Lecture 1 – Abundant clean energy for all

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Energy is fundamental to the growth of human welfare. Since 1800, global primary energy use has increased over 28 times, **[Exhibit 1]** and if that energy had not been available we could not have achieved the 100 times increase in global GDP which has occurred and the resulting revolution in living standards, initially in the early industrial countries and then increasingly across the whole world.

Decade by decade energy use has continued to increase. Over the last 20 years, global final energy demand (which measures energy at the point of use) has grown 1.8% per annum, while global GDP has grown increased by 3.3%.[1] And as we look forward, the demand for energy based services – such as air and road transport, cooling and heating – will grow and must grow rapidly to support increasing prosperity in many developing countries.

But today humanity gets 80% of our energy from fossil fuels, and emissions from fossil fuel use are driving climate change which threatens severe harm to human welfare across the world. We have to find a way to enable rapid growth in human demand for energy-based services, while limiting climate change.

In three lectures I will explore the fundamental technologies and economics of how to do that.

- Today's lecture will focus on the technological possibilities and I hope will leave you in a broadly optimistic mood, since I will describe how the technologies of clean electrification have the potential to deliver abundant clean energy for all and to do so faster and at lower cost than seemed possible just 15 to 20 years ago. I will also argue that we have the technologies to decarbonize heavy industry and long-distance transport sectors where direct electrification is more difficult and, in some cases, impossible: and that the costs to consumers of doing so are small. But I will highlight one major sector – food production and its related land use impacts – where we do not yet have a clear technological answer, and where reducing emissions may be far more difficult.

- In Lecture 2 I will explore some of the economic challenges we face in achieving the required energy transition, and in particular the need to distinguish between lower energy costs in the long run and the transitional costs of getting there, and between impacts on average and those faced by specific countries or groups of consumers. I will also in that lecture consider the opportunity and the challenges created by China's extraordinarily dominant role in almost all the key technologies which we will need to

[1] ETC (2025), *Energy productivity in an expanded electrified energy system.* https://www.energy-transitions.org/publications/energy-productivity/

build a zero-emission global economy.

- In Lecture 3, drawing on the analysis of lectures 1 and 2, I will then describe what we must do to maximise our chances of limiting global warming to well below 2°C in line with the objective of the Paris climate conference in 2015.

A key argument that I will make in that final lecture, drawing on the analysis of lectures one and two, is that while clean electrification can deliver a very large share of the emissions reduction we need, and at an eventually nil or indeed negative cost to consumers, it will not be sufficient in itself to achieve a well below 2° temperature limit. That means that in addition to very low or zero cost actions, we will have to take some which are more expensive.

And that means that we will have to make a climate case for mitigation action – the case that the costs of inaction would be far higher – and not solely a case based on technological optimism and economic opportunity.

That climate case ought to be clear. Today global warming stands at around 1.5°C above pre-industrial levels **[Exhibit 2]** with global average temperatures over the last three years either just below or just above that level. This, it is often said, does not formally breach the Paris commitment to limit global warming to 1.5°C, since that was intended to apply to a 2-decade moving average.

However the world's weather patterns are not interested in that formal definition, but are telling us today what a world of 1.5° warming looks like, with severe floods and droughts across the world in summer 2023 **[Exhibit 3]**, again in summer 2024 **[Exhibit 4]**, and again over the last 15 months **[Exhibit 5]**. And with each 0.1C degree of warming above 1.5°C, the adverse cost of climate change, and the costs of adapting to climate change, are going to increase.

Looking forward moreover a significant rise above 1.5°C now looks inevitable and a rise well above 2°C dangerously probable.

In 2021, the IEA's Net Zero scenario showed that a 38% fall in emissions would be needed during the 2020s to put the world on a path to limit global warming to 1.5°C **[Exhibit 6]** and contrasted this with the emissions path which might result from "Stated Policies", a scenario which the IEA judged would result in global warming of 2.6°C above pre-industrial levels by the end of the century.

With each subsequent set of IEA scenarios, the required emissions path for a 1.5° limit got steeper and has now become incredible. In the latest IEA World Energy Outlook **[Exhibit 7]**, even the most optimistic Net Zero scenario would result in1.65°C of warming by 2050, with a return to 1.5°C by 2100 only possible if we assume huge carbon dioxide removals in the second half of the century.[2] The latest Stated Policy scenario suggests global warming of 2.5°C by 2100, hardly improved at all since the 2021 projection.

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[2] IEA (2025) *World Energy Outlook 2025*. https://www.iea.org/reports/world-energy-outlook-2025

In the face of these developments, there are many voices calling for a "pragmatic" or "realistic" reset of climate ambitions **[Exhibit 8].** They include some, such as Dan Yergin and co-authors in a widely quoted article from Foreign Affairs, who urge that rising global demands for energy to support prosperity make a significant move away from fossil fuels impossible.[3]

They include Bill Gates, who argues that the best we can do – even with rapid technological advance – is a limit of very slightly below 3°C but who suggests that a temperature increase around that level would not be catastrophic, but something to which we can and must adapt.[4]

And they include Michael Liebreich, the founder of BNEF, who argues that we should recognise that the 1.5°C limit was always an impossible objective, and that we should focus instead on the "hard" Paris objective of 2°C.[5,6] He also suggests that we should focus almost entirely on the emissions which can be reduced with technologies whose application is likely to be costless, and significantly de-emphasise actions which might impose cost such as decarbonisation of aviation, shipping and heavy industry.

Such an approach largely avoids any need to gain public support for accepting mitigation costs, and therefore any need to make and win the argument that the costs of inaction, i.e. the adverse costs of climate change would be far higher.

So let me be clear upfront, in these lectures I will disagree profoundly with Yergin and Gates, since I think it is clear that climate change on anything like the level they see as acceptable will do enormous harm to human welfare.

And I will disagree somewhat with Michael Liebreich, since I believe that to get to well below 2°C we will have to gain political support for accepting some costs. Both:

- Because even though clean electrification will in the long term reduce costs to consumers, there are transitional costs which have to be anticipated and managed – a key theme of lecture 2.
- And because to keep global warming well below 2°C, we will need to decarbonise sectors where electrification does not provide anything like a complete answer.

If we are to win political support for accepting some costs, we have to begin by making the case that inaction will be far worse.

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[3] Foreign Affairs, Yergin et al. (2025) *The Troubled Energy Transition.* https://www.foreignaffairs.com/united-states/troubled-energy-transition-yergin-orszag-arya
[4] Gates Notes (2025) Three tough truths about climate. https://www.gatesnotes.com/home/home-page-topic/reader/three-tough-truths-about-climate

[5] BNEF (2025) *Liebreich: The Pragmatic Climate Reset – Part I.* https://about.bnef.com/insights/clean-energy/liebreich-the-pragmatic-climate-reset-part-i/
[6] BNEF (2025) *Liebreich: The Pragmatic Climate Reset – Part II: A Provocation* https://about.bnef.com/insights/clean-energy/liebreich-the-pragmatic-climate-reset-part-ii-a-provocation

The costs of inaction

Putting a monetary value on the harm to human welfare which will result from climate change is far more difficult than estimating the economic cost of mitigation which I will discuss in Lecture 2.

The precise mitigation cost depends on assumptions about future uncertain trends in the cost of different technologies. But at least the methodology for producing sound estimates is straightforward and the range of uncertainty somewhat bounded: we can calculate how many gigawatts (GWs) of solar, wind and nuclear power will be required to meet different shares of future estimated power demand, and we can multiply those GW volumes by assumed costs per MW to get total investment costs. We can estimate what total global aviation fuel demand will be, and how large the green cost premium might be if we use sustainable aviation fuel instead of conventional fuel. And so on for other technologies and sectors.

And that analysis suggests that we will need to invest somewhere around 1 to 2% of global GDP, over something like 30 to 50 years, to reach a global zero carbon economy in which GDP per capita will then be no lower and potentially a little higher than it would be if we continued to rely on fossil fuels for 80% of our energy.

