Accelerating Energy Transition Series

ENGINEERS AUSTRALIA

Thermodynamic Journey to Net Zero

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The Call to Adventure

In literature, every great journey begins with a call to adventure—a quest or mission that forces the hero to leave the ordinary world. The quest can be material (finding a treasure or saving a kingdom) or spiritual (self-discovery or redemption), but it always drives the protagonist to step into the unknown. Our 'pursuit of net zero' quest has all hallmarks of a great journey, whose roots lie in our ancestors discovering and harnessing fire as an external energy source, which they sustainably used to keep themselves warm, to cook food and as a source of illumination.

However, while humans have been harnessing energy resources for thousands of years, the current level of exploitation can only be traced back just over 100 years. Until the widespread use of steam engines during and after the First Industrial Revolution (1760–1840), the use of on-demand energy had remained limited to the relatively routine tasks of heating and cooking. Even through the Second Industrial Revolution (1870–1914) the primary energy consumption only doubled in 100 years (from 1800 to 1900) from about 5,600 terawatt-h to about 12,000 terawatt-h (see Figure 1). However, in the century that followed (from 1900 to 2000), global energy consumption increased by more than 10 times – from 12,100 terawatt-h to 123,000 terawatt-h.

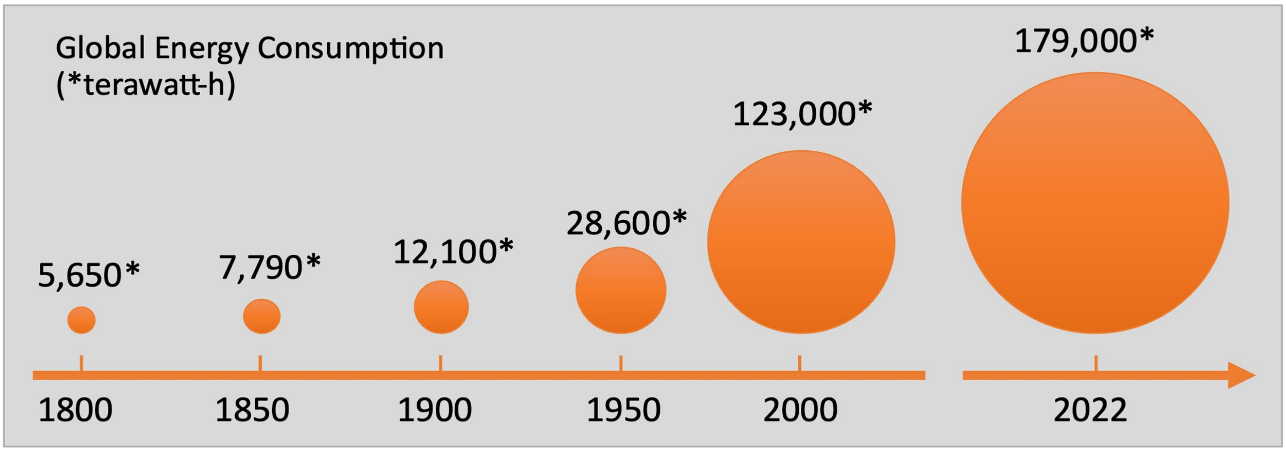

Figure 1: Global energy consumption (data source: https://ourworldindata.org/).

Humankind's relentless pursuit of energy sources and their exploitation is not unlike the central theme of James Cameron's *Avatar*, where the mining of unobtanium—a fictional, highly sought-after energy source—leads to conflict with the planet's natives. As human society has progressed, the need for energy has increased exponentially, bringing us to the epic challenge of climate change. The quest now is how we can continue to enjoy the lifestyle we've become accustomed to without emitting further CO_2

Crossing the Threshold

In all great journeys, there is a moment when the hero moves from their familiar world into the unknown. The protagonist is expected to have gathered all the necessary tools and acquired all possible knowledge for the arduous journey ahead. Like the heroes of all great stories, we will need to overcome challenges, biases and, particularly, misinformation. Among this misinformation is our inability to clearly differentiate between sources, carriers, and forms of energy. Furthermore, we will need to learn the foundational concepts of thermodynamics – the science of energy.

Energy sources

An **energy source** is something that is inherently available to harness – solar, geothermal, fossil fuels are examples of energy sources. Some energy sources are shown in Figure 2. Notably, the last four sources (tidal, wave, wind and hydro) can also be viewed as direct outputs of solar energy.

