



## ASPEN GLOBAL CHANGE INSTITUTE ENERGY PROJECT

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#### Clean Energy and a Stable Climate: Progress and Challenges from 1998-2018

Two interdisciplinary workshops at AGCI bracketed progress on the climate-energy problem across 20 years and yielded two major journal publications, one in *Nature* (Hoffert et al. 1998) and the other in *Science* (Davis et al. 2018).

The focus of the first workshop and paper articulated the magnitude of the climate-energy problem and what rate of carbon emission reductions was needed to stabilize the climate via carbon-free technologies coupled with aggressive efficiency improvement.

The focus of the second workshop and paper is how to tackle the most intractable aspects of decarbonizing the global energy system – long distance freight, air travel, cement and steel production—while providing highly reliable electricity systems.

In both cases, the stated end goal was achieving a global energy system with net-zero emissions of carbon into the atmosphere and thereby stabilizing the climate in the 21<sup>st</sup> century.

#### ***Hoffert et. al (1998): Energy implications of future stabilization of atmospheric CO<sub>2</sub> content***

The [1998 AGCI workshop](#) convened an interdisciplinary set of experts to explore how to power the total primary energy system of the world without emitting carbon dioxide. In 1998 the total primary energy supply (TPES) was about 10 terawatts (TW) of power (1 TW equals 1,000 billion watts); now in 2018, TPES has risen to 18 TW. In the 1998 Hoffert workshop, renewable energy systems, nuclear fusion, advanced fission designs, efficiency improvements, geoengineering, and land use practices were all considered on their merits known at the time.

Hoffert's workshop led to a paper in *Nature* by a sub-set of the workshop participants (Hoffert et

al. 1998) which included socio-economic integrated assessment model outputs (Wigley et al. 1996) providing scenarios that describe the climate at different concentration levels of atmospheric CO<sub>2</sub> (WRE 350, 450, 550, 650, 750 ppm, and the early 1990s IPCC business as usual scenario, IS92a). Each concentration stabilization results in a change in global average temperature. Roughly, the 450 ppm scenario equates to about a 2.5 to 3°C change in temperature – exceeding the recent Paris Accord goal of 2°C or less (Rogelj et al. 2011, 2016). At the time of the Hoffert paper in 1998, concentrations were at 366 ppm, but now in 2018 they have exceeded 400 ppm (these values do not include non-CO<sub>2</sub> greenhouse gases, which when added produce higher CO<sub>2</sub> equivalent estimates).

The Hoffert analysis outlined the quantity of carbon-free power that would be required into the 21<sup>st</sup> century with different assumptions about efficiency improvements and decarbonization of primary power for each of the WRE scenarios. The paper articulated the magnitude of the challenge and the resulting climate implications if a massive transformation of the energy sector failed to materialize:

“We find that CO<sub>2</sub> stabilization with continued economic growth will require innovative, cost-effective and carbon-emission-free technologies that can provide additional tens of terawatts of primary power in the coming decades, and certainly by the middle of the twenty-first century, even with sustained improvement in the economic productivity of primary energy.” (Hoffert et al. 1998)

In the conclusion, the paper recognized that significant improvement in technologies able to deliver 10 to 30 TW of carbon-free power and rapid deployment at massive scale would be required to avoid dangerous interference in the climate system, and remarked that market efficiencies alone may not drive the necessary rate of change.

### *Kaya Identity: Energy sector CO<sub>2</sub> emissions from 1990 to 2015*

Now some 20 years later, numerous studies have explored the pathways that could achieve a 2°C or lower increase in global average temperature from pre-industrial levels. Here we focus on carbon emissions from the energy sector recognizing that other greenhouse gases are also driving climate change.

Energy sector carbon emission drivers are described by the Kaya Identity (Kaya 1989), which considers world population, Gross Domestic Product (GDP) per capita, the energy intensity of a unit of the global economy (how much energy to produce a dollar of GDP for example), and the carbon intensity of the global energy system (how much carbon gets emitted to produce a unit of energy). These four factors multiplied together produce annual energy sector carbon emissions into the atmosphere (excluding land processes):

From a climate and energy policy perspective, the most obvious factor of the Kaya identity is the carbon intensity of energy supply. Bring that to zero and carbon emissions go to zero. But of course the size of the global economy and population are also key drivers of emissions in a global energy system where fossil fuels still account for about 80 percent of the total primary energy supply (REN 2015).

Since 1990 through 2015 both the economy and population have continued to grow. Population has increased 39 percent in this timeframe to 7.3 billion and the GDP has increased 99 percent to 75,489 billion USD (2010). Not surprisingly with these increases over 25 years, carbon emissions are up 57 percent (IEA 2017). Notwithstanding their fundamental role in emissions, population and economics are often left out of policy discussions leaving carbon intensity and efficiency as perhaps more tractable levers for change.