Estimating the cost of inaction is far more difficult.

- We need to translate possible increases in global average temperature into assumptions about climate and weather in specific regions, and that translation is uncertain.
- From that we need to progress to the possible future incidence of extreme weather events – heat waves and wildfires, droughts and floods - and estimate their direct economic cost, and both those translations are uncertain.
- While still more uncertain are any estimates of possible longer term and indirect effects – for instance of migration driven by sustained drought and the political instability which it may induce.
- Finally, we face a fundamental conceptual problem – how do we measure the value of human lives lost?

Not surprisingly therefore, estimates of the cost of inaction come with very wide ranges. In Nick Stern's 2006 Review of the Economics of Climate Change, he estimated costs anywhere from 5 to 20% of global GDP.[7]

But uncertainty is no argument for inaction, indeed the more uncertain we are about future costs, the stronger the case for action to avoid them. And every serious analysis indicates a cost of inaction far higher than the cost of mitigation.

[7] Nick Stern (2006), *The Economics of Climate Change: The Stern Review.* https://www.lse.ac.uk/granthaminstitute/publication/the-economics-of-climate-change-the-stern-review/

- We know what a world of even +1.5°C looks like – it looks like Exhibits 3-5 – over 900 dead in floods in Pakistan,[8] $70-130BN of property and other capital losses in Los Angeles.[9]
- We know that the identifiable costs of climate induced damage to property have increased dramatically over the last 20 years, with BNEF estimating that they have now reached a level of about $1.5trillion per year, which is the same order of magnitude as the investments we must make to limit further warming **[Exhibit 9].**
- We know that the incidence of heat waves, drought and wildfire events will increase dramatically as we go from 1.5°C warming to 3°C warming, and we can estimate what a changing climate will do to agricultural productivity in different regions, or to required investment in coastal defences, and other adaptation costs.
- And putting it all together, a recent report by experts at Cambridge University and BCG estimates that if we allow the average global temperature to increase to +3°C by 2100, rather than limiting it to 2°C, we will face additional cumulative losses equivalent to 11- 24% of GDP between now and then, which could be avoided if we invested 1-2% of global GDP to keep global warming below 2°C **[Exhibit 10].**[10]

The difference is so vast that the conclusion is clear: however uncertain are estimates of the costs of inaction, we know they are massively higher than the cost of mitigation. And that is before we allow for either:

- The value of biodiversity or natural beauty in themselves, whatever their calculated economic value, with for instance 70 to 90% of tropical coral reefs likely to die if temperatures remain continually above 1.5°C.
- Or the risks that global warming above some level generates irreversible physical effects such as the collapse of the Greenland ice sheet; or indeed physical effects which themselves increase global warming yet further, such as the abrupt thawing of permafrost and the release of trapped methane. Science can only provide us with wide temperature ranges at which these "tipping points" might be triggered, but the ranges provide a strong argument for limiting global warming to below 2°C and ideally to the 1.5°C limit which we are already breaching **[Exhibit 11].**

Some of the "pragmatists" I referred to earlier argue that we should exclude from discussion about climate change "catastrophic" scenarios which consider global warming well above 3°C, on the grounds that these are now very unlikely. But even if we concentrate on the temperature range of 2-3°C towards which we are heading on stated or current policies, the cost of inaction will be very high and the risks enormous.

[8] BBC News (2025), *More than two million people evacuated from deadly floods in Pakistan.* https://www.bbc.co.uk/news/articles/cn0xjd7wvy1o
[9] UCLA Anderson Forecast (2025), *Economic Impact of the Los Angeles Wildfires* https://www.anderson.ucla.edu/about/centers/ucla-anderson-forecast/economic-impact-los-angeles-wildfires
[10] BCG (2025), *The Economic Case for Climate Investment is Clear, but Not Broadly Understood.* https://www.bcg.com/press/12march2025-economic-case-climate-investment

And those costs and risks do not lie in the far distant future but within the lives of people living today.

The question of how far ahead we should have concern for future generations can be debated. In Lampedusa's great novel The Leopard, Prince Fabrizio argues that "*We may worry about our children and perhaps our grandchildren; but beyond what we can hope to stroke with these hands of ours, we have no obligations".*[11] I would argue for a considerably longer time horizon, extending at least to those who will be loved by those we love. But even if we limit ourselves to two generations, 2100 is near.

Last year I became a grandparent, and in 2100 my granddaughter will be still only 75 years old, with hopefully a few more decades of healthy life before her; and she may perhaps have children who will live to 2150 and grandchildren who will live well into the late 22nd century.

I think that if we leave to my granddaughter's generation a world that warms by 2.5°C by 2100 – which is where we are heading on stated policies – I and the rest of my generation will have failed terribly to care for this world.

I therefore believe that we must limit global warming to below and ideally well below 2°C, even if some cost has to be accepted to achieve that objective.

The purpose of these lectures is to show how that is technologically and economically achievable. In doing that I will draw extensively on the insights included in the multiple reports which the Energy Transitions Commission has produced over the last 10 years: but I should stress that my conclusions are personal rather than reflecting an official ETC position.

Technologies and costs; abundant clean electricity for all

In 2008 I became the first chair of the UK's Climate Change Committee (CCC), created by the Climate Change Act of that year. The Act had mandated a reduction of UK emissions of 60% below 2050 levels by 2050, but we recommended and the government accepted a higher 80% target, confident that new technologies would enable us to achieve this at a reasonable cost. But if you had asked me in 2008 whether a 100% reduction by 2050 was possible, I would have said only at very significant cost.

Only 11 years later in 2019 however, the UK adopted the target of achieving net zero emissions by 2050, and by the time of the COP26 climate conference in Glasgow in 2021, so too had most other countries, and thousands of companies and financial institutions.

That rising ambition reflected in part increased awareness of the severity of the climate change threat: but also a pace of cost reduction in key technologies far faster than the CCC and other experts anticipated 15 or 20 years ago.

In 2008, at the CCC, we thought that solar PV costs might fall by something like 25-40% by the 2020s: in fact they are now over 90% lower **[Exhibit 12]**, and the price of wind turbines

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[11] Giuseppe Tomasi di Lampedusa (1958), *The Leopard*

has fallen 40% in real terms across the world, but even more rapidly in China, a difference to which I will return in Lecture 2 **[Exhibit 13].**

That solar price collapse in particular has driven growth in solar PV installations far faster than almost any expert group anticipated. **Exhibit 14** shows the actual trend compared with what the International Energy Agency anticipated in successive annual projections. And across most of the world, we have reached a point where the cheapest way to produce a kilowatt hour of electricity is from solar or wind resources. Over the last 3 years Pakistan has seen a huge wave of roof top solar PV installation which has taken solar's share of electricity supply from trivial in 2020 to around 20% today,[12] whilst solar PV imports into Africa rose 60% in 2025.[13]

That of course still leaves us with a challenge of what to do when the sun doesn't shine and the wind doesn't blow. But the price of lithium ion batteries has also collapsed, down 94% in 15 years **[Exhibit 15]** Initially the most dramatic falls initially were in battery packs for electric vehicles, but over the last three years there have been huge falls in the cost of stationary battery storage systems, **[Exhibit 16]** which are increasingly delivered in containers which package together battery cells, transformers, inverters and other battery management system elements.

And that has created a world where the solar + battery combination is going to be the cheapest way to produce round-the-clock renewable electricity in most of what we label the global sunbelt, where the main renewable resource will be solar and the main balancing challenge from day to night **[Exhibit 17].** (Though it is worth noting that the most favourably placed regions are those blessed with <u>both</u> abundant solar and wind resources such as North Africa, Chile and Australia)

In the high latitude windbelt, where our main renewable resource will be wind and the main balance challenge is seasonal, the challenges are more difficult and a wider array of storage and flexibility technologies will have to be deployed. But recent ETC analysis still shows that in almost all climatic regions, the future <u>total system cost</u> of power systems which derive the vast majority of their power from intermittent renewables will be lower than the price of electricity today, and particularly so in both China and in global sunbelt countries such as India **[Exhibit 18].**[14]

In addition, as soon to be published ETC analysis will show, nuclear and geothermal sources can be cost-effective in many countries.