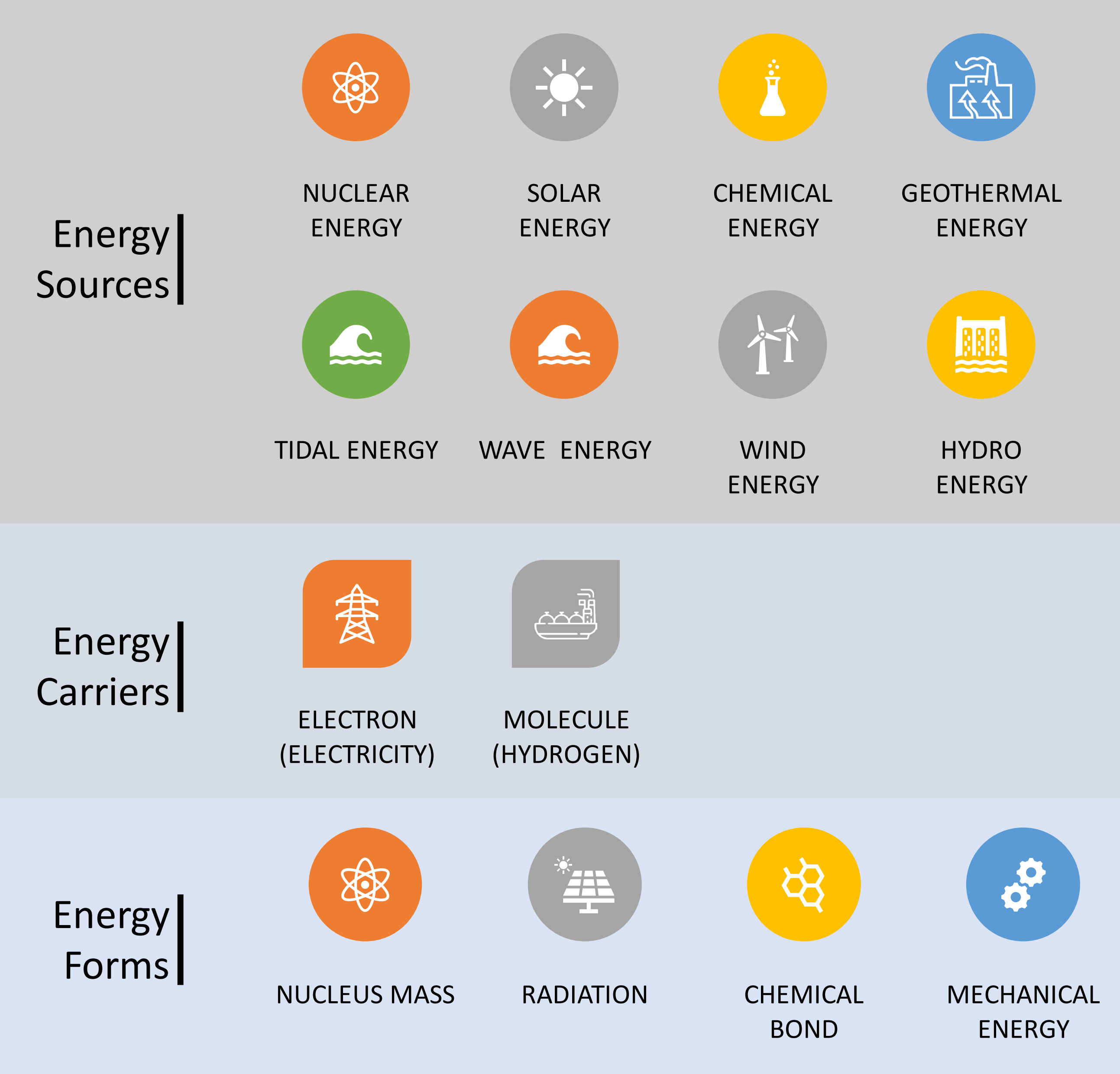

Figure 2: Broad types of energy sources.

Energy carriers

An ***energy carrier*** is a means by which we transport energy in a suitable form to a consumer. Electricity (as electrons) and hydrogen (as a molecule) are energy carriers (see Figure 2) – bearers of energy – but are not energy or energy sources. The One Ring in the *Lord of Rings* can be seen as an ‘energy carrier’ because it holds and transfers the immense dark energy of the character Sauron, but it itself is not an energy source.

It is a common practice to confuse energy carriers with being energy themselves. For example, the terms ‘electricity’ and ‘energy’ are often used interchangeably – sometimes to the point where electricity is referred to as the ‘total energy consumed or produced’ in a jurisdiction. This is like the popular TV series *Breaking Bad*’s Jesse using word ‘elements’ for ‘chemicals’ – much to the frustration of the protagonist Walter White.

In most countries, including Australia, electricity accounts for only about 15–20% of the total energy consumed. In Australia, South Australia leads in renewable electricity generation. In 2022, South Australia commendably produced 70% of its electricity (but not its ‘energy’) renewably, which amounted to about 12% of its total energy usage (83 TWh). However, it is common for media reports to erroneously claim that South Australia produces 70% of its ‘energy’ renewably.

Energy forms

In the movie, *The Matrix*, humans are conceptualised as being able to provide bioelectric energy to power machines. While this is a dystopian concept, it reflects the real-world idea that humans are capable of producing not only mechanical (muscle) energy but also heat and electrical energy. These energy forms (see Figure 2) represent the thermodynamic states of energy. For instance, the chemical energy in fossil fuels is stored as bonds between constituent atoms, geothermal energy is stored as heat, and wind energy exists in the form of kinetic energy. Unfortunately, the raw form of energy from different sources is often not directly suitable for modern use. For example, the chemical energy in fossil fuels must be converted into kinetic energy (a car’s motion) for the vehicle to move, and the kinetic energy of wind must be transformed into electricity (kinetic energy of electrons) to be useful. In conventional power plants, generating heat by burning fuel is a key step in electricity production. This transformation of the chemical energy stored in fuels into heat is commonly known as ‘combustion’.

Humans have known fire as source of warmth for quite a long time.

Hero discovered that fire could also be used for making things move.

Despite this discovery nearly 2,000 years ago, muscle power remained the only way to move things until the middle of the 17th century.

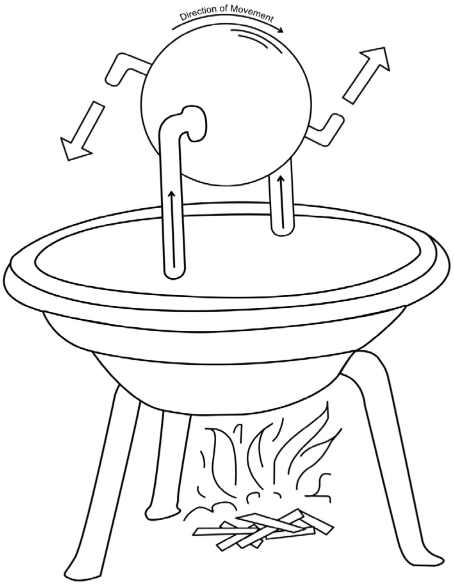

Figure 3: Hero’s Aeolipile.

