# True Sustainability with Low Embodied Energy

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## Abstract

As more companies, institutions, governments, and individuals set and commit to carbon dioxide (CO2) reduction goals, and as policies, technologies, and infrastructure grow to meet intermediate goals, we find ourselves facing an emerging challenge of embodied energy. Energy is invested or used in the manufacture of (energy-saving) products and (energy) infrastructure. In the near term, a bow wave of CO2 emissions from infrastructure tends to counter the progress toward reductions from lower consumption. Will that bow wave undermine the important pace of reductions necessary to stave off runaway Climate Change?

Indeed, we must replace our consuming of our stored solar energy assets (fossil fuels) with our daily solar income (vast and renewable). But, a whole other challenge, of reducing the use of stored solar for building the new energy infrastructure, emerges. This challenge mandates a Doing More With Less program, as we are now still just doing more with not enough less. Our current state of the art for renewable energy infrastructure – mounting, PV panels, concrete ballast, Electric Vehicles, and storage – is metal and material intensive, high in embodied energy, and ultimately more costly than it could be. The science of tensioned cables for the mounting of solar photovoltaic panels can significantly reduce embodied energy to a fraction of conventional mounting. True sustainability will require lowering embodied energy, as energy infrastructure must be replaced as service lifetimes are met.

Keywords: Embodied, Invested, Production, Energy, Emissions, GHG, Sustainability, Carbon


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## 1. INTRODUCTION

Embodied energy is the energy required to produce or make the things humans use or rely on. Sustainability is essentially what human civilization is actively pursuing at this time on a global scale, with Climate Change prevention and mitigation the primary goal. Accumulating Green House Gas (GHG) emissions, particularly CO2 from human activity, is the leading cause of Climate Change. Efforts to build up the infrastructure for a sustainable future aimed to reduce the emissions will involve a grand accounting of emissions, from manufacturing and power generation to usage and consumption energy and to other GHG emitting activities. This paper, intended to generally inform on the subject of embodied energy in the transition to renewables, will address such accounting.

Sustainability is the ability to sustain life and future generations of life without diminishing the natural capital upon which all life depends. In essence, it means living on income rather than savings and respecting the natural cycles on earth – thermal, hydrological, carbon, and so on. True sustainability assures that the approach to obtaining sustainability does not itself lead to non-sustainability.

True sustainability with low embodied energy is a challenge, as the recurring remnant embodied energy works up against the GHG/CO2 budget in the longer term, as well as cumulatively forming a bow wave of GHG/CO2 emissions in the buildup of the low carbon infrastructure in the shorter term. We will see that staying within the carbon budget is more difficult than dealing with a surge in carbon emissions early in the transition to renewable energy.

## 2. EMBODIED ENERGY

The path toward 100% renewable energy will inevitably face the challenge of providing an alternative to the fossil fuels sourcing of the production, process, and high heat energy needed to make things. Ultimately relying on Carbon Capture technology leaves us reliant on non-renewable fossil fuels, which is not true sustainability. To deal with the availability and intermittency issues of renewable energy we will have lots of energy storage (at Utility Scale and/or widespread Distributed Generation), which means higher embodied energy and more CO2 emissions.

A practical solution for achieving a sustainable future involves scaling up of the existing state of the art (SOTA), while embarking on Research & Development to reduce embodied energy and to advance the state of the art, especially in the areas of energy storage and reliability, but also in Carbon Capture and Nuclear power – our backup plan in light of our persistent embodied energy, high heat challenges.

Embodied energy (aka Invested Energy) is inescapable, as it accompanies the buildup and maintenance of renewable energy infrastructure and large scale electrification of the economy, done so to prevent further Climate Change and to transition away from nonrenewable fossil fuels. It is all about GHG emissions, especially CO2. We can discuss emissions baselines, targets, and annual reductions, but the CO2 Budget metric (of about 900 Gigatons, or billion tons) is perhaps the most important. As of 2016, globally we had about 900 Gigatons of CO2 emissions left before worsening Climate Change and passing Tipping Points (of irreversible, accelerating Climate Change).

Embodied energy is a three part problem:

- A CO2 Bow Wave from initial infrastructure buildup (constituting embodied energy)
- Breakthroughs and technology advances over the next decades that reduce operational energy CO2 emissions at the cost of higher embodied energy, a second Bow Wave of sorts when those breakthroughs are built up (commercialized)
- Remnant embodied energy to maintain the lower operational energy infrastructure in the face of an exhausted CO2 Budget, amounting to billions of tons CO2 emissions per year (a fraction of the projected 51Bt/y) when the remaining CO2 Budget has dropped to zero.

