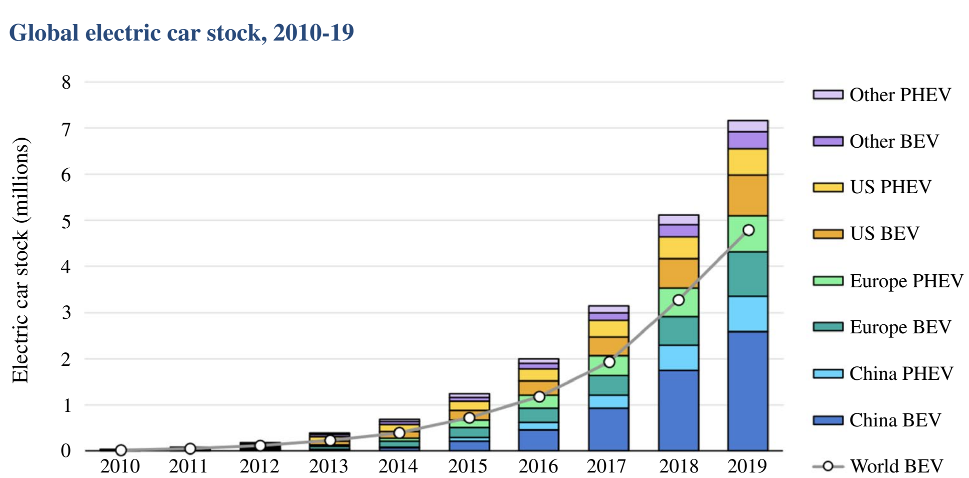


Figure 7. Electric vehicle distribution by region. PHEV is plug in hybrid electric vehicle and BEV is battery electric vehicle and there are approximately 1.4 billion vehicles globally so there is a very large opportunity space. IEA (2020) Global EV Outlook 2020. All rights reserved.[18] Sources: IEA analysis basd on country submissions, complemented by other sources. For more details, see Figure 1.1 in the main report.

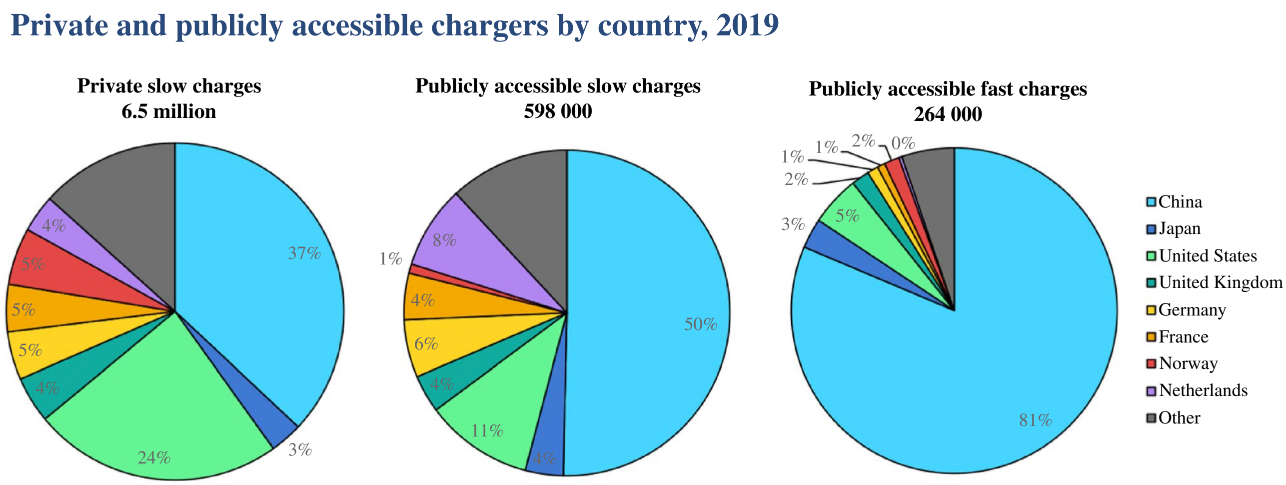


Figure 8. Global access to charging stations for electric vehicles IEA analysis based on country submissions, complemented by other sources. IEA (2020) Global EV Outlook 2020. [18]

vehicles is the relative energy efficiency for EVs is greater than for hydrogen powered vehicles.[19,20] The situation for large long-haul trucking may be substantially different. Some calculations show that fuel cell powered trucks can be twice as efficient as current diesel powered trucks.[19,20] The materials challenges with the electrification of transportation are numerous as we switch from a high energy density supply like gasoline. The need to improve storage, weight and efficiency remain paramount in this transition. This will be covered in more detail in the article by T. Lipman and P. Maier.[21]