The discovery of fire (the combustion of wood) is believed to be humankind's first encounter with the benefits of energy, such as staying warm; thus, we can reasonably believe humans have been aware of heat as a form of energy for thousands of years. However, for mechanical energy needs, such as transportation or moving goods, humans remained reliant on muscle power for a long time, as they had not yet figured out that heat could be converted to mechanical energy on demand. Then came a breakthrough: in the first century BCE, a Greek–Egyptian mathematician and engineer, Hero of Alexandria, described a device depicted in Figure 3. This device, called an Aeolipile, featured a central water container that, when heated, produced steam. As steam was ejected from two nozzles, it expanded, causing the spherical nozzle-bearing chamber to rotate. In that process, Hero had discovered that heat could be converted into mechanical energy. Was this the beginning of energy misuse that Hero helped unravel? We may never know, but we do know that different energy sources contain energy in different forms. Dictated by the laws of thermodynamics, there is always an interplay between energy sources, carriers, and forms as energy moves from "cradle to grave'. Typical conversion paths for different energy sources are illustrated in Figure 4. It's important to note that, ultimately, all the energy we use is converted into irrecoverable heat. This is part of trials and tribulations we attribute to the laws of thermodynamics.

Energy Source	Native Energy Form	Typical Energy Conversion Steps	Ultimate Energy Form
Nuclear Energy	Nucleus Mass	Nucleus Mass → Heat → Kinetic → Electrical	Heat
Solar Energy	Radiant	Radiant → Electrical	Heat
Chemical Energy	Chemical Bond	Chemical Bond → Heat → Kinetic → Electrical	Heat
Geothermal Energy	Heat	Heat (as a heating source) or Heat → Kinetic → Electrical	Heat
Tidal/Wave Energy	Kinetic	Kinetic → Electrical	Heat
Wind Energy	Kinetic	Kinetic → Electrical	Heat
Hydro Energy	Kinetic	Kinetic → Electrical	Heat

Figure 4: Energy utilised from any source ultimately turns into waste heat.

Units do matter

Another source of misinformation in energy conversations is the use of ***power*** and ***energy*** units interchangeably. This is akin to a voyager confusing the speed with the distance to destination. Like speed is distance travelled per unit of time, power is energy *delivered or consumed per unit of time* (for example, per hour). The standard units for energy and power are joule and watt (or joules/s) respectively. But these are not the units we use in day-to-day conversation. In popular conversations (including media), we often use kilowatt (kW) or megawatt (MW) for power, with 1 kW being equal to 1,000 W and 1 MW being equal to 1 million watts. However, the units used for energy generation or consumption (as opposed to power) – kilowatt hours (kW-h) and megawatt hours (MW-h) – are sources of greater confusion. By definition, 1 kW-h of energy is equal to the amount of energy produced (or consumed) by a device rated at 1 kW power if it operated for 1 hour. By extension, if a solar panel plant is rated at 5 kW power, and operates for 3 hours, it will produce a total of 5x3 = 15 kW-h energy (not power). Unfortunately, in several media commentaries the two units (kW, kW-h) are used interchangeably, often to paint a rosy picture of our ability to produce and store renewable energy. For battery storage, for instance, the quantity that matters most is the storage capacity (kW-h); the power rating (kW) is purely about the maximum current it can deliver at the rated voltage. If one only reports the power rating, then it implies that a battery can deliver this power continuously indefinitely. That is obviously not possible, because every battery has a finite storage. For example, a 1,000 kW-h battery, rated at 100 kW, will last for 1,000/100 = 10 hours of continuous operation. In summary, for renewable energy generation and storage systems, one needs to pay attention to both the 'energy' (for example, kW-h/year) and 'power' (kW) rating of the devices. Other energy units that are common in practice are megawatt-h (which equal to 1,000 kW-h), gigawatt-h (1,000 megawatt-h), terawatt-h (1,000 gigawatt-h) and petajoules (equal to 0.2778 terawatt-h).

Thermodynamic systems

Overcoming misinformation about our journey to net zero is one of several challenges before we even get to the 'battlefield'. In this analogy, the 'battlefield' is the **system**, which is essentially the domain of interest around which we make the energy balance and track the forms of energy that get exchanged across the boundaries of the domain. For example, the beaker shown in Figure 5 may be considered a system. Anything outside the beaker boundaries is considered 'surroundings'. It is possible to have flow of mass, energy or both across a system. When both mass and energy (including heat) are allowed to flow, the system is referred to as an open system. When only energy is allowed to flow, the system is called a closed system. Finally, there could be a system perfectly insulated so that no mass or energy can flow in or out; such system is called an isolated system. This concept of systems – our battlefields – is necessary for understanding the laws of thermodynamics.