The somewhat politically charged goal of global Zero Net Carbon by 2050 is not practical, as it largely depends on technology, know-how, and breakthroughs not even developed, yet. Global zero net carbon by 2100 is a more practical scenario. The 2050 goal essentially ignores the embodied energy issue. The 2100 goal provides time to resolve the embodied energy issue. We do not want the Perfect (Zero Net Carbon) be the enemy of the Good (highly reduced CO2 emissions).

## Approach to CO2 Emission Reduction Calculations

The two prongs of the approach to calculating CO2 emission reductions reflect the fundamental nature of the categories of emissions. The approach to calculating CO2 emission reductions is illustrated in Figure 1.

The Top / Down Prong identifies reductions by added infrastructure and products and has 6 main development areas: Solar PV, Wind, EVs, Efficiency, Energy Storage, and Buildings. The focus is on consumers and products, with calculations based on direct assessments and analysis.
The Bottom / Up Prong identifies reductions by modifications of existing infrastructure, especially in manufacturing and production of material, which are energy intensive (not amenable to the diffuse less intensive renewable energy). The focus is on suppliers and providers, with calculations based on historical data.

Forestry, agriculture, and aviation will follow another path to Zero Net Carbon, and will somewhat depend on the progress in the other categories (two prongs). This third prong (or path) is beyond the scope of this paper, as the solutions and implementations go beyond technology and scaling up, facing revolutionary change politically and socially. Aviation, though extensive in our modern world, is basically a non-essential activity and, thus, could be scaled down. Renewable fuels and electric propulsion are already in development and show promise, as progress has already been demonstrated. Agriculture can also look at renewable fuels to power its operation and to organics to help replace the use of fertilizers. Forests provide a sink for carbon, but tropical deforestation contributes about 1/5 of global GHGH emissions. Forests are not so much a technology issue, as they are socio-political – we choose to allow their overuse and destruction. We could choose less consumption of forest resources, and we can choose to manage sustainable forests.

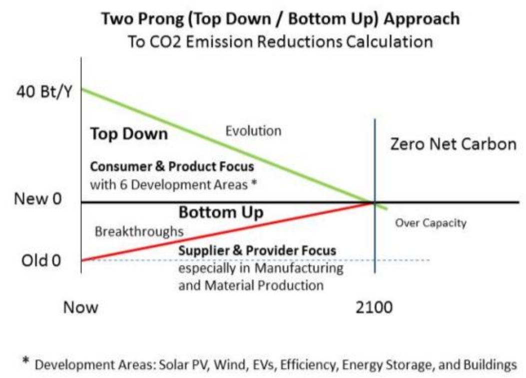



**Figure 1: Emissions Reductions Approach**

## Considerations for Calculating Infrastructure Build Up CO2 Numbers

Actual calculations, raw data, and derivations are documented in a white paper titled "True Sustainability With Low Embodied Energy" [Clemens, 2021]

Service Lifetimes (assumed 30 years for Solar PV and Wind, 15 years for EVs, Energy Storage 10 to 20 years)
Invested Energy (per Watt, capacity)

Production (Emission Free)
Timeframes 2021 – 2050 (30 years) and 2050 – 2100 (50 years)
Build Up linearly over Timeframe
Costs in 2020 year dollars
Physical constants
Conversion data from public available sources (Ex., 1 KWh = 3412 BTU = 3,600,000 Joules)
Capacity (of Build Up) to meet established goals with practical assumptions (Ex., 30% solar electricity)
Gasoline when burned releases 157.20 lbs CO2/MBTU (without ethanol) [1 pound (lbs) = 0.454 kilogram]
CO2 Avoided depends on power plant fuel (electricity):

| | |
|---|---|
| Coal (Anthracite) | 228.6 lbs emitted per MBTU |
| Natural Gas | 117.0 lbs emitted per MBTU |

(A composite of sorts averages the two values for 170 lbs CO2 emitted per MBTU)

Build Up Goals / Targets:
- Solar PV in U.S. to have 30% Solar Electricity by 2050: 1500 GW [100% by 2100: 3000 GW]
- Wind power in U.S. from 107.4 GW to 425 GW by 2050, additional growth thereafter
- EVs replace the world's 1.6 B vehicles about 15 years (depends on manufacturer plans)
- Efficiency measure reduce energy consumption 20% across all sectors (affecting 2/3 of emissions)
- Buildings (1 M in U.S.) replaced/built per year and saves 20% in energy

Top down CO2 emissions reductions from added infrastructure in 6 main development areas are calculated based on build up rates. Build up rates are estimated based on CO2 reduction targets and EIA projections and the associated expected performance of the added infrastructure. Invested Energy (IE) and associated CO2 emissions, based mainly on material content and quantity, for the U.S. through 2050 and 2100 are calculated first, then global IE and CO2 emissions are calculated based on their current relative size. Global energy consumption and CO2 emissions are roughly 4 to 1, global to U.S., as China grows. Calculation of embodied energy starts with calculating material content and quantity, then determining the energy to produce the material (Table 1), followed by calculating CO2 emissions from sourcing of energy used to produce the material.