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[12] WRI (2025), *The Perfect Storm Fueling Pakistan's Solar Boom.* https://www.wri.org/insights/pakistan-solar-energy-boom

[13] Ember (2025), Africa's solar imports surge 60%, giving the first evidence of a take-off in solar in Africa. https://ember-energy.org/latest-updates/africas-solar-imports-surge-60-giving-the-first-evidence-of-a-take-off-in-solar-in-africa

[14] ETC (2025), *Power Systems Transformation: Delivering Competitive, Resilient Electricity in High-Renewable Systems.* https://www.energy-transitions.org/publications/power-systems-transformation/

There is therefore no doubt that we have the technologies to produce massively increased quantities of completely clean electricity, eliminating fossil fuels almost entirely from power generation.

And with that clean electricity we can then replace fossil fuels in end applications, and in doing so achieve a revolution in energy efficiency.

Energy is fundamental to human welfare, but in today's fossil fuel-based system the majority of energy inputs are wasted. We start with about 170,000 TWh of "primary energy" – coal, oil and gas – but by the time we have turned that into the "final energy" which we actually use, we have lost 49,000 TWh (almost 30%), in the energy conversion losses which arise in fuel refining and combustion-based electricity generation **[Exhibit 19]**.[15]

But even "final energy" as conventionally defined – such as diesel or gasoline put into a fuel tank – is not useful energy such as kinetic energy in the car wheels; and an internal combustion engine turns about 70-75% of the chemical energy in the fuel into wasted heat, and only about 25-30% into the kinetic energy we actually want. Across all applications, wasted heat losses mean that 122,000 TWh of final energy produces only 64,000 TWh of useful energy.

These heat losses reflect the inherent thermodynamic inefficiency of heat to work translations but can be almost entirely eliminated in the electrified world. An electric vehicle turns around 90% of the energy in the battery into energy in the wheels: and electric heat pumps can use thermodynamics in our favour, using work to extract heat from the ambient air, and putting 3 to 4 kWh of heat into our homes for every 1 kWh of electricity input. That 300-400% efficiency – which in future could increase to 600-700% – compares with the maximum efficiency of a gas boiler of only 90%. Induction cookers can deliver 85-90% of input energy into heat within the pan: a gas burner can be only 30-40% efficient and traditional biomass cooking systems only 10-20%.

Looking forward, we should expect to see, and should want to see, big increases in the demand and supply of the energy-based services which can improve people's lives. I personally hope that major cities will invest in public transport, pedestrian and cycling facilities which reduce our reliance on cars, but even if they do that, global road transport kms travelled could increase 70% by 2050 **[Exhibit 20]**. Air travel will probably increase by at least 150% percent, so too will the demand for cooling, while heated floor area could increase by a smaller but still significant 25%.

But given the inherent efficiency advantage of electricity, and the potential to subsequently improve still further the efficiency of electrical equipment, these increases in energy based services could be met while reducing final energy demand 50% below a business as usual level and 25% below today's level, with electricity use growing to meet as much as 60% or 70% of final energy demand **[Exhibit 21].**

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[15] ETC (2025), *Energy productivity: Increasing efficiency in an expanded, electrified energy system.* https://www.energy-transitions.org/publications/energy-productivity/

Over the next 30 years indeed it will be possible, primarily through electrification, to reduce primary energy consumption by 36% and final energy by 24%, while increasing the consumption of useful energy by 64% and global GDP by over 100% **[Exhibit 22].**

The electric future is thus inherently more energy efficient than the fossil fuel one, and in most applications it will deliver energy service services at lower cost to consumers. Electric vehicles are inherently cheaper to run than internal combustion engines; in China they are also already cheaper to buy upfront.[16]

Heat pumps can deliver heat into the home at lower cost than gas boilers as long as the cost of electricity is less than 3 times the cost of gas.

And this electric advantage will grow over time, because the technologies of clean electricity production and use are inherently capable of achieving future cost reductions which fossil fuel-based systems will never achieve.

Technology fundamentals; the electro tech opportunity

Since 1975, the price of solar PV per watt of power has come down not 90%, not 99%, but 99.9% **[Exhibit 23].** Since 1990 the cost of lithium-ion batteries has fallen 99%. Only in the last 10 years have these technologies got so cheap that we can easily see how transformative they are going to be, but the long-term trends show that there is something distinctive about these technologies which enables them to achieve cost reductions not seen elsewhere.

Since 2008 solar PV costs have come down far faster than the CCC's hopelessly pessimistic 25-40% projection, but conversely, while we assumed the cost of carbon capture and storage technologies might fall by a similar 25%, there has been almost no cost reduction at all. **Exhibit 24** shows analysis from the ETC's 2022 report on carbon capture utilisation and storage.[17] It shows that for actual projects developed in 2008-15, the cost trend was up not down. On the right it shows planned projects which hope to deliver at lower costs, but hardly down from the 2008 level. In essence what we seem to have is some technologies, such as solar where cost reduction is relentless and fast, and others, such as carbon capture and storage, where it is slow and uncertain **[Exhibit 25].**

A clear pattern has emerged: **[Exhibit 26]**

- Wherever technologies can be commercialised in the form of highly standardised units, manufactured on a huge scale in factories using standardised manufacturing equipment, and dispatched to customers in a close to plug-and-play form – solar PV,

[16] BNEF (2025)*, Global Electric Vehicle Sales Set for Record-Breaking Year, Even as US Market Slows Sharply, BloombergNEF Finds.* https://about.bnef.com/insights/clean-transport/global-electric-vehicle-sales-set-for-record-breaking-year-even-as-us-market-slows-sharply-bloombergnef-finds/

[17] ETC (2022)*, Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited.* https://www.energy-transitions.org/publications/carbon-capture-use-storage-vital-but-limited/

containerised storage battery systems, electric vehicles – we see learning curve and economy of scale driving dramatic cost reductions.

- But wherever technologies require bespoke engineering specific to a particular site or industrial process – carbon capture and storage, biofuel production, or large-scale first-of-a-kind nuclear plants – actual cost reductions often disappoint.

So in part the technologies of renewable electricity generation and direct electricity application achieve faster cost reductions because they are more susceptible to standardisation, mass manufacturing and plug-and-play deployment.

But also, because the production and use of electricity requires a combination of interrelated technologies for manipulating photons, electrons, ions, and magnets, electrical and magnetic fields – a so-called "electro tech stack" which combines 5 key hardware technologies: **[Exhibit 27]**

- Solar PV panels which turn a flow a flow of photons into a flow of electrons.
- Lithium-ion (and other chemistry) batteries which can manipulate ions to store and then release electricity.
- Electric motors which turn electric current into mechanical work and electric dynamos which achieve the reverse, for instance in wind turbines.
- Power electronics which enable us to use electricity to control electricity, to switch it on and off millions of times per second, and to run motors on a variable speed rather than on/off basis.
- And embedded computing capacity, semiconductor chips embedded within electrical equipment which enable the intelligent management of electrical power.

All of these technologies have seen dramatic improvements in performance, reduction in cost, and in several cases reductions in size, over the last several decades. And further rapid progress is inevitable for two reasons:[18]

First because they all rely on the foundation of material science as it relates to the electrical and magnetic properties of inorganic materials, and our understanding of that science is likely to improve at an accelerating rate as a result of the application of artificial intelligence (AI).