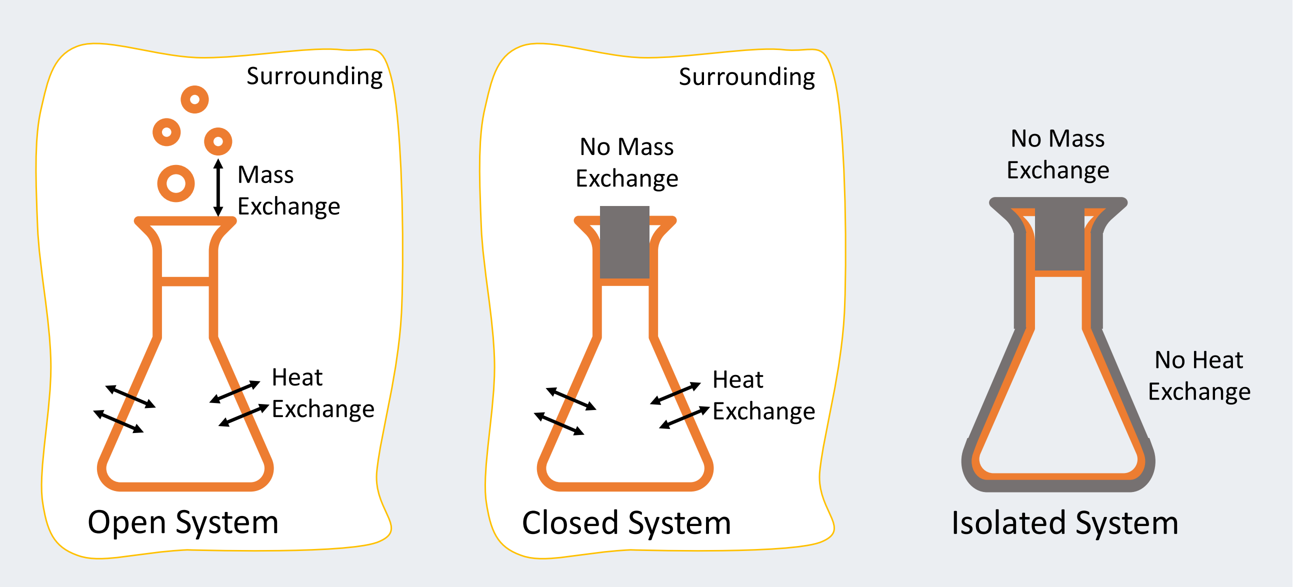

Figure 5: Thermodynamic systems.

Enthalpy

Literature abounds with objects or individuals possessing energy, like the One Ring in *The Lord of the Rings*. While not so magically apparent, every object, living or non-living, possesses energy. For example, a fixed quantity of water in the flask (system) in Figure 5 at room temperature (25°C) contains a certain amount of energy. If we cool the water to 0°C, we must remove energy from it, resulting in water with lower 'contained energy'. If we continue to remove energy, the water will turn into ice, with even less 'contained energy'. This 'contained energy' in substances or objects is referred to as enthalpy. Instead of saying that the 'contained energy' in water decreases as it cools to ice, scientists and engineers simply say its enthalpy has decreased. The concept of enthalpy aids in understanding energy balances when processes transition from one stage to another. For example, when coal is burned in a furnace (a system), the resulting enthalpy of CO_2 is lower than the combined enthalpy of the coal and oxygen initially present. Thus, the enthalpy of the system (coal, oxygen, and CO_2) decreases, releasing energy in the form of heat.

Entropy

Entropy in any system is a measure of its disorder and randomness. Because of its perceived nature, it is unsurprising that entropy often carries a negative connotation in popular culture. For example, in his novel *Lord* *of the Flies*, William Golding depicts the breakdown of order and the gradual descent of the island – initially in perfect order – into a chaos as entropy increases. This entropy increase is often seen as a poor consequence of our actions; however, the increase in entropy is a vehicle for us to achieve the intended outcome. Our individual interactions with the universe are shaped by entropy. For example, we are able to walk (or stop) because we have friction that allows our body's mechanical energy to dissipate as heat to our feet and the surface, thereby increasing entropy. Imagine standing on frictionless surface: if we were stationary, we could not walk, or if we were in motion, we could not stop – this is what a universe without entropy increase would look like. So, entropy increase is necessary for our existence.

Numerically, when a system moves toward greater uncertainty, we say its entropy has increased. Conversely, when a system moves toward lower uncertainty, we say its entropy has decreased. The entropy of a closed or open system may increase or decrease, the entropy of an isolated system can only stay constant or increase—it can never decrease. As depicted in Isaac Asimov's science fiction short story, *The Last Question*, the entropy of our universe (an isolated system) continues to increase, and there is no way to stop this process. The story stipulates that once the universe's entropy stops increasing, all of the universe's energy will have been distributed uniformly, leaving no potential for any further energy exchange. As a result, the universe we know will end and a new one will be created.

Trials and Tribulations

Every journey is marked by challenges or trials that the hero must face. These obstacles are more than just physical – they often involve the hero's inner struggles. The journey of energy transition will be no different; it will test humanity's resolve to learn new ways and unlearn old ones. In the energy transition, these trials will involve subjecting every step of the net zero journey to the laws of thermodynamics, which are universal and cannot be violated.

Trial under moral order

In all great voyages, the protagonist expects fairness, believing that the universe operates according to a set of ethical rules or natural justice. In *The Odyssey*, Odysseus endures hardships, hoping that his suffering will eventually be rewarded. His expectation of fairness is tied to the belief that his heroic deeds and struggles merit a just outcome. In the energy transition, fairness in the process is embodied by the First Law of Thermodynamics, which stipulates that, although energy can be converted from one form to another, the total energy is always conserved.