**Table 1: Energy Required To Produce Material**

Energy Required To Produce Material [source: www.lowtechmagazine.com]

| | |
|---|---|
| Wood from standing timber | 0.830-1.950 KWh/kg (3-7 MJ) |
| Steel from recycled steel | 1.665-4.170 KWh/kg |
| Aluminum from recycled Al | 3.15-4.75 KWh/kg |
| Iron from Iron Ore | 5.55-6.95 KWh/kg |
| Glass from sand, et cetera | 5.0-9.7 KWh/kg |
| Steel from Iron | 5.55-13.9 KWh/kg |
| Silicon from silica | 63.9-65.3 KWh/kg |
| Aluminum from bauxite | 63-95 KWh/kg |
| Electronic grade Silicon Si | 2,108-2,154 KWh/kg |

## The Practical Scenario

The practical scenario for achieving ongoing CO2 emissions reductions recognizes the technological realities and limits of today to achieve significant reductions by 2050, with Solar at 30% of electricity generation and Wind at fully developed optimal sites. Solar grows to 15 times and Wind to 4 times current capacity in the United States and similarly elsewhere, summarized in Table 2.

**Table 2: CO2 Numbers Through 2050**

| **Categories (Energy – related)** | **Invested Energy (U.S.) CO2 Level** | **Invested Energy (U.S.) thru 2050 CO2 released** | **U.S. CO2 Reductions through 2050** | **Global CO2 Reductions thru 2050** |
|---|---|---|---|---|
| Solar PV | 195 Mt/y | 5.85 B tons | (522Mt/y) 15.7 B | 62.8 B |
| Wind | 30 Mt/y | 900 M | (490Mt/y) 14.7 B | 58.8 B |
| Electric Vehicles | 169 Mt/y | 5.07 B | (501Mt/y) 15 B | 60 B |
| Efficiency | 236 Mt/y | 7.08 B | (507Mt/y) 15.2 B | 60.8 B |
| Energy Storage | 16 Mt/y | 480 M | 0 | 0 |
| Buildings (1M/Y) | 8 Mt/y | 240 M | (35Mt/y) 1.0 B | 4 B |
| **TOTALS** | **654 Mt/y** | **19.6 Bt total (78 Bt Global)** | **61.6 Bt (U.S.)** | **246 Bt (Global)** |

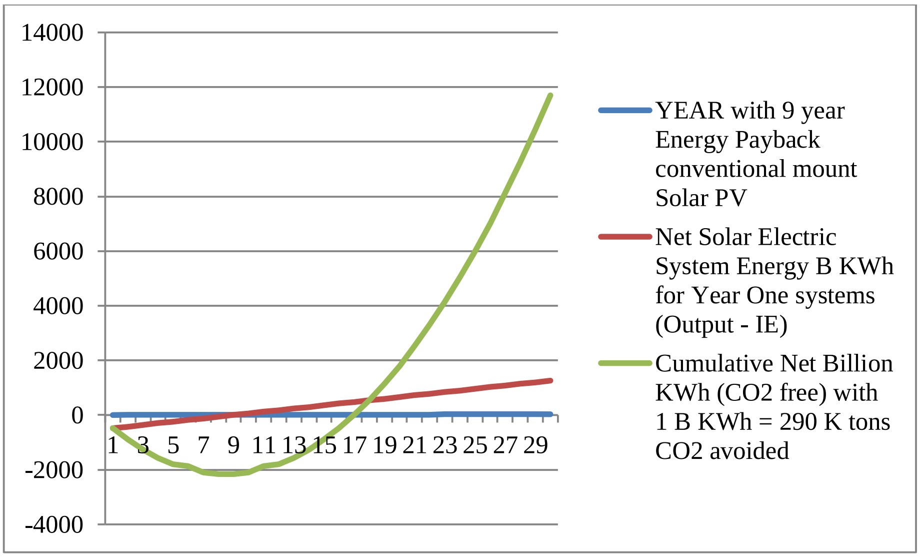
The efficiency category is most interesting. With a reasonable assumption that across all sectors there is a feasible reduction of energy consumption (thus CO2 reductions) of 20%, the returns continue on past the 2021 to 2050 timeframe. Be efficient now and save indefinitely. The investment (invested energy) is not insignificant, as energy-saving equipment, machinery, resources, and appliances across all sectors are replaced. The practical scenario for achieving ongoing CO2 emissions reductions (to Net Zero Carbon from 40 Bt/y in 2019) by 2100 involves adding more solar PV, wind capacity, and energy storage and is summarized in Table 3.