So what is the progress in carbon intensity and efficiency? The 25 year record of carbon and energy intensity offers a mixed picture. Globally, energy intensity has improved 32 percent since 1990 (IEA 2017). This is good news and demonstrates a partial decoupling of energy in a growing economy. To the extent this can be accelerated, the prospects for climate stabilization rapidly improve. Efficiency improvements have multiple benefits, but in this context, and most importantly, they reduce the amount of carbon-free power needed for the global economy to function while at the same time stabilizing climate at a desired level.

Progress on decarbonizing energy supplies is less encouraging over the same 25 year period. The global economy's carbon intensity has remained flat, increasing one percent over the 1990 – 2015 timeframe. In other words, the amount of carbon emitted as a percentage of the TPES is almost identical to what it was in 1990. Despite relatively flat values for carbon emissions from 2014-2016, more recent data shows a 1.6 percent uptick in global CO<sub>2</sub> emissions from energy in 2017 and an increase of 1.3 percent over the 10 year average (BP 2018). The “peak carbon” sought as a key indicator of a sea change in the energy-climate problem hasn't turned just yet.

The longer the delay in decarbonization, the steeper the emissions decline needed to reach the Paris Accord's desired outcome. Solar and wind have made significant advances in the TPES over this timeframe—and their continued exponential growth is a key to optimism—but they are still a very small piece of the pie.

Rapidly developing countries are driving significant emissions increases, often relying on carbon intense sources of energy, further complicating this equation. For example, over the 1990-2015 timeframe coal use rose 75 percent (IEA 2017). Combined with the legacy of emissions in Europe and North America since the Industrial Revolution, this produces a complicated landscape of policy negotiations. So, the unfolding of the Kaya Identity globally isn't homogenous across nations. Inequalities in energy and energy sources, rates of economic growth and populations, access to efficient technologies all influence how factors of the Kaya Identity change over time.

But ultimately the global result of carbon dioxide emissions—not the nation-to-nation differences—drive climate change. And while it is important to understand the individual factors of Kaya, it's the total (i.e. the product resulting from Kaya's multiplication) that matters. Total carbon emissions drive changes in the global climate with temperature as just one key metric. Extreme weather and climate events, ecosystem stresses, ocean acidification, and sea level rise are other metrics of critical importance.

The Kaya Identity's global factors for the period of 1990 – 2015 are summed up in the following Table (based on IEA 2017), with 1990 values set to 100 creating a comparative index. The last column indicates the percent change over 25 years. Purchasing Power Parity (PPP)<sup>1</sup> is used as the metric for GDP based on 2010 USD.

The progress being made by renewables is buried within the carbon intensity values shown in Table 1. Renewable power increased 17 percent in 2017 (BP 2018), and double digit rates of increase for renewables other than hydro can propel wind and solar from each less than one percent of TPES in 2015 to a major fraction in the coming decades. Coupled with continued progress on improving energy intensity, this can transform the trajectory of the last 25 years to one commensurate with climate stabilization goals.

	1990	1995	2000	2005	2010	2014	2015	% 90-15
CO <sub>2</sub> emissions index	100	104	113	132	148	158	157	57%
Population index	100	108	116	123	131	137	139	39%
GDP PPP/pop index	100	103	116	131	148	162	165	65%
Energy Intensity–TPES/GDP PPP	100	94	85	81	76	70	68	-32%
Carbon Intensity–CO <sub>2</sub> /TPES	100	99	99	101	101	102	101	1%

### ***Davis et. al (2018): Net-zero emissions energy systems***

Similar to the 1998 workshop, the [2016 AGCI workshop](#) that led to the just released 2018 *Science* paper by Davis et al. included a diverse set of energy, carbon, engineering, utility, and ecological experts. Their task was to explore the most difficult aspects of achieving net-zero emissions this century – approximately 25 percent of the pie more intractable to existing technology and systems.

While we have learned much about what needs to happen to achieve climate stabilization in the intervening 20 years from Hoffert to Davis (for example the extensive literature on stabilizing the climate at 2°C or 1.5°C, significant challenges remain, particularly for the more difficult aspects of the energy system such as aviation, steel and cement manufacture, and long haul transport.

The Davis paper explored a multifaceted systems approach whose cornerstone was the increasing electrification of the energy system. An overarching concept emerged in the workshop and the subsequent paper that energy systems serving different sectors can no longer be thought of as separate components treated independently, but must evolve to take advantage of an integrated systems approach.

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<sup>1</sup>From IEA 2017 the definition of purchasing power parities is “... are the rates of currency conversion that equalize the purchasing power of different currencies.”