We can understand this using the energy balance of a typical coal-fired power plant, as shown in Figure 6. First, coal (with an equivalent stored energy of 100 MW-h) is combusted in the furnace, where the process is typically quite efficient, converting up to 90% of the energy to useful steam. The 10% loss in the boiler can be attributed to two factors: (i) there's a limit to how much we can insulate the system, leading to energy loss to the surroundings, and (ii) burning coal produces flue gas that contains heat, some of which can be recovered by using it to preheat the air for combustion, although not all of it can be recovered. The steam is then sent to the turbine, where its heat is converted to mechanical energy. Here, more than 60% of the heat in the steam is lost as waste energy, with only about 40% converted to mechanical energy, which powers the turbine to produce electricity. Modern generators are quite efficient, converting up to 97% of the mechanical energy into electricity. One might wonder why so much energy is lost in the step of converting steam heat into mechanical energy. Some of the losses can be attributed to: (i) frictional losses, (ii) steam leakages, (iii) heat losses to the surroundings, and (iv) the inherent energy losses that occur when converting one form of energy (heat) into another (work or mechanical energy).

The 'inherent' energy loss, accounting for more than 60% of the total energy losses in the turbine, is a consequence of the Second Law of Thermodynamics, which imposes a limit on how much of the steam's heat energy can be converted into mechanical energy to drive the generator. These losses cannot be avoided, regardless of the turbine's engineering design. We will explore this human limit further in the next section. However, in accordance with the First Law of Thermodynamics, the total energy input and output still equal 100 MW-hours.

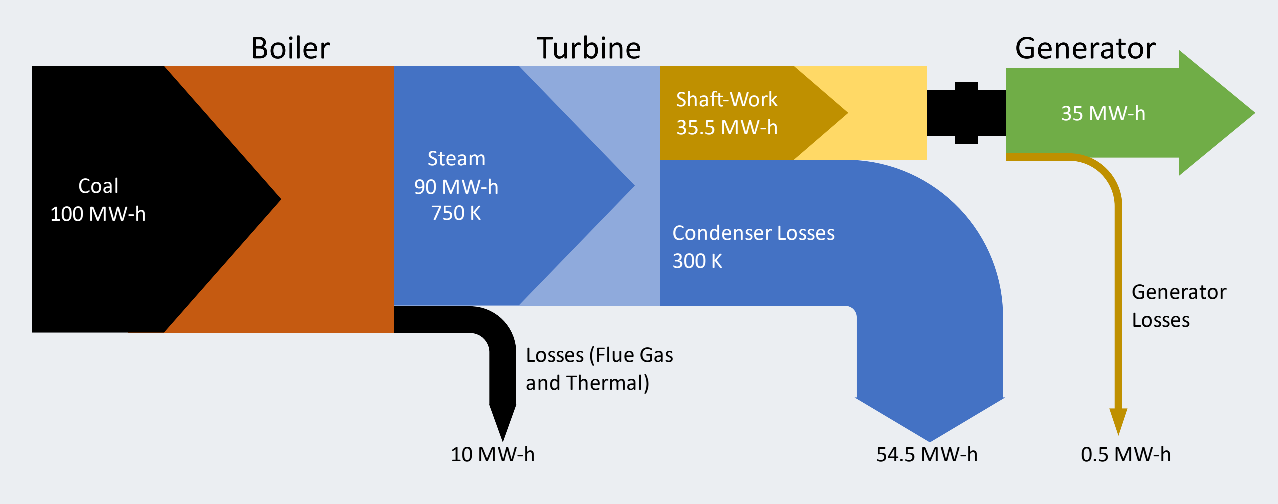

Figure 6: Energy balance of a typical coal-fired powerplant.

Figure 7 shows a similar energy balance diagram for the production of electricity from green hydrogen exported from Australia to (say) Japan. The process begins with the collection of 100 MW-h equivalent of solar radiation. For a solar cell powered by the Sun's unconcentrated radiation, the theoretical maximum efficiency of a photovoltaic cell, as dictated by the Second Law of Thermodynamics, is about 43%. However, the average efficiency of practical cells is usually around 25%. The electricity produced is then used for the electrolysis of water to produce hydrogen, with a typical electrolysis efficiency of 70%. In this step, we lose 8 MW-h of energy as heat, leaving 17 MW-h converted to hydrogen gas. Hydrogen is the lightest element, and in its gaseous state it requires enormous storage vessels. Therefore, it is proposed that gaseous hydrogen be converted to liquid via a refrigeration process. Hydrogen has a very low condensation temperature of -253°C, and cooling hydrogen to this temperature requires significant energy. In this process, we lose about one-third of the hydrogen's energy, leaving liquid hydrogen with about 11 MW-h of energy. According to some estimates, an additional 10% of this energy is needed for storage, transportation, and handling of the hydrogen. Thus, the hydrogen consignment that arrives in Japan has an energy value of about 10 MW-h.

As with all processes, the fuel cell that converts hydrogen's energy into electricity has thermodynamic efficiency limits. The typical efficiency of a low-temperature fuel cell is about 60%, yielding about 6 MW-h of equivalent electricity. It's important to note that we have lost 94 MW-h of solar energy as heat in this process, but the total sum of energy in and out is still 100 MW-h. Therefore, the total energy remains conserved.