**Table 3: CO2 Numbers Through 2100**

| **Categories (Energy – related)** | **Invested Energy (U.S.) CO2 Level (2050+)** | **Invested Energy (U.S.) thru 2100** | **U.S. CO2 Reductions through 2100** | **Global CO2 Reductions through 2100** |
|---|---|---|---|---|
| Solar PV | 195 Mt/y (390) | 25.5 B tons | (1562 Mt/y) 93.8 B | 375 B |
| Wind | 30 Mt/y (60) | 3.9 B | (1273 Mt/y) 78.1 B | 312 B |
| Electric Vehicles | 169 Mt/y (169) | 13.6 B | (1.03) Bt/y51.5 B | 206 B |
| Efficiency | 236 Mt/y (0) | 7.1 B | (1.13 Bt/y) 56.5 B | 226 B |
| Energy Storage | 16 Mt/y (51) | 3.1 B | 0 | 0 |
| Buildings (1M/Y) | 8 Mt/Y (8) | 0.6 B | (70Mt/y) 3.5 B | 14 B |
| **TOTALS** | **654 Mt/y (678)** | **54 Bt total U.S. (216 Bt Global)** | **283 Bt (U.S.)** | **1133 Bt (Global)** |

The transition to Electric Vehicles will produce good net reductions in CO2. An average passenger EV has an IE (assumed similar to that of ICEVs) of 11 tons of CO2 emissions, while annually reducing almost 3 tons of CO2 over an ICEV. If the entire 1.6 B ICE Vehicles in the world were EVs, we would be expending about 1 B tons of CO2 per year to save/reduce/avoid about 4 B tons of CO2 annually.

The practical scenario will have achieved a 100% renewable clean electric grid by 2100, along with expanded electrifications of transportation and other sectors, but, will have used up the 900 Bt CO2 Budget. There remains the reference 1990 level of energy consumption…mainly the heavy industries producing machinery, ships, structural steel, cement, and automobiles. To contend with this (Bottom/Up) part of the challenge, the approach to manufacturing and such will have changed. Annualized Invested Energy from the new infrastructure buildup (of renewable energy generation, energy-saving non-generation, and Electric Vehicles) totals about 4 Bt CO2 per year. Solar KWh production from the buildup is illustrated in Figure 2.




CO2-free KWh from Solar PV in U.S.

Note: In 2020, U.S. annual electricity production was 4,009 B KWh [expected to rise to 5,700 B by 2050]
Annualized Solar PV KWh production from added PV in 2021-2050 is 11,700/30 = 390 B KWh/Y (10%)
Solar PV KWh production from added PV by 2050 is 1500 B watts x 1.2 KWh/W/Y = 1800 B KWh/Y (30%)

**Figure 2: Solar PV Build Up KWh Production**

In summary, from 2021 to 2100 (80 years), globally we have released about 216 B tons of $CO_2$ to build the infrastructure that reduces, saves, or avoids 1133 B tons of $CO_2$. Projected infrastructure includes:

12,000 GW Solar PV 55% of grid capacity (enough solar panels to cover half of Texas)
1,800 GW Wind 45% of grid capacity
1.6 B Electric Vehicles
20% Demand Reduction via Efficiency across all sectors
10 B KWh (7 B KWh Utility Scale plus 3 B KWh Distributed Generation) Energy Storage
100% Residential & Commercial Energy Storage (10 KWh each, then to 20 KWh by 2100)
20% Lower Operating Energy in most or all Buildings
*Hydropower, Nuclear power, and Coal/NG powered electricity generation 10% of grid capacity as a Backup*
Carbon Capture, Renewable Hydrogen, and Concentrated Solar Thermal TBD
The practical scenario acknowledges the achievement of a 100% renewable energy electric grid in 2100, requiring recurring IE (after 2100) causing the release of 1 to 10 B tons of $CO_2$ per year, and the exhaustion of the (900 Bt) $CO_2$ Budget by 2050, necessitating measures to either Capture Carbon, use Hydrogen (sourced from RE), or develop concentrated solar thermal - all with cost and technology risk implications.