Electrification of buildings

In 2020, in the United States 114 million households and more than 4.7 million commercial buildings consume more energy than the transportation or industry sectors, accounting for nearly 40% of total US energy use and more to the point, buildings account for 72% of US electricity use and 36% of natural gas use. Building energy use is increasing both due to new construction as well as retrofitting of older buildings. Given the large amount of energy used and that much of it is greenhouse gas producing, the buildings area is an ideal target for electrification. **Figure 9** illustrates the differences in usage for office buildings and multifamily homes in New York City. There are large variances in use. We note that these can change when moving from cold to warm climates or from rich to poor where in the latter case cooking and lighting were the primary energy uses with wood and kerosene being the source. To attain both flexibility and sustainability electrification of building functions is crucial.

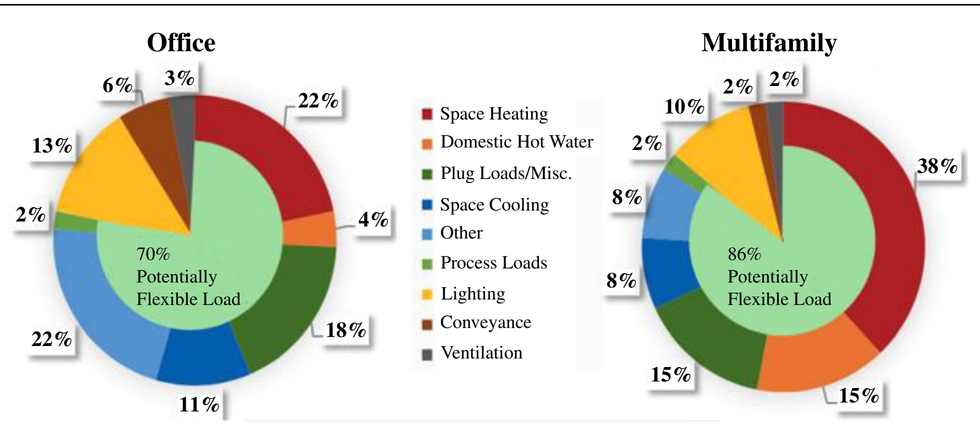


Figure 9. Data from the Rocky Mountain Institute shows compartitive data for Office and multifamily dwellings in NY city. Note the percent of load that can be flexible and note the relative importance of space hearting and hot water. *Source* RMI 2020 Decarbonising NY Buildings Through Improved Data and Controls.[22]

Many systems associated with buildings are ideal for electrification. For example, electrically powered heat pumps are very competitive with natural gas for heating but they can also cool. There is a need for more technological innovation in building systems from lighting, to communications, heating and cooling and windows. Recent studies and some developmental efforts indicate that there is a substantial overall energy cost reduction opportunities for retrofitting existing buildings and this is of increasing interest at all levels from the national to the local community levels. In addition, there is a clear need enable their integration in new construction. All of these areas are challenging from a materials perspective as will be discussed in the article on buildings. It is clear that developing an integrated approach to the electrification of building function such as l heating and cooling, windows, lighting and communications will require new functional materials and new smart materials to be integrated with the active systems. This is a challenge for new construction and even a greater one for the retrofit market. This will be covered in more detail in the article by Cui et al.[23]

Electrification of the chemical industry

One of the largest energy users and thereby one of the largest CO_2 producers is the commodity chemical industry. If you could decarbonize the chemical industry this would have a significant impact on global CO_2. Electrifying the chemical industry is a route to this goal but here it is not just a matter of moving to electrons but many refining processes will have to be optimized specifically to use electrons, unless renewable electrons are just used to produce thermal energy.