Second, because progress along one dimension creates demand for progress along all the others. For instance:

- Dramatic reductions in battery storage costs over the last few years are now driving ever more demand for solar PV.
- Dramatic reductions in the cost of miniature electric motors, and the power electronics to control them, enable the development of ever more effective drones, which creates demand for further improvements in battery technology.

[18] See Packy McCormick and Sam D'Amico (2025), T*he Electric Slide; The history, 99% decline and the future of the Electric Stack, for* an excellent detailed analysis of these interrelated technologies and estimates of the pace of cost decline. https://www.notboring.co/p/the-electric-slide

- Falls in the cost of solar PV panels mean that other cost elements within a complete installed PV system become more important, increasing incentives to achieve reductions in the cost and size of other elements such as inverters.
- While the ability to miniaturise motors and batteries, power electronics and embedded computing ability, will be a key driver of the development of so-called "physical" or "embedded" artificial intelligence, the extension of AI capabilities to the physical environment through the sensor and actuator technologies which make possible robotics, including of the humanoid sort.

In addition, hardware advances and cost reductions are also driving continual software and business innovation, with for instance the rising share of intermittent renewable supply increasing the importance of smart grid and smart building control systems which can optimise grid capacity management and enable flexible electricity demand in response to fluctuating supply **[Exhibit 28].**[19,20]

These interconnections between the different elements of the "electro tech stack", plus further advances in material science, including in ways enabled by artificial intelligence, together with large scale investment, economy of scale and learning curve effects, are certain to keep driving cost reductions and performance improvements in all the key technologies of clean electricity, increasing the cost advantage versus fossil fuels **[Exhibit 29].** Fossil fuel extraction and combustion technologies are of course not static; the development of fracking techniques for instance significantly cut shale oil and gas extraction costs between 2000-2020. But the costs of the electro tech stack will inevitably fall far faster.

The future energy system will be electric: and will be one of abundant clean energy for all.

And also, inherently more sustainable than our current fossil fuel-based system.

Inherently more sustainable

The future is electric and that implies hugely increased global electric demand. How much, and how soon depends upon the pace at which countries seize the opportunity for growth in energy-based services which electricity can provide support.

Estimates for future electricity demand change quite fast. When the ETC first looked at China's electricity system in 2019, we, like many Chinese experts, projected electricity demand growing from 6,500 TWh in 2019 to 11,000 TWh by 2030, potentially reaching a peak of 15,000 TWh by 2050/60.[21] But demand has already grown to 10,000 TWh and latest

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[19] See ETC (2025), *Achieving Net Zero Buildings; Electric, Efficient and Flexible* for discussion of major cost reduction potential from technology enabled demand response. https://www.energy-transitions.org/sector/buildings/

[20] See ETC (2025) *Power Systems Transformation*, Chapter 2 for discussion of innovative grid management hardware and software technologies. www.energy-transitions.org/wp-content/uploads/2025/07/Power-Systems-Transformation_Main-report_vf.pdf

[21] ETC (2019), *China 2050: A fully developed rich zero-carbon economy.* https://www.energy-transitions.org/publications/china-2050-a-fully-developed-rich-zero-carbon-economy/

estimates by the Institute for Climate Change and Sustainable Development (ICCSD) at Tsinghua University suggest that 20,000 TWh demand is possible by 2060.

Similarly, while the ETC's initial work in India, conducted along with The Energy and Resource Institute of India (TERI), envisaged demand rising from about 1,300 TWh in 2019/20 to about 5,500 TWh by mid-century, latest trends, which show demand up a third between 2019 and 2025, may suggest a considerably higher figure.[22]

Meanwhile, the development of artificial intelligence has produced a major short-term surge of electricity demand, potentially reaching 3,000 TWh by 2035 and 4,000 TWh by 2035.[23]

The ETC's overall estimates of global electricity demand in 2050/60 have varied in a range of 60,000 to 80,000 TWh,[24] but significant further growth will occur beyond mid-century since many lower income countries, especially in Africa, will still then have far lower electricity use per capita than required for high living standards.

In addition, electricity demand for hydrogen production via electrolysis might amount to 15,000 TWh,[25] and it is almost certain that new currently unknown uses for electricity will emerge. Energy is so fundamental to human prosperity that once it is available at low cost, humanity will find new uses for it.

It is therefore reasonable to assume that sometime in the second half of this century the world might use around 100,000 TWh of electricity per annum versus 32,000 TWh today.

Producing that electricity, primarily from renewables, will of course require land for solar panel and wind turbine installations, polysilicon for solar panel manufacture, and rare earth permanent magnets for wind turbine dynamos. And using that electricity will require copper for transmission and distribution networks, lithium and perhaps nickel and cobalt for batteries, and rare earths for the permanent magnets in millions of electric motors.

All of which for some people creates a concern that as we fix the climate challenge, we will simply create new unsustainable demands for natural resources which take humanity's impact beyond acceptable planetary boundaries along other dimensions.

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[22] ETC (2020), *Renewable power pathways: Modelling the integration of wind and solar in India by 2030.* https://www.energy-transitions.org/publications/renewable-power-pathways/

[23] See ETC (2025), *Energy productivity: Increasing efficiency in an expanded, electrified energy system.* chapter 4 for analysis of potential electricity demand from AI training and inference. The range of uncertainty is very wide because of the offsetting impact of super rapid growth in computing demand vs super rapid improvement in energy efficiency (i.e. required energy input per unit of computing) https://www.energy-transitions.org/publications/energy-productivity

[24] See ETC (2022*), Fossil Fuels in Transition: Committing to the phase-down of all fossil fuels.* https://www.energy-transitions.org/publications/fossil-fuels-in-transition/

[25] Since the ETC 2021 report on the potential role of hydrogen in the energy transition, ETC (2021)*, Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy,* reasonable projections of future demand for green H2 have been reduced, in part because of the continued rapid improvement in direct electrification technologies (e.g. in heavy duty trucks). An electricity demand of about 15,000 TWh would result from a green H2 demand of about 300m tonnes per annum. https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/

In which case the only way to deal with the climate crisis is to constrain growth in energy-based services, to fly less, drive less and heat or cool our homes more frugally.

But detailed analysis of the resource requirements for our new energy system – set out in the ETC's 2023 report on M*aterial and Resource Requirements for the Energy Transition –* shows that there are no significant planetary boundary limits to the supply and use of clean electricity, and that our new clean electricity based system will have a local environmental impact which is a fraction of that imposed by the existing fossil fuel energy system, and an even smaller fraction of the impact of our existing system of food production.[26]

The future electric energy system indeed is renewable and sustainable for reasons inherent in the fundamental nature of the technologies involved.

Limitless renewable electricity resources

Not only is green electricity going to be cheap – its supply is effectively limitless relative to demand.

For many decades, some scientists have dreamt that nuclear fusion will be able to deliver limitless, zero carbon, safe, cheap electricity. And I don't exclude the possibility that nuclear fusion on earth may eventually be part of our limitless green energy future.

But the wonderful reality is that human beings already enjoy the benefit of limitless energy delivered from an unbelievably massive nuclear fusion plant placed 93 million miles away from Earth – the sun.

Each day the sun shines down on earth almost 8000 times as much energy as all human uses and we only need to capture and use 1/80 of 1% of that energy to have a completely decarbonised energy system.[27]

And if we produced all of 100,000 TWh hours of electricity from solar PV, the panels would only need to cover about 1% of the global land area, and about 0.3% of the global surface area if we could also use some of the surface of the oceans **[Exhibit 30].**[28]

In fact it would never make sense to rely only on solar PV; optimal renewable systems will use mixes of renewable resources – solar, wind and hydro, and geothermal – in line with local resource endowment. And nuclear fission will play a significant role in some systems whatever the pace of fusion developments.