## Groundrules & Assumptions

Some key groundrules and assumptions to note in the practical scenario:

1) Energy demand is assumed flat between 2050 and 2100 (mainly due to efficiency measures, economic reality, and policies), with increased demand met with $CO_2$-free supply.
2) The quantity of automobiles ceases to increase. The transition to EVs is complete before 2100. The Invested Energy of EVs is assumed the same as that of Internal Combustion Engine vehicles.
3) An aggressive Electrification "of everything" is pursued to the greatest extent possible.
4) Hydropower capacity is assumed to remain flat (w.r.t. production capacity).

5) Nuclear power is assumed to fall off by natural attrition, as plants reach the end of their Service Life times. Nuclear will need breakthroughs before again growing in capacity.
6) There will be a significant contingency of coal and natural gas powered electricity plants in 2050.
7) In the 2020 – 2050 interval efficiency measures are assumed across all sectors, resulting in a 20% energy demand reduction. These are economically beneficial investments that have been happening for decades.
8) Energy storage can be embodied energy intensive and significant R&D effort is assumed in 2050 – 2100, service life times of 10 years through 2050 expanding to 20 years through 2100.
9) Reliability (service life) improvements will play a positive role in reducing GHG emissions.

GHG emissions globally in 2021 (starting in 2019) are at 40 B tons CO2 (equivalent) per year.

The Paris Agreement, established at (Conference Of Parties) COP 21 in 2015-2016 and organizing commitments by member countries to document releases and reduce emissions, allows for a GHG Peak to occur in the near future, estimated to be around 2030 and achieve Zero Net Carbon by 2100, or 0 Bt CO2 per year.
Swedish scientist Svante Arrhenius considered in the 1890's what would happen if we doubled the amount of carbon dioxide in the atmosphere, stating that the average temperature of the earth would rise 5 degrees Celsius. One hundred years later we are seeing that scenario play out, with the near future temperature rise scenarios shown in Figure 3 below. With no climate policies in place, we are heading to a 4.8 degree Celsius rise. The best we can hope for is a 1.5 degree Celsius rise, which would involve humanity going to Net Zero Carbon.

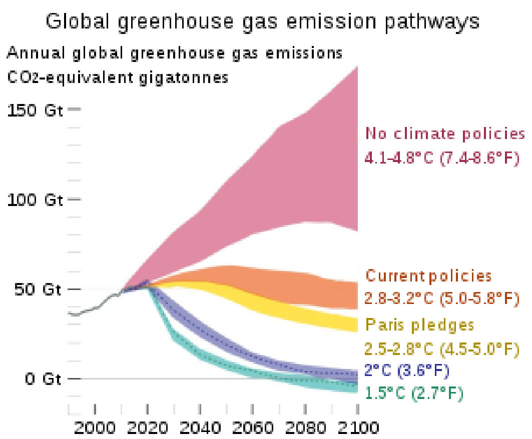



**Figure 3: Global greenhouse gas emissions pathways**

The Intergovernmental Panel on Climate Change (IPCC), formed in 1988, is the United Nations body for assessing the science related to Climate Change. The IPCC periodically releases assessments that determine the state of knowledge on Climate Change, including where there is agreement in the scientific community. The IPCC looks at various scenarios reflecting the different possible temperature rises in the future, from the desired limit of 1.5 degrees C (since pre-Industrial Age), up to 4.8 degrees C (amounting to a doubling of pre-Industrial Age CO2).

In his book "How to Avoid a Climate Disaster", Bill Gates breaks down 2020 GHG emissions into 5 categories by % and establishes the goal to be Nero Net Carbon by 2050:

| | | |
|---|---|---|
| Making Things | 31% | 12.4 Bt/Y re 2019 |
| Plugging In | 27% | 10.8 |
| Growing Things | 19% | 7.6 |
| Moving Around | 16% | 6.4 |
| Keeping Cool/Warm | 7% | 2.8 |

Innovation and breakthroughs will be required to meet the 2050 target, what might be called the best case scenario (called the Breakthrough Scenario herein). Gates pushes for electrification of just about everything (transportation, home heating and cooling, manufacturing processes, etc.). Without breakthroughs, growth in Nuclear power would be needed to get to Zero Net Carbon by 2050. Gates recognizes the ultimate challenge in zeroing out carbon in Making Things and relies on yet to be fully developed and scaled up Carbon Capture, alluding to Invested Energy (IE), the energy to Make Things, now mainly dependent on burning fossil fuels. As of 2021, there are no operating Carbon Capture systems due to the exorbitant cost.