Figure 10 illustrates one view of how the transformation can occur.[9] There are many materials challenges associated with optimizing refining of chemicals to take advantage of renewable electrons. One thing of note is renewable hydrogen can also have a large role in the decarbonization of the chemical industry. Given that many industrial processes are run at high temperature there is an opportunity to use CSP and electrical heating to generate thermal energy instead of fossil fuels. Nearly 78% of industrial energy is used for heating and 58% of this is for processes below 400 °C.[24] A number of potential roadmaps have been developed that feature new electrocatalysts to reduce reaction temperatures, closed cycle processes and. alternate chemistries. Key targets are olefins (ethylene and propylene), ammonia, aromatics (benzene and toluene), and methanol.

Interestingly, there are a number of recent papers where both experiment and modeling support a greater efficiency for ammonia production through the electrochemical process rather than the conventional Haber Bosch process.[26,27] There is a broad increasing interest in finding electrochemical and high temperature electrochemical routes to important energy pathways such as NH_3 production, CO_2 reduction and hydrogen production. In addition, there are challenges associated with the integration of all of these different technologies. A key element of this transformation is that current processes cannot "just" be converted to electrification but new reaction pathways, materials and reactors will need to be developed. This will require integration of renewable electrons, heat and hydrogen to create truly sustainable industrial processes. The electrification of the chemical industry is such a challenging problem it will be covered in more detail in the articles by K.M. Van Geem and B.M. Weckhuysen[28] and Eryazici et al.[29]

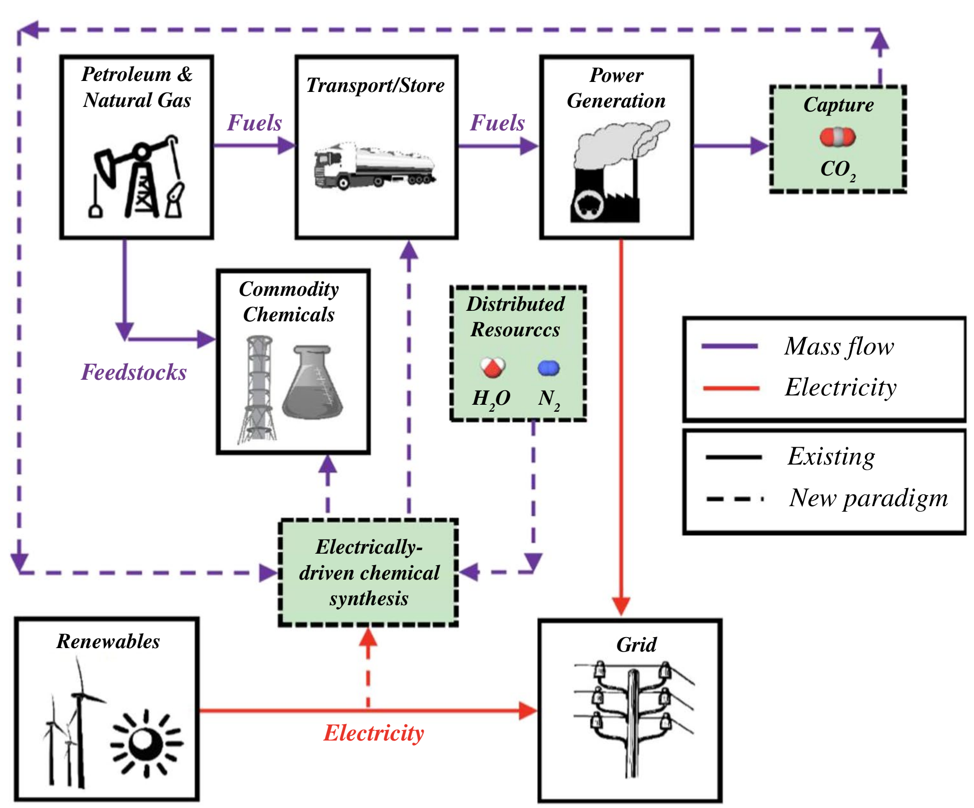


Figure 10. One approach to the integration of electrification in the chemical industry (Voltachem). This is an ongoing effort to both create a roadmap as well as to enable electrification of the industry. Reprinted from Joule 1, 1, Zachary Schiffer and Karthish Manthiram, "Electrification and Decarbonization of the Chemical Industry," 10–14, Copyright 2017, with permission from Elsevier.[25]

Global Societal Impacts of Broad Scale electrification

Social justice and access to renewable energy is a critical aspect of the adoption of renewable electrons.