Some of the non-solar renewable resources moreover, are also abundantly available. The International Energy Agency estimates that the total technical potential for offshore wind is as

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[26] ETC (2023)*, Material and Resource Requirements for the Energy Transition.* https://www.energy-transitions.org/publications/material-and-resource-energy-transition/

[27] Solar radiation energy reaching the earth's surface is about 3.4m EJ per year which is 945 million TWh. Divided by human final energy demand of 122,000 TWh, this is about 7,700 times 2023 demand, and a higher 15,000 times 2023 useful energy demand (see Exhibit 22).

[28] See ETC (2021), *Making clean electrification possible*, Page 66. www.energy-transitions.org/wp-content/uploads/2022/07/ETC-Global-Power-Report-Final.pdf

much as 420,000 TWh hours, which is at least 10 times what will be needed as an optimal offshore wind element within the future global electricity system.[29]

Now of course solar and wind developments or hydro or geothermal, may have environmental local environmental and aesthetic impacts which we will need to manage. And local land availability may be a constraint in specific densely populated nations:

- China, with a population density of 151 people per km^2, could easily meet a mid-century electricity demand of 20,000 TWh (equal to 14.3 MWh per person and twice the current level) while devoting only a trivial % of its land area to solar PV.
- But if Bangladesh, with a population density 9 times higher, had half that per capita demand in 2050, and attempted to meet it all with solar PV, the panels would have an aggregate area equal to around 15% of the total national land area, in a country where almost all land is already intensively used.

Though even that might be possible, because of the potential of the rapidly growing technology of "Agri PV" **[Exhibit 31]** with solar panels installed above productive agricultural land. Soon to be published analysis by The Energy and Resources Institute of India, (TERI), using extremely conservative assumptions, suggests that in India the Agri PV potential could easily reach 1,750 GW of installed solar capacity, which could produce 3,000 TWh per annum, around 50% of India's projected electricity demand in 2050. This would have minimum impact on food production and in some situations an increase, and could significantly reduce water demands since evaporation is partially trapped under the panels. Total eventual potential could be several times that level.[30,31]

Applied globally, Agri PV has enormous potential. And at the global level there is no doubt that we have far more than the land, the solar and the wind resources needed to meet the vast majority of massively expanded future electricity demand.

Plentiful minerals

As for the minerals required to support a deeply electrified future economy, ETC analysis supports the same optimistic conclusion – adequate resources are available and the environmental impact of extracting them is far less than that of the existing fossil fuel-based energy system.

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[29] See IEA (2019), *World Energy Outlook*, Chapter 14.

[30] Out of India's land area of 297m hectares, ~170m hectares is classified as agricultural, mainly devoted to crops. After excluding land which is either protected, has too steep a slope, lower solar radiation, or subject to flooding or high wind risks, 47M hectares might have potential for Agri PV, but within this the highest immediate potential lies in 2.8m hectares where the existing crops are the most suitable for Agri PV, and where therefore the installation of Agri PV would not require any change in the crop cultivated. This 2.8m hectares could support 1,750 GW of solar capacity.

[31] Long distance international grid interconnection could be an alternative way to meet the clean electricity demands of land constrained countries. See ETC (2025), *Connecting the world: long distance transmission as a key enabler of a zero-carbon world*. https://www.energy-transitions.org/publications/long-distance-transmission/

The details of that analysis are set out in the ETC's 2023 report on *Materials and Resources for the Energy Transition.* [32] Key points are that:

- For all the major minerals required – lithium, nickel and cobalt for batteries, polysilicon and silver for solar panels, or rare earths for magnets which go into wind turbines and electric motors – there are plenty of economically accessible resources. In some cases projections of demand threaten to exceed already declared "reserves", but "resources" greatly exceed "reserves" and both estimated reserves and resources tend to increase over time as new demands become apparent. The US Geological Survey's estimate of economically accessible lithium resources, for instance, was 53 million tonnes in 2019 but is now 115 million, a figure which compares with the 19 million tonnes of pure lithium required to equip 2 billion autos with a 60 kWh battery.[33] The biggest challenge relates to copper, with growing demands for transmission and distribution networks and for electric wiring within new buildings, but feasible paces of mine development and expansion can meet future demand.
- There is huge potential for technology innovation to reduce future demand for the most sensitive materials. In 2019 over 75% of passenger EV batteries were based on either NMC or NCA cathode chemistry, with the C standing for cobalt; and projections suggested that cobalt demand could increase two and a half times by 2030, with major concerns about the environmental, social and political risks created by supply concentration in the DRC. But the rapid emergence of the Lithium Ferrous Phosphate (LFP) battery chemistry, which requires no cobalt and which is likely to soon account for over 50% of vehicle batteries, has produced a dramatic downward revision: between 2019 and 2022, BNEF reduced its forecast of required 2030 cobalt supply by 50% **[Exhibit 32].**
- The is also a huge potential to reduce future mineral demands via recycling, and strong regulations are being imposed in many countries to require this. By 2040 90% of lithium in end-of-life batteries could be recycled, and by 2050 recycled lithium could meet 60% of lithium demand.
- New mines of course create a new demand for land, sometimes in sensitive areas such as tropical forests, but the total land footprint of today's mining industry is only 1/500th of the land devoted to agriculture, and the additional land to support new mineral supply required for the energy transition will be about 1/5000th of today's agricultural land. Not surprisingly therefore mining plays, and will play, a very minor role in deforestation and other forms of biodiversity loss. The International Resource Panel estimates that less than 1% of global biodiversity loss results from mining activity [**Exhibit 33]**, with the biggest impacts imposed by coal and gold mining, not by the minerals needed for the energy transition.
- Extracting minerals using fossil fuel energy will inevitably result in emissions but even given current production processes, total future cumulative mining emissions will be less than the annual emissions from the fossil fuel economy which those minerals enable us to replace. And mineral extraction can and will be electrified. In a maximum

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[32] ETC (2023), *Material and Resource Requirements for the Energy Transition.* https://www.energy-transitions.org/publications/material-and-resource-energy-transition/
[33] USGS (2025), *Mineral Commodity Summaries 2025.* https://pubs.usgs.gov/publication/mcs2025

efficiency and recycling scenario, total future cumulative emissions for mineral extraction would be just a third of annual emissions from the fossil fuel system.

- Finally, new mines and lithium extraction processes are bound to have a local environmental impact, including via demand for water. But total annual water demands for all energy transition related mines will be less than a half of those imposed by today's fossil fuel-based system, and about $1/700^{th}$ of those resulting from agriculture. Meanwhile, local air and pollution effects can be dramatically reduced by new technology, and by the strong regulations which can and should be imposed.

The overall picture is therefore clear. Mining will of course have an environmental impact which needs careful management. It is impossible for 9 billion people to live prosperous lives without a significant adverse impact on some local natural environments. But the impact of the new system must be compared with the impact of the old. And across all relevant measures, our new electrified energy system will be far more sustainable than the old fossil fuel one which we are replacing.

An essentially renewable system

Which is not just a happy accident, but inherent to the very nature of the renewable system which we are building.

We often use that word "renewable" but fail to reflect on how fundamentally different this system is from one based on fossil fuels.

Until now, to get energy, we have had to take massive amounts of fossil fuels out of the earth each year – 7000 million tonnes of coal, 36.5bn barrels of oil, 3.9tr cubic metres of gas – and burn it in chemical reactions which produce 35 billion tonnes of CO_2, plus large scale methane emissions.

And then the next year, we have to do the same all over again.

In a renewable system by contrast, we take much smaller quantities of inorganic minerals and we put them into structures – silicon in the solar panels, copper in the wires, lithium in the batteries, rare earths in the motors. The photons of sunlight and the motion of the wind then generate streams of electrons which we can use to heat or cool buildings and drive our machines, all of which happens silently, and with almost no local pollution, let alone global atmospheric pollution.

And at the end of the year those structures are largely unchanged, and already in place to do the same job all over again.

Of course it's not quite like that, because some atomic and molecular structures undergo complex microscopic change and degradation – batteries for instance slowly losing capacity as the result of the buildup of crystal/salt formations.