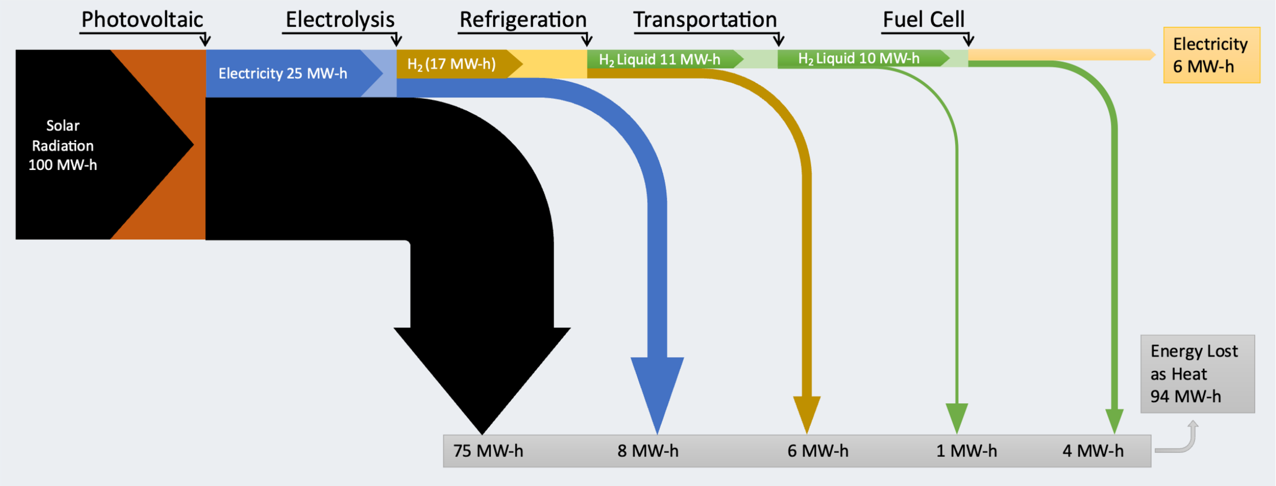

Figure 7: Energy balance for a typical hydrogen export value chain.

Trial under cosmic irony

Cosmic irony refers to the idea that the universe is indifferent to, or even appears to actively work against, the protagonist's expectations of fairness. In energy systems, this apparent unfairness is imposed by the Second Law of Thermodynamics, which applies penalties when we attempt to convert energy from one form to another, particularly when transforming heat into mechanical energy. For instance, some inefficiencies in the energy balance examples above could potentially be mitigated through better process design, but a significant portion, dictated by the Second Law of Thermodynamics, is beyond human control.

Earlier, we learned that all processes are accompanied by an overall increase in entropy; in other words, no process can occur that leads to a decrease in the total combined entropy of the system and its surroundings. When we convert mechanical energy to heat, there is an overall increase in entropy, making it possible to convert all available mechanical energy into heat. However, the reverse process – converting all available heat into mechanical energy – would, under practical circumstances, result in an overall decrease in entropy, which is not permitted by the Second Law of Thermodynamics, and hence is not possible.

In essence, the Second Law of Thermodynamics, through the concept of entropy, determines whether a process permitted by the First Law of Thermodynamics can actually occur. For instance, while the First Law allows both a glass object falling from a table and shattering on the floor, and the reverse process – where the shattered pieces reassemble and leap back onto the table – the Second Law permits only the former, where the net entropy increases, and rules out the latter, where the net entropy would decrease. Applying this analogy, if we use a certain amount of energy to generate hydrogen (and oxygen) from water (via electrolysis), we should not expect to recover the full amount of that energy by recombining the hydrogen and oxygen thus produced.

Some wins simply happen and others take effort

We have all witnessed certain phenomena simply happening. It may be glaciers disengaging from mountainsides and collapsing violently, causing great destruction along the way. Or a storm ripping off a roof and scattering debris everywhere. But can a storm blowing from the opposite direction fix the roof? Or can a glacier simply move up, fixing itself and all the destruction it caused earlier? Unfortunately, no. Why is that? The answer lies in the laws of thermodynamics.

Figure 8 illustrates four different scenarios based on the entropy and enthalpy changes that a system can undergo. If a system is in a state of losing enthalpy and gaining entropy (Quadrant 1), it will proceed spontaneously. A ball placed on a slope falls into this category. Not surprisingly, as soon as we let it go, it starts rolling and moving downward. After reaching the bottom of the slope, the ball continues its journey through the ridges, losing energy to friction (heat losses) and ultimately stopping at some point. The combustion of coal or gas also falls in the first quadrant: once combustion is initiated, it proceeds spontaneously and uninterrupted until the fuel or oxygen is exhausted. Once a carbon atom is converted to CO_2, it is theoretically possible to convert it back to carbon and oxygen. However, this process lies in the opposite quadrant (Quadrant 3), where the process will never occur unaided; it will require energy. The combined action of enthalpy and entropy changes ensures that we expend significantly more energy in converting CO_2 back to carbon and oxygen than we originally extracted by burning carbon. Even photosynthesis, which is a 'natural' process, lies in Quadrant 3 because it cannot proceed without the supply of light energy. Quadrant 2 is where the enthalpy of the process decreases while entropy increases. The process of dissolving sugar in water falls into this quadrant. When we add sugar to water at room temperature, it dissolves spontaneously until we reach the solubility limit. However, if we want to dissolve more sugar, we simply need to increase the temperature. Finally, the reverse process of sugar crystallization from sugar syrup falls in Quadrant 4.

Returning to our hydrogen export energy balance, the process of electricity production via a fuel cell is spontaneous. Although this process has a thermodynamic efficiency limit, it does not require an additional energy source other than hydrogen itself. In contrast, all other processes require an external energy source and are not spontaneous. Therefore, it is not surprising that the overall efficiency of the entire hydrogen export value chain is so low.