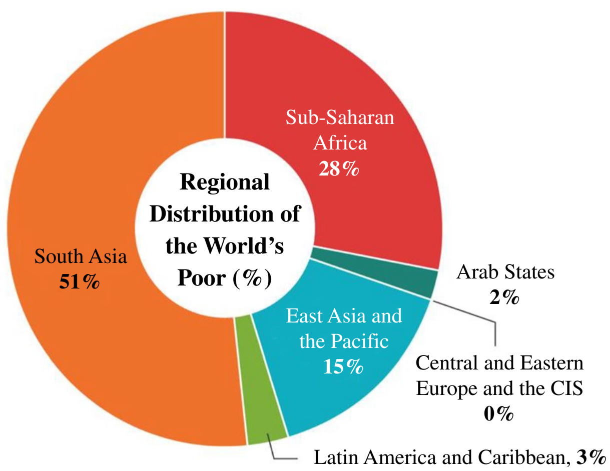


Figure 11. Shows a recent compilation of the worlds poor based on the Multidimensional Poverty Index (MPI) as used by the UN· as Derived from World Bank World Development Indicators 2015.[30]

Access to sustainable electricity is increasingly enabling for both economic and social wellbeing (**Figure 11**). Unfortunately, for much of the world, this is out of reach. Currently, more than 1 billion people have no access to electricity and all that it enables including refrigeration for food and medicine, cooking/heating and lighting, and communications.

Unfortunately, more than 3 billion people are still cooking on sources such as kerosene and wood, which have significant health risks resulting in nearly a million lung-related deaths annually. This has huge effects especially on women who are exposed to the pollution associated with these sources of heat.

While there are energy access issues even in the more developed countries, many of the people in the world have no access at all. The consequences of no energy access have broad implications on many parts of life from the standard of living (housing, drinking water, sanitation, cooking) to education (years of schooling and attendance) and health (nutrition and child mortality).[31] This will be exacerbated as a consequence of COVID and with an anticipated increase of almost 20% in people living below the poverty level.[31] For example, child mortality can be decreased by vaccination and improved food quality but that requires refrigeration which needs abundant local energy. It is of course a difficult problem of how to achieve energy democracy given the resources and politics around the world. But the challenge is to think about how materials can help solve some of these problems.

Some of the key basic social justice principles include[32] access (equality of access to goods and services), equity (overcoming unfairness caused by unequal access to economic resources and power), rights (equal effective legal, industrial and political rights), and participation (expanded opportunities for real participation in the decisions, which govern their lives).

Renewable electrons offer the opportunity for the impoverished nations to provide electricity to remote regions because of the opportunity to create more affordable local nano- and micro-electrical grids. However, it is well documented that as the standard of living increases so does the average carbon footprint. As such it is critical that renewable electrons play a significant role in the electrification of poorer nations in order to mitigate this increase carbon emission. Materials are going to play an enormous role in enabling this transition and this will be covered in more detail in the J.C. Stephens article.[33]

Summary

This issue will start by focusing on how the make the energy promise of renewable electrons reliable. This includes discussion of storage in forms, including chemical, thermal, and mechanical energy. Another way to store this energy is through the renewable production of hydrogen. We next consider the application of these electrons to electrification of the transportation, buildings and industrial sectors. We understand this is a broad swathe of technologies, and to achieve the goal will necessitate a new energy infrastructure that can only occur with a large scale integration across all of these areas and are thus enabling for each other. Finally, we will discuss how materials can be used to help ensure this transition to renewable electrons is done in a manner that promotes social justice and encourages energy democracy. These articles make the case that the proposed transformation can occur more rapidly and a lower cost than initially envisaged, and materials innovations will continue to play a key role in this transformation.

Funding

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