Which means that we need to repair, replace and recycle as much as possible, and also source some new mineral input to keep the system going.

But the difference with the fossil fuel system is still fundamental. The future electricity-based energy system is in its very nature renewable, and for that reason faces no long-term planetary boundaries at a scale relevant to human energy demand.

Our electric future is therefore not only one in which we enjoy abundant electrical energy at zero marginal cost but also one with close to zero marginal environmental impact, dramatically reducing all forms of local pollution, and eliminating about 60% of all our greenhouse gas emissions.

But eliminating 60% of all emissions is not enough to prevent global warming significantly above 2°C.

Beyond electrification: hard to abate sectors and food production

Total anthropogenic CO_2 emissions are estimated at around 39 Gt per annum, of which around 33 Gt derives from fossil fuel combustion in the energy, building, industry and transport sectors of the economy, and another 6 Gt from land use change such as deforestation primarily resulting from food production.

In addition, methane emissions amount to 375 million tonnes, of which about 35% derives from fossil fuel production and processing activities upstream from end applications, about 20% percent from waste management activities, and just over 40% from food production, in particular the rearing of ruminants to produce red meat. **Exhibit 34** shows the estimated breakdown of CO_2, N_2O and CH_4 (methane) emissions by sector in 2020.[34]

To express methane in CO_2 equivalent terms, we have to make assumptions about the relevant time period: using a 100-year period 375m tons of methane has a global warming impact equivalent to about 11 Gt of CO_2, on a 20-year basis, it could be as much as 30 Gt.

But if for now we take the 100-year approach, and allocate the methane emissions from fossil fuel production and processing to end use sectors, we can think of 51 Gt of CO_2 equivalent emissions as deriving from three broad sectors of the economy **[Exhibit 35]**, with:

- About 30 Gt, roughly 60%, resulting from activities which either already are electrified, or can certainly be electrified at low/nil eventual cost – with this category including buildings heating, road transport and low-to-medium heating applications in industry.
- About 10 Gt arising from long-distance transport – shipping and aviation – and from heavy industries (iron and steel, cement and chemicals), sectors where electrification will be either more difficult or in some cases impossible.
- And a final 10 Gt deriving directly or indirectly from agriculture, of which 90% arises from either land use changes, methane emissions or nitrous oxide, with less than 10% from energy use which could be electrified.

[34] The breakdown shown in Exhibit 34 was based on analysis reported in the ETC (2022) *Mind the Gap* report 2022. Data by sector is imperfect, with different sources suggesting materially different figures as a result of different methodologies e.g whether the sectoral data include an allocation of methane emissions arising from upstream fossil fuel production and processing and whether figures for chemicals include end of life emissions from incineration or degradation of plastics as well as from plastics manufacture. The ETC will produce an updated estimate of sectoral emissions in 2026, but the broad division of emissions shown in Exhibit 34 is unlikely to change significantly. www.energy-transitions.org/wp-content/uploads/2022/04/Mind-the-Gap-How-Carbon-Dioxide-Removals-Must-Complement-Deep-Decarbonisation-to-Keep-1.5C-Alive-1.pdf

As we go up that bar, **[Exhibit 36]** the nature of the technological challenge we face changes. To simplify greatly, we go from:

- The physics of photons, electrons, and ions, and the manipulation low/medium temperature heat and kinetic energy
- To the chemistry of iron ore reduction, limestone calcination and nitrogen-based fertiliser production, and the use of new molecular fuels in ships and planes
- To the biology of photosynthesis and the production of carbohydrates and proteins.

And as we go up **[Exhibit 37]**, we go from:

- Known electrification technologies which we can be very confident will enable us to reduce both emissions and costs.
- To known technologies which are likely to impose a green cost premium, i.e. a cost penalty from making products or services in a zero-carbon fashion.
- To the agricultural sector where we do not yet have a clear new technology answer to the emissions challenge, and where actions which are already technologically feasible are likely to add significant cost.

Any credible strategy for limiting global warming to well below 2°C cannot therefore rely on clean electrification alone, but must also include actions to reduce or offset emissions where electrification cannot provide the answer.

The "hard to abate" sectors

The sectors of the middle wedge are often labelled "hard to abate" – though in fact, as I will argue later this evening and in Lectures 2 and 3, they have some features which may make them easier to decarbonise than for instance residential heat.

But they are undoubtedly "more difficult to electrify" – though for two quite different reasons as between long-distance transport and heavy industry:

Kinetic energy in shipping and aviation

In the case of shipping and aviation, the fundamental energy need is no different from road transport.

We want to generate kinetic energy in propellers or turbines to drive ships or planes forward, exactly as we do in wheels to drive cars and trucks, and at present we do that with combustion engines which impose high energy losses in heat to work translation.

And just as in road transport, electric motors could be used in aviation and shipping instead of combustion engines, and if they were used would deliver large energy efficiency improvements.

But what we lack for these sectors is batteries with sufficient energy density – in either volumetric or gravimetric terms – to support long-distances between recharging. Current achievable densities of around 800 Wh per litre and 500 Wh per kg at the cell level can support increasingly long-distance road passenger and road freight transport and short distance aviation and shipping **[Exhibit 38]**. But we would need gravimetric energy densities about six times higher before long distance aviation (say over 3,000 km) would become possible.[35]

Relentless improvements in battery energy density – which on current trends increase by about 50% each decade[36] – will take us in that direction, and in the long run densities of 3,000 kWh per kg are theoretically possible with batteries which use oxygen as the active cathode material – so-called lithium air or lithium oxygen batteries.[37,38]

But it will take several decades at best before that technology can be commercialised, and even in a "maximum electrification" scenario, it is difficult to see electric flight counting for more than 2-3% of aviation traffic by 2050 and a similarly low percentage of total shipping traffic.[39,40] For those several decades, therefore, long-distance shipping and aviation will depend on an energy dense liquid fuel, with decarbonisation achieved by changing either the type of fuel used or the way we produce it:

- In the case of shipping using moving from marine fuel oil to either methanol or ammonia.
- And in the case of aviation, continuing to use essentially the same jet fuel, but produced with biofuel or synthetic input rather than using fossil fuels.
- And with for both sectors the alternative of continuing to use fossil derived fuels but offsetting the emissions by carbon removals.

The good news is that these technologies are now available; the challenge is that in both cases the new green technology costs far more than the fossil fuel alternative, and will almost certainly continue to cost more for several decades.

This reflects the fact that, unlike in applications where we can use electricity directly, these new technologies have no inherent efficiency advantage versus fossil fuels. Indeed, in some ways they face an inherent inefficiency penalty; in both shipping and aviation, the energy losses between primary energy input and final energy fuels will increase as a result of a shift to decarbonised fuel options **[Exhibit 39].**

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[35] ETC (2025), *Carbon in an electrified future: Technologies, trade-offs and pathways* https://www.energy-transitions.org/publications/carbon-in-an-electrified-future/

[36] The rate of increase has recently been faster in volumetric density, but for aviation in particular gravimetric density is the key limiting factor.

[37] Science Direct (2023), *Lithium-Air Battery.* https://www.sciencedirect.com/topics/engineering/lithium-air-battery

[38] ETC (2022), *Making Net-Zero Aviation Possible.* https://www.energy-transitions.org/publications/making-net-zero-aviation-possible/#download-form

[39] ETC (2025), *Carbon in an electrified future: Technologies, trade-offs and pathways* https://www.energy-transitions.org/publications/carbon-in-an-electrified-future/ http://www.systemiq.earth/wp-content/uploads/2025/11/Carbon-in-an-electrified-future-Exec-Summary.pdf

[40] ETC (2022), *Making Net-Zero Aviation Possible.* https://www.energy-transitions.org/publications/making-net-zero-aviation-possible/#download-form

Chemical reactions in heavy industry

The challenge in heavy industry is quite different. The CO_2 emissions here do not arise because we use combustion generated heat to produce work, but from the chemical reactions required to produce the materials which a modern economy requires **[Exhibit 40]**

- Using carbon in coking coal as the reduction agent to produce primary iron from iron oxide ores.
- Turning calcium carbonate into calcium oxide in order to produce cement and then concrete.
- Deriving hydrogen from methane to combine with nitrogen to produce ammonia and then urea fertiliser.
- And in the case of plastics, delivering a product which is inherently constructed from carbon molecules which need to be sourced from somewhere.