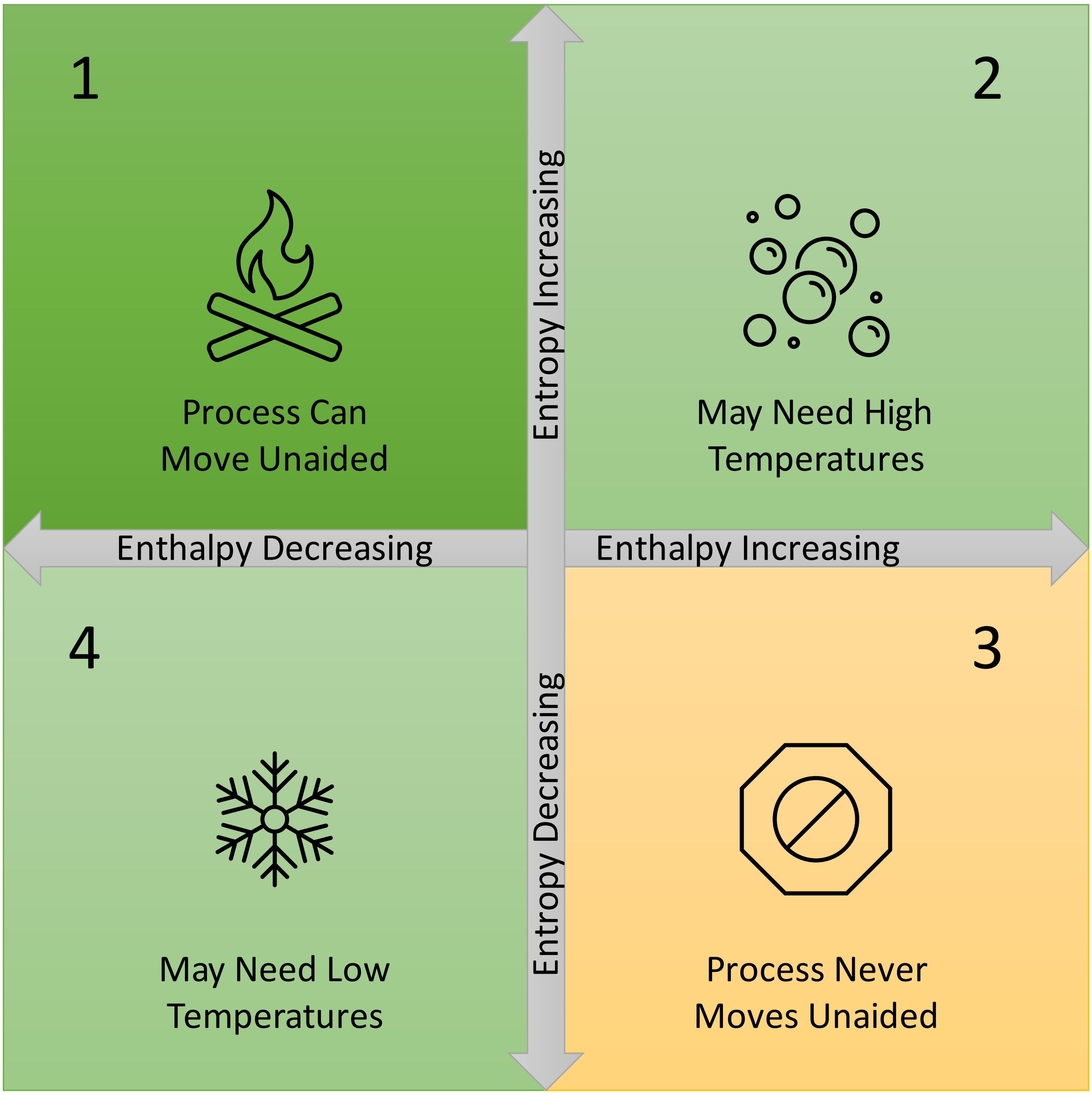

Figure 8: Spontaneity of a process depends on both its enthalpy and entropy changes.

Transformation

A central theme in the literary journey is the transformation of the protagonist. The journey is as much about internal change as it is about reaching a destination. In *The Alchemist* by Paulo Coelho, for example, Santiago's journey leads him to the realisation that the treasure he sought was not a material one, but a deeper understanding of himself and the world. In our journey to net zero, we will encounter many disappointments, especially if we fail to pay attention to the laws of thermodynamics. In the past, there have been individuals who have proposed generating energy from nothing. Engineers refer to such devices as perpetual motion machines. However, the laws of thermodynamics do not permit the existence of a perpetual motion machine. While a perpetual motion machine is an extreme example, we should carefully subject each new idea about energy transformation to the laws of thermodynamics, especially those that seem too good to be true. If this results in the protagonist being branded an obstacle, it may be worth it, as the cost of expecting to violate the laws of thermodynamics is too high.

The Destination

Every journey has a destination; for the net zero journey, it is 'destination green'. However, strictly speaking, the only truly 'green' energy on Earth is that which originates directly from the sun in its raw, nascent, and pristine form. Everything else falls short of being completely 'green.' Fossil fuels, understandably, are categorically 'black' in the present-day definition and contribute to CO_2 emissions. However, other energy sources also carry varying degrees of environmental impact, at least for a period of time.

Take, for instance, electricity generated from a solar panel. It may seem to have no net emissions of CO_2 during its use. Yet, the production of solar panels requires energy and may have already led to considerable CO_2 emissions at the manufacturing site, along with potentially adverse contributions to water and air pollution. In addition, at the end of their useful life, solar panels will require energy to manage the waste associated with the solar energy system, where recycling may either not be entirely possible or may further contribute to carbon emissions or other forms of pollution (e.g. environmental landfill). It's essential to factor in the equivalent CO_2 emissions from all these environmental drawbacks. According to some estimates, it takes 3 to 5 years after installation for solar panels to become carbon neutral. In essence, no form of energy suitable for humankind's current needs starts out as absolutely 'green' from the beginning. All these factors should be considered before we declare that we have arrived at our destination.