The Paris Agreement stresses the importance of (Developed Countries like the U.S. and China) helping Developing and Poor Countries toward low carbon economies, through financing and technology transfer. But, how do High Carbon countries do this helping? Chemistry Professor Neocles Leontis of Bowling Green State University (BGSU) in Ohio has noted a CO2 Budget of 900 B tons of CO2 to limit temperature rise and avoid worsening Climate Change. Using only current state of the art (and not relying on new breakthroughs) and acknowledging the current 40 Bt/Y, one can see a CO2 Budget Gap emerging before 2050. Invested energy emissions are a significant and persistent portion of the CO2 Budget.

The practical scenario leaves us with about 1 Bt/Y for IE(RE) and 1 Bt/Y for IE(EVs) through 2050. The IE(Non-RE/EVs) is the toughest to predict or levelize – if ½ of the Making Things CO2 Budget (of 12.4 Bt/Y) were eliminated by evolutionary technology, planning, and policy, then there would remain an IE(Non-RE/EVs) of 6 Bt/Y. We are looking at a total of 8 Bt/Y of Residual IE by 2100, down from a projected peak of 51 Bt/Y from all sources. Accounting for residual emissions for Growing Things and Moving Around (as for heavy equipment, airplane operation, trains, and trucks), and unless Energy Storage, Carbon Capture, Hydrogen, and Nuclear power are advanced, we will likely see a 21st Century CO2 Budget Gap of over 500 B tons of CO2.

Meeting the CO2 Budget in time to achieve Zero Net Carbon (and maintaining thereafter), and staving off worse Climate Change, must involve minimizing the Invested Energy used to build the energy infrastructure.
In the decades ahead, Making Things will increasingly be the major GHG contributor [in 2100]:

| | | |
|---|---|---|
| Making Things | 90% | 8 Bt/Y |
| Plugging In | 0% | |
| Growing Things | 5% | 1 Bt/Y |
| Moving Around | 5% | 1 Bt/Y |
| Keeping Cool/Warm | 0% | |

## 3. LOW EMBODIED ENERGY SYSTEMS

Innovation to reduce the embodied energy (invested energy, IE) of renewable energy systems should be addressing the 1 Bt/Y of CO2 emissions. The Tensioned Cable System (TCS) for mounting solar panels (first produced and installed for the University of Findlay in Ohio in June 2012 – See Figure 4) is low embodied energy and reduces energy payback of conventionally ground mounted solar electric systems from 9 years to 6 years. If the 3000 GW of Solar PV (in the U.S. by 2080) capacity modeled in the practical scenario were TCS mounted, then about 70 Mt/Y of CO2 emissions could be eliminated in the U.S., or about 280 Mt/Y globally – that is ¼ of the residual IE(RE). With less impact to land, the TCS also has lower Disposal Energy, as there is less mined material and less concrete to repurpose, resulting in lower Disposal Cost. Such technology exists now and can reduce system installed cost.

The economics of low embodied energy systems are favorable, even without anti-carbon policies or carbon disincentives such as Carbon Taxes. Material-intensive, high embodied energy systems, are costlier (to account for extraction and processing), and will become more costly as demand increases during the infrastructure build up and as fossil fuel production decreases past Peak.

Absent are metal post, beams, stringers, and concrete

**Figure 4: TCS G1 in September 2020**

The practical place to implement low IE RE is in Developing Countries, where the Paris Agreement intends to develop low carbon economies. The high carbon U.S. is rapidly developing large utility-scale solar farms, which can operate well in its highly developed electrical transmission and distribution system. What about Developing and Poor Countries lacking such infrastructure? Smaller scale, low impact, versatile solar electric systems would be appropriate and affordable.

The cost of material-intensive products correlates to their embodied energy. Implicitly and generally, lower embodied energy products mean lower cost. In summary, the case for low embodied energy renewable energy systems rests on these main points:

- Helps preserve the limited CO2 Budget for preventing worse Climate Change in the longer term.
- Helps relieve the CO2 Bow Wave concurrent with large, fast buildup of renewable energy and energy efficient systems, thus, helping to prevent arrival of Climate Tipping Points, where accelerating Climate Change could happen irreversibly.
- Tends to lower costs of renewable energy and energy efficient systems.
- Reduces the development risk otherwise associated with the pursuit of breakthroughs, while the natural pursuit of doing more with less leads to time-proven positive results.

## Economics

The industrial age has prospered with the availability and low cost of energy – coal, oil, and natural gas. Not without some investment (in exploration technology, extraction equipment, transportation and distribution systems, etc.). There are enough fossil fuels left to serve us a few more generations. But, we are spending our (solar) energy savings, and quite rapidly, despite billions of earth's inhabitants in poverty. Sustainability will require a transition to our (solar) energy income and will require technology and global cooperation (and tens of trillions of dollars in investment). True sustainability will require scientific truth, transparency, global perspective, and an appreciation for the long term.