In each of these sectors, there are large high temperature heat inputs, and a range of new technologies are being developed which can electrify even the highest temperatures – above 1000°C – required in iron and steel, cement, ceramics and some other industrial processes. These technologies span from shockwave heating, which exploits the potential to translate electrically generated work into heat, to more direct electricity to heat translation processes such as arc and plasma heating, conventional resistance systems, microwave and induction.[41]

But in each industry too, the chemical reactions currently used to produce materials would result in CO_2 emissions whatever the heat generation mechanism.

Here too, however the good news is that we already have technologies which could enable us to produce all of these materials without CO2 emissions **[Exhibit 41].**

But here too, as with shipping and aviation, these will impose a significant green cost premium, for several decades, and in some cases forever.

- In iron making, we could use hydrogen as the reduction agent rather than carbon, and several variants of H2 based technology are now being developed across the world. This is a pellet of sponge iron produced via hydrogen direct reduction at the SSAB pilot plant in Lulea in northern Sweden; and this from a pilot plant run by the China Iron and Steel Research Institute in Shandong province China. And it is possible that green hydrogen made from zero carbon electricity may eventually be so cheap that hydrogen-based iron reduction will eventually beat the use coking coal on price; but today the green cost premium is large, and unlikely to disappear for several decades at least.

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[41] See ETC (2025), *Carbon in an electrified future: Technologies, trade-offs and pathways*, section 1.1. https://www.energy-transitions.org/publications/carbon-in-an-electrified-future/ http://www.systemiq.earth/wp-content/uploads/2025/11/Carbon-in-an-electrified-future-Exec-Summary.pdf

- An alternative approach would be to add CCS to existing blast furnaces, or to the processes that derive carbon monoxide (which is also a reduction agent) and H_2 from methane; but adding CCS to any of these processes must by definition add cost.

- And a long-term possibility is to directly electrify iron making via electrolysis or electrowinning – illustrating the point indeed that chemical reactions are in the fundamental sense electric.[42] But that technology is unlikely to be commercially viable before the 2040s.

- In cement production meanwhile, we could electrify the heat input, but as long as we start with limestone (calcium carbonate) we will produce CO_2 whatever the heat source. That CO_2 can be captured and stored, but inevitably that means higher cost.

- While to make plastic production zero emissions, we will either have to source carbon molecules from bio sources or direct air capture, or apply CCS to the continued use of fossil fuels, or recycle plastics mechanically or chemically, or store plastics at end of life in an environmentally secure form. But all of those routes are likely to result in more expensive plastics.

Across both the long-distance transport and heavy industry, we must therefore assume that significant cost premia will exist for many years. These premia will tend to reduce overtime, both because key inputs such as green hydrogen will fall in cost, and through technological innovation – for instance in high temperature heat generation, in new cementitious materials, or in electricity-based iron making. And it is possible that at some time there may be technological breakthroughs so significant that they entirely eliminate the green cost premia in some of hard to electrify sectors.

But any credible strategy for limiting global warming below 2°C cannot rely on the assumption or hope that those breakthroughs will occur, but instead start with the reality of the green cost premia which exist today.

At the level of the intermediate products sold from business to business – iron, aluminium, cement, ammonia – these cost premia are currently very large **[Exhibit 42].** Recent analysis,[43] estimates that decarbonising iron production could add 75% to the price of a ton of iron, while decarbonising aluminium, cement and ammonia could increase their prices 18%, 80%, and 75%. Similarly large cost premia are observed in the production of zero carbon plastics, shipping fuel and sustainable aviation fuel.

Decarbonisation will therefore not be economic unless significant carbon prices or equivalent regulation increase the cost of producing products or services in today's emissions intensive fashion.

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[42] See ETC (2025), *Carbon in an electrified future: Technologies, trade-offs and pathways,* chapter 1.2 for an assessment of the progress of these electrical technologies. https://www.energy-transitions.org/publications/carbon-in-an-electrified-future/ http://www.systemiq.earth/wp-content/uploads/2025/11/Carbon-in-an-electrified-future-Exec-Summary.pdf

[43] Systemiq analysis for the ETC, ETC (2020) Making Mission Possible. https://www.energy-transitions.org/wp-content/uploads/2020/09/Making-Mission-Possible-Full-Report.pdf

But while the cost premia are large at the intermediate product level, the impact on consumer prices is still small **[Exhibit 43].**

- Adding 75% to the cost of a ton of iron may would add a smaller 45% to the cost of a ton of steel, and only 7% to the cost of key components for the automotive or construction sectors: and adding 75% to the cost of producing ammonia, adds a much lower 9% to the cost of wheat production.

- And once we go through these value chains to what the end consumer actually buys **[Exhibit 44]** – for instance a car or a loaf of bread, the price impacts are more like 1%. Similarly with shipping: even if shipping freight rates doubled, the impact on the cost of a pair of jeans made in Bangladesh and bought in London would be so small that consumers would not notice.

The only exception to the general pattern is aviation where a large premium for sustainable aviation fuels could imply a significant increase in ticket prices. If SAF costs twice as much to produce as conventional jet fuel, and fuel costs account for 25% of total operating costs, requiring the use of SAF for 100% of the fuel burn could increase ticket prices 25%.

But even in the case of aviation, the impact on consumer living standards will still be trivial. Sensible carbon pricing policy entails a slowly growing carbon price over time, and sensible regulation would require a slowly rising percentage of fuel to be zero carbon. The price impact would therefore not be instant, but emerge gradually over several decades.

And over those several decades there is large potential for improvements in aviation energy efficiency, potentially reducing fuel burn per passenger kilometre by 30% or more by 2050.[44] Air travel prices in 2050 may therefore actually be lower in real terms than today, even if carbon prices or regulation drive a shift to more expensive sustainable fuels.

In addition, air travel accounts for only 3% of consumer expenditure even in rich developed countries, so even the increase “relative to business as usual” will be very small as a share of consumer spending, and more than offset by the significant savings which consumers make from cheaper road transport.

A path to near complete decarbonisation of the hard to electrify sectors is therefore not only essential if we are to limit global warming to well below 2°C, but technologically possible and less economically and therefore politically daunting than often suggested.

We sometimes call these sectors “hard to abate”, but as I will argue in Lecture 2 and 3, they should not be if we have good policy well implemented.

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[44] See ETC (2022) *Making Net Zero Aviation Possible*, page 36-38. https://www.energy-transitions.org/publications/making-net-zero-aviation-possible/#download-form

Food production and land use change

That is not however the case with food production and land use change – the most difficult issue in climate change mitigation, and a really fundamental one since it derives from the inherent inefficiencies of the photosynthetic process, and of our current means of animal protein production.

Each year human beings in total use about 125,000 TWh of non-food energy. Meanwhile if 9 billion people in 2050 each enjoyed an adequate calorific intake of say 2,200 calories per day, that would mean 7,400 TWh of energy intake in the form of food. Required food energy input is thus only about 6% of total human non-food energy use.

But unlike our energy for heating, cooling and machinery operation, we cannot substitute electrons for carbon-based molecules in the food we eat.