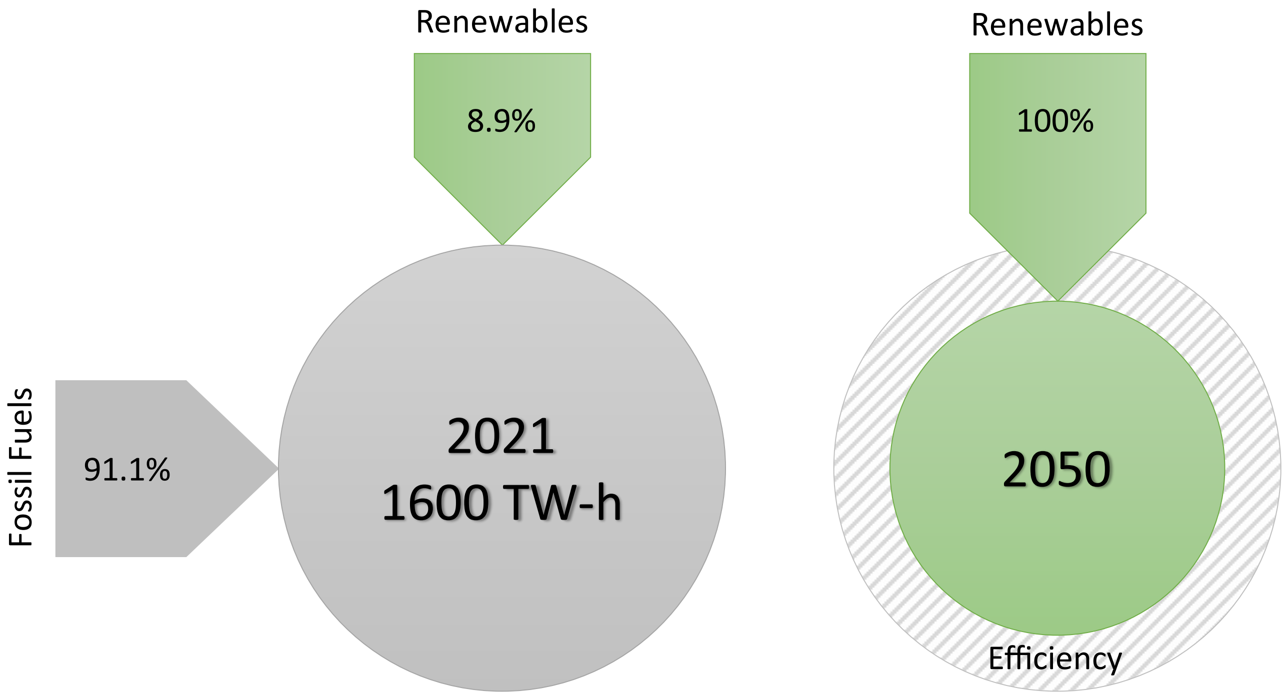

Figure 9: Australian energy consumption in 2021 and 2050. Countries need to also improve their energy efficiency in parallel to their transition to green energies.

In 2021–22, Australia consumed a total of about 1,600 terawatt-hours of energy, with less than 10% coming from renewable sources (Figure 9). Therefore, we face an enormous task to achieve net zero by 2050. Irrespective of the political debate on the composition of future energy sources, it is indeed possible to achieve this goal. The task will accelerate if we simultaneously also reduce our energy footprint while employing green energy sources. This is like the protagonist giving up greed for the greater good. Are we all prepared to be Charles Dickens' *A Christmas Carol* hero, Ebenezer Scrooge, who was at first very greedy, but later gave up some of his wealth for the greater good? In simple terms, achieving a just global net zero can only happen if wealthier countries act more selflessly. They must lead the way, and develop new infrastructure (including energy efficient townships, public transport, utilities) that reduces their energy footprints.

About the Authors

***Vishnu Pareek** is a John Curtin Distinguished Professor in Chemical Engineering and the Dean of Engineering at Curtin University. Previously, he was Head of School for the WA School of Mines: Minerals, Energy, and Chemical Engineering. Prior to this role, he led the School of Chemical and Petroleum Engineering and the Department of Chemical Engineering at Curtin University]. He holds a PhD from the University of New South Wales, an MTech from IIT Delhi, and a BE (Hons) from the University of Rajasthan, Jaipur, all in chemical engineering with high distinctions. Prof Pareek's expertise lies in energy foundations, thermodynamics, and fluid flow. In 2019, he was named a John Curtin Distinguished Professor for his excellence in research and academic leadership. He enjoys cricket, classical music and birdwatching in his spare time.*

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***Raj Sharma** is currently an Adjunct Professor at Curtin University's WA School of Mines: Minerals, Energy and Chemical Engineering. He has a PhD from the Colorado School of Mines in chemical and petroleum refining engineering. Before commencing his academic career at the Indian Institute of Technology Kanpur in 1982, Prof Sharma served with Tosco Corporation as a senior research engineer. Subsequently, he was appointed as the Founding Head of Department at Malviya National Institute of Technology, Jaipur in 1989, where he served until 1999. Since then, he has held senior positions with multiple academic and industrial organisations, such as the University of Natal, Durban, the University of Mauritius, the Columbia University, and National Technology Enterprises Company (NTEC), Kuwait. Prof Sharma has expertise across multiple areas of chemical engineering, but he has particular interest in energy research. The focus of his teaching is to produce not just engineers but leaders, which has seen his students widely excelling in their chosen fields. He is a very capable cricketer, and actively plays golf.*