The Paris Agreement prescribes financial help and technology transfer to Developing and poor countries, hopefully not to take the Western (Developed) world's path to prosperity, but to create a low carbon economy that provides the basics to survive and thrive. Of course, Climate Change is set to hit the Developing and poor countries worse, with sea-level rise (flooding), drought, etc. affecting them to the point of inducing mass migrations. Developed countries, such as the U.S., face a lot of challenges handling immigration.

The U.S. and other Developed countries have high carbon economies. To date, the Industrial Age has caused the emission of about 2000 Gigatons of CO2. Scientists claim that a budget of about 1000 Gigatons remains before worsening Climate Change, which will bring about catastrophic damages and big hits to the economy. Interestingly, Europe achieves each unit of GDP with a quarter less energy than the U.S. Architect, inventor, and design science advocate R. Buckminster Fuller recognized the geologic value of gasoline at about $1M per gallon. Forty years ago Bucky Fuller suggested that it was cheaper to pay people to stay home, to avoid the gas guzzling trips to work, which did not necessarily contribute to the productive economy, though part of the consumptive economy. Bucky also had the foretelling suggestion that we build a global transmission system, so that the sunlit day side could power the dark night side, without large scale energy storage.

As we learn to more efficiently utilize fossil fuel energy, an ironic paradox emerges – Jevon's Paradox, identified at the start of the Coal Age – the more efficiently we use a limited resource, the more of that limited resource we will use. Efficiency steps up demand, and demand induces greater supply, and supplied demand consumes the limited resource, be it coal, oil, or natural gas.

Given any progressive technology, reliability and efficiency improvements historically have followed, such as in Solar PV panels (from years to decades in Service Life) or in cars (from 100 to 300 thousand miles and from 15 to 35 mpg). We will rely on such improvements in the decades and century ahead. Jevon's Paradox and Capitalism's emphasis on consumption will be huge challenges to overcome, as profits get conflated with progress on the path to sustainability, low carbon, and avoidance of a climate disaster. Before geologic discoveries of large deposits of coal (and oil), and efficient ways to extract or use it, costs were high and production low. Efficiency became the key. Efficient boilers and machines to get more work with less coal stepped up the demand and consumption of coal. A similar phenomenon occurs with embodied energy and renewables (solar and wind) – as we use less energy in making the infrastructure, we see demand (for low embodied energy products and systems) going up, as acquisition costs (leveraged by the lower embodied energy) go down. This paradox of sorts can induce transition to solar in the midst of economic stress and high material costs, of which we clearly face in the future.

There is a tendency to focus on operational or end use consumption of energy and accompanying emissions. The ongoing electrification of our economy and lives will leave Making Things the clear leader in GHG emissions. Embodied energy (from Making Things) will be an increasing hurdle to achieving Zero Net Carbon (and, thus, True Sustainability) without busting the CO2 Budget (for avoiding worse Climate Change). The process energy for Making Things is not naturally occurring. Solar and wind energy is diffuse and low intensity, while process energy is concentrated and high intensity. Carbon Capture and continued fossil fuel use is not a long term sustainable solution.

It is important that we know our CO2 (emission) Budget to stave off worsening Climate Change, particularly warming. There are currently at least 15 phenomena in nature that are at risk of runaway behavior, worsening Climate Change, such as polar ice melting, carbon sink forests diminishing, and ocean circulation changes. As of 2016, 900 Billion tons of CO2 was the Budget before we pass Tripping Points. No scenario realistically gets us to Zero Net Carbon by 2050, which would have reliably assured a Stable Climate. Indeed, assuming that breakthroughs do happen as hoped, there is a chance to reach Zero Net Carbon by 2050, albeit not practical or probable. As annual reductions increase over time, the Invested Energy (IE) needed to build up and maintain the clean energy and clean living infrastructure, and the associated emissions, will be increasingly significant, as it chips away at the CO2 Budget and contributes to the CO2 Budget Gap.

The dilemma of embodied energy (invested energy for the infrastructure to fight Climate Change) is in the near term somewhat mitigated by following the old adage of the early environmental movement: REDUCE, REUSE, and RECYCLE, and mostly in that order. In the long term, recycling will be essential, and low embodied energy infrastructure is inherently easier and less costly to recycle. Implement low embodied energy now to reduce the CO2 Bow Wave, to prepare for recycling in the future, and to reduce hurdles to achieving Zero Net Carbon.