Instead, we derive food from photosynthesis of vegetable matter, and that's a far less efficient way of converting solar energy into usable energy than when we convert photons into electrons in a solar panel. Research by Tim Searchinger and others for the World Resources Institute shows that even fast-growing sugarcane on highly fertile land in the tropics converts only around 0.5% of solar radiation into energy in sugar, while for maize grown in Iowa the solar to biomass-energy conversion efficiency is a still lower 0.3%.[45] By contrast, a field of solar PV panels might achieve an average yield of 15%, and this figure is continually increasing with technological advance.[46]

Inevitably therefore photosynthesis to make food requires large areas of land and even more if we consume our food as animal protein and in particular red meat protein, because animals, and in particular cows, are stunningly inefficient chemical processers **[Exhibit 45].**

Egg production converts about 25% of the vegetable protein in feed into animal protein, a pig about 9% and cattle just below 4%. The complete process for converting solar energy into beef protein, thus has an efficiency of less than a 20th of 1% **[Exhibit 46].**

Which is why, on almost every relevant dimension, the food system has an impact on the environment massively greater than all the solar and wind farms, and all the mines for all the minerals we need to support our new clean electric energy system.

- The 50m km² which we devote to food production, of which 80% is for meat and dairy, is 100 times the land required for solar and wind power generation, 500 times the land currently allocated to mining activities, and 5000 times the additional land allocation required to mine all the mineral resource we will need in the energy transition.
- Water use in agriculture is 500 times that required in all mining activity.
- And over 90% of annual deforestation results from agriculture, with most of that driven by cattle pasture or by the arable production of feed for various categories of animal protein production.

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[45] The development of "energy cane", a variant of sugar cane which is bred/ genetically engineered to optimise energy and carbon capture rather than sugar food production allows higher % efficiencies of 1-2% and potentially higher. But as a means of producing food energy, sugar cane is the relevant highest available efficiency.

[46] WRI (2015), *Avoiding Bioenergy Competition for Food Crops and Land.* Avoiding Bioenergy Competition for Food Crops and Land | World Resources Institute (wri.org)

That deforestation accounts for about 5 Gt of annual GHG emissions; in addition annual methane emissions from ruminant animals and waste management are equivalent to about 4 Gt of CO_2, nitrous oxide emissions resulting from fertiliser application are about 1.5 Gt CO_2e equivalent, for a total of 11 Gt per annum of which only 0.7GT results from the energy use in agricultural processes which we could electrify.[47]

Reducing these emissions, as well as those where electrification gives us a clear answer, is therefore essential if we are to limit global warming to well below 2°C, but none of the major proposed routes to do so is progressing at anything like the pace required.

- Land use related emissions could in theory be eliminated by hard supply side constraints: and at COP 26 in Glasgow, 140 countries representing 85-90% of the world's forest area committed to halt and reverse forest loss and land degradation by 2030. But, while the long-term trend of deforestation has slowed down from previous decades, large scale forest loss continues and increased significantly after 2022 **[Exhibit 47]**.
- And methane emissions could in theory be offset by CO2 removals rather than by actually reducing the size of cattle and sheep herds. Indeed, that is precisely what major countries with large ruminant animal herds and methane emissions often assume in their emission reduction strategies.[48] But actual purchases of removals across the world are growing at a snail's pace. In its 2022 report *Mind the Gap*, the ETC estimated that carbon dioxide removals would need to reach 5 Gt per annum by 2030 if the world was to be on a path compatible with limiting global warming to +1.5C **[Exhibit 48].**[49] But actual carbon removal credits purchased in 2024 are estimated at 48m tonnes **[Exhibit 49].**[50]

These failures reflect two fundamental challenges.

- First that it is very difficult to stop deforestation pressure unless the consumer demands that drive them are eliminated.
- Second that any solution which depends on paying for removals will by not be costless and will only occur if someone pays for them.

And underlying both of those is that unlike in the electrifiable sectors of the economy, we do not yet have a new technology which can meet existing and future consumer demands in a zero emissions fashion.

In the long run we probably will. Because as a report by Rethink X in 2019 set out,[51] it is technologically possible to produce protein synthetically via precision fermentation, and to produce cell-based meat equivalents. And the costs of precision fermentation per kilogram of protein have declined dramatically over the last 50 years **[Exhibit 50]**.

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[47] See ETC (2020)*, Making Mission Possible: Delivering a Net-Zero Economy, Box A* for a breakdown of agriculture and land use emissions. Making-Mission-Possible-Full-Report.pdf (energy-transitions.org)
[48] See, for instance, New Zealand's Nationally Determined Contribution (NDC) which Carbon Tracker ranks as Highly Insufficient, https://climateactiontracker.org/countries/new-zealand/targets/
[49] ETC (2022)*, Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive.* https://www.energy-transitions.org/publications/mind-the-gap-cdr/
[50] Group of Thirty (2025), *Carbon pricing and markets: enabling efficient emissions reduction*.
[51] RethinkX (2019)*, Rethinking Food & Agriculture 2020-2030 (2019).* https://www.rethinkx.com/publications/rethinkingfoodandagriculture2019.en

Those costs moreover are certain to fall further as knowledge increases, and as the cost of increasing knowledge declines as a result of artificial intelligence.

Over time indeed the technical efficiency of synthetic processes will inevitably rise and costs inevitably fall, while real animal cows, however genetically engineered, will stay roughly as inefficient processers as they are today **[Exhibit 51]**.

At some time, therefore, it is close to inevitable that synthetic meat proteins will beat natural meat proteins, on nutrition, taste and cost.

But the crucial phrase is "at some time": and while Rethink X's description of the fundamental technology trends is compelling, its forecast of the pace of commercial developments has been proven massively over optimistic. Just six years ago they predicted that by 2030 70% of all beef protein would come from new non-animal-based production technologies: but today that share is still stuck at around 1%.

This reflects the fact that meeting expectations of food taste and feel is far more challenging than producing electricity from solar not coal, or making a car accelerate with electricity not gasoline. In addition, there are deeply embedded cultural attachments to existing ways of producing food, even if new ways might be objectively superior.

Synthetic protein will I suspect be a technology which powerfully demonstrates "Amara's law", that we tend to overestimate the effects of a technology in the short term and underestimate it in the long term.[52]

And the short term here could last for several decades.

Reducing the 11 Gt of emissions which come from food production is likely therefore to be the most difficult challenge we face as we attempt to cut global emissions fast enough to limit global warming to well below 2°C.

Keeping global warming well below 2°C – three challenges.

So let me sum up **[Exhibit 52]**. I believe it is essential that we limit global warming to well below 2°C. And that means we will eventually have to reduce all net greenhouse gas emissions from all sectors to zero.

But how we do that and how difficult it will be, varies by three broad sectors.

- About 60% of emissions will be eliminated through electrifying end applications, and decarbonising electricity generation, primarily with renewables but also with a role for nuclear. And the good news is that a deeply electrified energy system will deliver energy services at lower cost than today's fossil fuels based system, and will have a far reduced environmental impact. The future is electric and getting there fast will be a win-win for humanity.

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[52] Computer Society (2024), *Amara's Law and Its Place in the Future of Tech.* https://www.computer.org/publications/tech-news/trends/amaras-law-and-tech-future

- But close to another 20% of emissions come from long distance transport and heavy industry sectors which are difficult to electrify. Here too we already know the technologies that can take us to net zero, including a role for electricity in high temperature heat. But applying those technologies will result in green cost premia, certainly for several decades and in some cases forever; the good news however is that the consumer impact of these premia is small.
- Finally for the last 20% of emissions, which derive from agriculture, food and related land use changes, the path to decarbonisation is not yet clear. We do not yet have certain and acceptable new technology-based solutions: and alternative approaches have been ineffective so far and will not be costless

In Lecture 3 I will describe the implications for required action to limit global warming to well below 2C. But before that in Lecture 2 I will consider the economic challenges of transition, which are important even in the clearly electrifiable sectors of the economy.

I hope I however that Lecture 1 has left you in an at least reasonably optimistic mood. Energy is fundamental to human welfare and we have the technologies to deliver abundant, cheap and clean energy to all humanity.