## Integrated Systems Approach

The Davis paper conveys an integrated approach (Figure 1 below) – a matrix of existing and emerging technologies working together to match the very diverse set of energy requirements in the 21<sup>st</sup> century while achieving net-zero emissions.

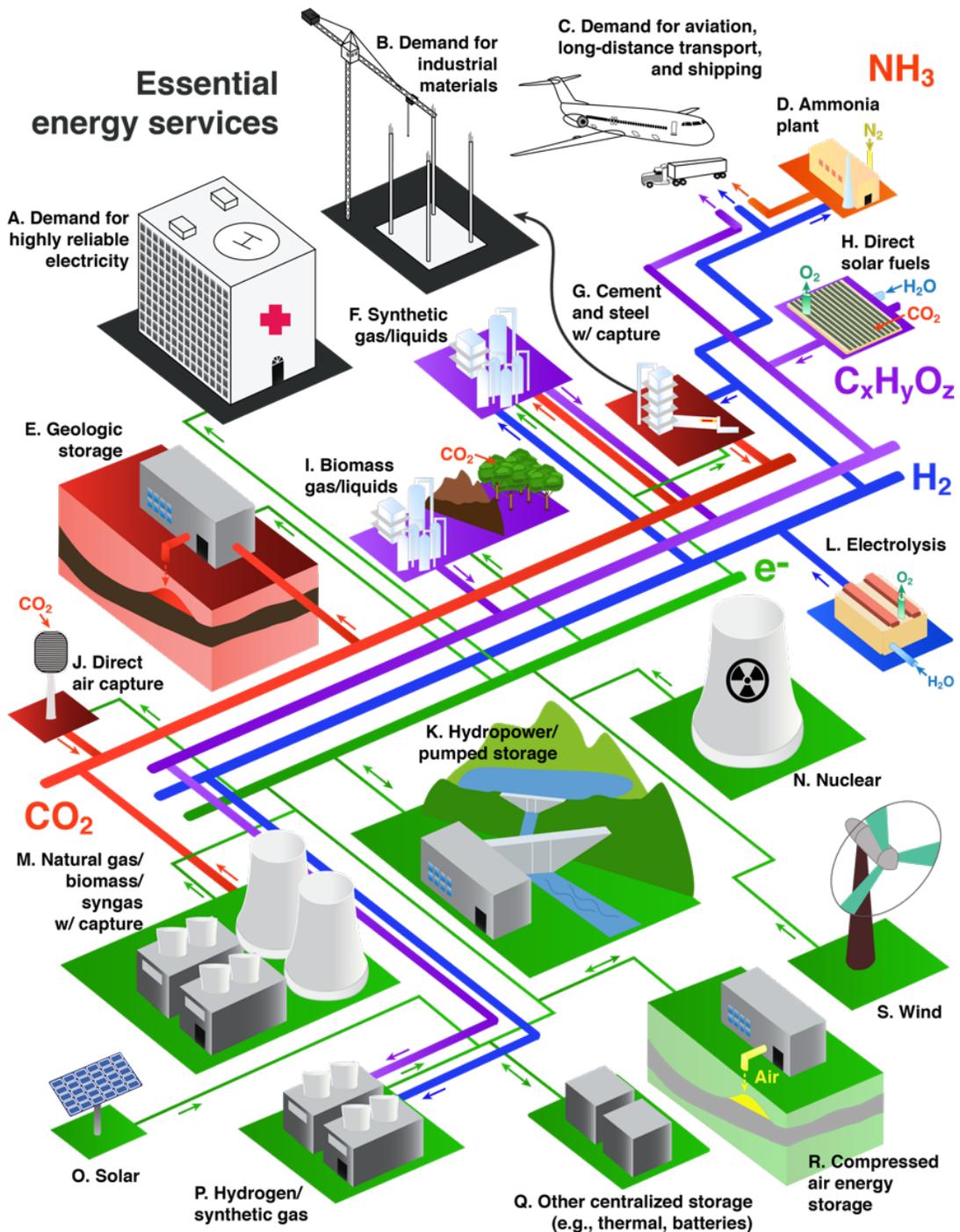


Figure 1. Integrated Systems Approach (Davis et. al 2018)