The combined Bow Wave from all $CO_2$ reduction measures represents a temporary uptick of several billion tons of $CO_2$ in a 10 year or longer period, coinciding with the near term increases in $CO_2$ emissions from infrastructure buildup. Net reductions occur only after the Energy Payback period.

Pursuing low Invested Energy infrastructure means lower rates of fossil fuel consumption, less costly recycling, lower risk of Climate Change worsening, and lower cost risk in the future, when energy and material costs are likely higher. Identifying the advantages of lower IE will justify incentivizing the development of IE-reducing technology, such as structural alternatives (to steel, aluminum, concrete, and glass), design with less material, hydrogen, concentrated solar thermal, and even Carbon Capture.

## 4. CONCLUSIONS

There may be a conclusion to a study, an article, or a white paper, but there is no conclusion to the sustainability story. True sustainability is technically impossible if we are consuming the resources that now sustain us. Climate Change is the blaring red flag that tells us we are using up our limited resources. We would have reached the Embodied Energy challenge whether we experienced (human induced) Climate Change or not. At least we are acknowledging Climate Change and are making plans to fix, or rather, to mitigate it.

The translation to a clean energy economy seems destined to be led by the free market system, with low cost and high profit the operative principles. Climate Change represents an added (emerging) cost to the market equation. The lure of free solar energy and the promise of technology is the market's answer to the greatest Incurred Cost imaginable, Climate Change. But, is this a setup to the greatest Paradox of our time? That we may be designing more efficient means of consuming even more of the limited resources we call fossil fuels?

Low embodied energy (i.e., low invested energy in Making Things) is a logical pursuit in our transition from quantity limited fossil fuels to renewable fuels, electricity, and materials. It is logical to incentivize the pursuit of low embodied energy in our free market economy. Certified Low Embodied Energy may one day coexist with Certified Organic, Low Sugar, Fat Free, and Gluten Free in the lexicon of the market. The first order, material-based Invested Energy estimating approach herein would need to be more rigorous and inclusive of all invested energy sources, such as machining, transportation, and installation energy. Encouraging is the fact that these secondary embodied energy demands can be supplied by the new clean energy infrastructure. Material production stands as the main challenge in achieving low embodied energy and true sustainability.

Despite identification and planning for Climate Change (Global Warming) going back decades, the past decade has seen at least a 15% increase in global GHG emissions, attributable to population induced demand growth and perhaps to the renewable energy build up already in progress. The buildup (of Solar PV, Wind, and Electric Vehicles) has only just begun, with the bow wave of associated $CO_2$ emissions coming in the next decade. We can only hope to begin the sustained decline in $CO_2$ emissions by 2030. The $CO_2$ Bow Wave, though seemingly lost in the current rise of global emissions, is foretelling of the challenge ahead, that is, the needed revolution in the approach to Making Things. We are prioritizing the reductions in end use emissions, and expanding emission-free electric generation, while not emphasizing lower embodied energy. It is not profitable, yet, to find alternatives to coal and natural gas for Making Things.

Incentivizing low embodied energy now can be relatively less expensive than dealing with worse Climate Change mid-century, as we are already facing trillions of dollars in losses to the economy in the decades ahead due to Climate Change. The new (Buildup) Invested Energy portion of the $CO_2$ Budget going forward, at about 200 Bt of $CO_2$, is too large to ignore. The old legacy Invested Energy of the current manufacturing-focused Industrial Complex (with emissions on the order of 10 Bt/y of CO2) is also too large to ignore.

The goal of doing more with less can cost less. The Tensioned Cable System for mounting Solar PV panels (G1 or all metal G1M) costs less than conventional mounting, reduces Invested Energy CO2 emissions, creates semi-skilled jobs, and is amenable for broad use in Developing Countries. The Practical Scenario addressed herein for the U.S. will cost about $4.5 - 6T through 2050, still less than the cost of the Cold War ($6T in 1980 dollars), which went a long way to preserving the fossil fuel-dependent economy of the post WWII years.

The significance of Invested Energy and associated CO2 emissions grows over time. Ultimately, we face releasing 4 Bt of CO2 per year to maintain the 100% renewable energy/clean Electric Grid and perhaps 6 Bt of CO2 per year to Make Things. The last 20% of annual reductions are faced at a time (mid-century and beyond) of Climate Tipping Points – including sea level rise, carbon sink forest loss, and ocean circulation changes. The real deal will be finding new ways to produce material without burning fossil fuels, sooner rather than later.

Let us develop a Design Science of Doing More with Less and direct investment and effort into reducing Invested Energy (embodied energy), optimizing and economizing the global plan for reducing GHG emissions.

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