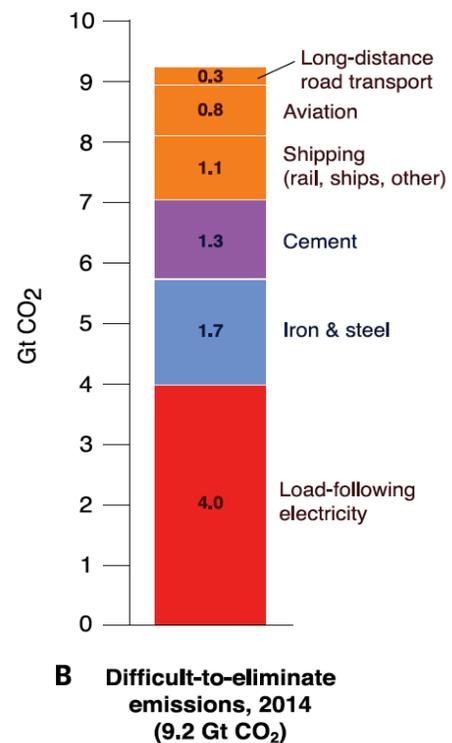
The color scheme of the heavy and light connecting lines represent different types of network connections. The red represents carbon management where CO<sub>2</sub> can be sequestered or utilized as a feedstock in synthetic gases or liquids. Purple represents the production and distribution of synthetic fuels. Blue represents the production and utilization of hydrogen. Green represents the production and distribution of electricity. Orange represents a potential role for ammonia. Ammonia is perhaps less familiar in this context, but it can be combusted as fuel while recognizing the need to control byproducts such as NO<sub>x</sub> and it can also be used a hydrogen feedstock. The figure doesn't convey all end uses, but rather is representative of how to satisfy some essential services using a systems approach.

The magnitude of the hard to satisfy uses (for example load-following electricity, long-distance transport, aviation, cement and steel manufacturing) is represented in the following Figure 2 also from Davis et al. 1998. Of the total CO<sub>2</sub> emissions associated with industrial processes and fuel combustion – some 33.9 GtCO<sub>2</sub> in 2014 (IEA 2016), the most intractable of these with existing practices and technologies (those listed in Figure 2) amount to about 27 percent. What follows highlights just one of the “difficult-to-eliminate” processes or sectors, aviation.

### Aviation

Aviation at 0.8 GtCO<sub>2</sub> per year represents about 2.4 percent of the total fossil combustion and industrial emissions. While not the largest in the “difficult-to-eliminate emissions” set shown in Davis Figure 2, flight sets a premium on the amount of weight allowable as fuel combined with the amount of cargo or passenger space left for economic return. Given the unusual on-board energy requirements of flight, particularly over long distances, it is very hard to beat jet fuel in terms of how much energy it packs into a given volume (~37.4 megajoules per liter) and mass (~42.8 megajoules per kg).

While electrochemical batteries are already being used in experimental light aircraft for short duration or distance flights, long haul transport needs for people or freight far exceeds the volumetric or gravimetric density of batteries with today's technology or foreseeable technological improvements. Hydrogen is more plausible as an energy source for aviation than batteries, but it too has limitations. Liquid hydrogen has a very high energy per unit mass (~120 MJ per kg), but a relatively low energy per unit volume (~8.5 MJ per liter). To containerize the hydrogen as a liquid requires awkward and heavy cryogenic containment vessels. Once energy is expended to cool hydrogen to a liquid state (-253°K), to keep it from boiling off once stored, requires a pressurized



**B** Difficult-to-eliminate emissions, 2014 (9.2 Gt CO<sub>2</sub>)  
 Figure 2. Emissions generated by the most difficult to decarbonize parts of the economy (Davis et. al 2018)

and insulated container. As indicated in Figure 1, more potential may exist for aviation to rely on carbon neutral synthetic liquid fuels made with chemical or biological processes.

In this brief overview we characterized just two of the many elements discussed in the Davis paper; 1) a systems approach integrating components, processes, and distribution networks relevant at different scales and, 2) how to provide an energy source for aircraft able to satisfy space and weight limitations without sacrificing range or payload typical in modern aviation. Overall, perhaps the single biggest shift in the TPES suggested in the paper is the far greater electrification of primary energy and the multiple benefits this provides across many applications.

### *Summary*

The Hoffert et al. paper of 1998 was prescient in articulating the magnitude of the climate-energy problem. Its unique analysis charted historical data on population, economy, energy intensity and carbon intensity up through 1990 and then showed what would be needed to achieve stabilization at roughly double pre-industrial concentration carbon dioxide in the 21<sup>st</sup> century. It also charted how much carbon free energy would be required assuming different energy intensity improvements. It didn't attempt to answer specific technological pathways but did place squarely the magnitude of the challenge ahead.

Now some 20 years later, Davis et al. provides a framework for a systems approach with multiple technologies and processes as a plausible way forward, not only relevant to the most difficult 27 percent of fossil emissions from combustion and industrial processes, but also relevant to decision-making today as the global energy transformation unfolds while achieving climate stabilization via net-zero emissions this century.

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