TRANSITION TO RENEWABLE ENERGY: HOW SUSTAINABLE ARE THEY ?

Santappa- Raghavan Memorial Lecture
CSIR-Central Leather Research Institute, Chennai
October 28, 2020

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www.swaminathansivaram.in

PROFESSOR M. SANTAPPA AND DR. K.V RAGHAVAN : TWO DOYENS WHO EMBELLISHED CSIR -CLRI

1923-2017
Director CLRI: 1973-81

Professor and Head, University Department of Physical Chemistry, A. C. College of Technology, University of Madras

1943-2017
Director CLRI : 1994-96

RRL-J (NEIST) : 1964-83
Deputy Director, CLRI: 1984-94
Director, IICT-H : 1996-2003

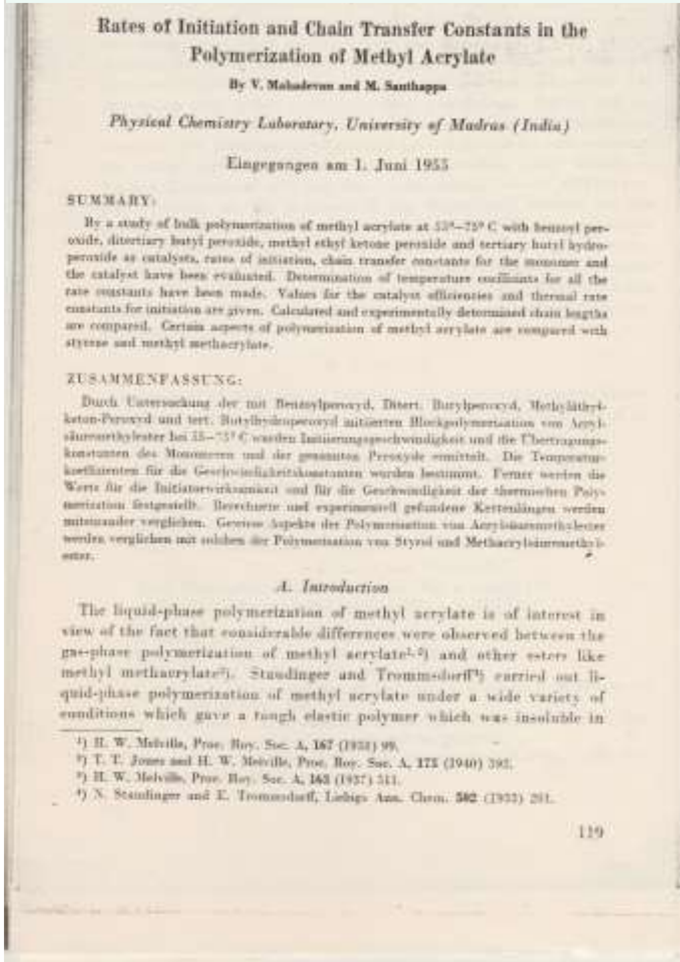
DR K.V.RAGHAVAN: A GENTLEMAN SCIENTIST

- True to the discipline in which he was trained, Dr. Raghavan was a thinker with a systems approach, leader and administrator, *par excellence*
- His career long (39 years) association with three CSIR laboratories and Director of two is unprecedented in the history of CSIR
- His understanding of CSIR was deep and insightful; his demeanour was exemplary, was a great listener and a seeker of consensus
- This made him a valuable asset in S&T field, both within CSIR and outside

PROFESSOR MUSHI SANTAPPA: A POLYMER PIONEER

- A pioneer in polymer science in India; established a vibrant school of polymer science research at the University of Madras in 1952 and later at CLRI
- Received two PhDs, University of London in 1949 and University of Manchester in 1951
- Professor Meredith G. Evans, his mentor at Manchester triggered his interest in studying kinetics of free radical chain reactions in polymerization
- Several students, close to sixty, especially in Southern India, pursued teaching and research in polymer science, inspired by his training and legacy
- Authored a book, State of the Art in Polymer Science and Engineering in India, in 1996

Rates of initiation and chain-transfer constant on the polymerization of methyl acrylate, V. Mahadevan and M. Santappa, Macromol. Chem., **1955**, 16, 119.



Rates of Initiation and Chain Transfer Constants in the Polymerization of Methyl Acrylate

By V. Mahadevan and M. Santhappa

Physical Chemistry Laboratory, University of Madras (India)

Eingegangen am 1. Juni 1955

SUMMARY:

By a study of bulk polymerization of methyl acrylate at 55°–75° C with benzoyl peroxide, ditertiary butyl peroxide, methyl ethyl ketone peroxide and tertiary butyl hydroperoxide as catalysts, rates of initiation, chain transfer constants for the monomer and the catalyst have been evaluated. Determination of temperature coefficients for all the rate constants have been made. Values for the catalyst efficiencies and thermal rate constants for initiation are given. Calculated and experimentally determined chain lengths are compared. Certain aspects of polymerization of methyl acrylate are compared with styrene and methyl methacrylate.

ZUSAMMENFASSUNG:

Durch Untersuchung der mit Benzoylperoxyd, Ditert. Butylperoxyd, Methyläthylketon-Peroxyd und tert. Butylhydroperoxyd initiierten Blockpolymerisation von Acrylsäuremethylester bei 55–75° C wurden Initiierungsgeschwindigkeit und die Übertragungskonstanten des Monomeren und der genannten Peroxyde ermittelt. Die Temperaturkoeffizienten für die Geschwindigkeitskonstanten wurden bestimmt. Ferner werden die Werte für die Initiatorwirksamkeit und für die Geschwindigkeit der thermischen Polymerisation festgestellt. Berechnete und experimentell gefundene Kettenlängen werden miteinander verglichen. Gewisse Aspekte der Polymerisation von Acrylsäuremethylester werden verglichen mit solchen der Polymerisation von Styrol und Methacrylsäuremethylester.

A. Introduction

The liquid-phase polymerization of methyl acrylate is of interest in view of the fact that considerable differences were observed between the gas-phase polymerization of methyl acrylate[1,2] and other esters like methyl methacrylate[3]. Staudinger and Trommsdorff[4] carried out liquid-phase polymerization of methyl acrylate under a wide variety of conditions which gave a tough elastic polymer which was insoluble in

[1] H. W. Melville, Proc. Roy. Soc. A, 167 (1938) 99.
[2] T. T. Jones and H. W. Melville, Proc. Roy. Soc. A, 175 (1940) 392.
[3] H. W. Melville, Proc. Roy. Soc. A, 163 (1937) 511.
[4] N. Staudinger and E. Trommsdorff, Liebigs Ann. Chem. 502 (1933) 201.

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SANTAPPA AWARD IN POLYMER SCIENCE : RECOGNIZING EXCELLENCE IN SCIENCE

- **1979** : The Society established at the Department of Physical Chemistry, AC College of Technology Campus, Madras (Chennai)
- **1984**: The first International Conference devoted to Polymer Science in India, organized in Chennai by Professor M. Santappa, then Director, CSIR-CLRI, Chennai; global participation and sponsored by IUPAC
- **1984**: 60^{th} birthday of Professor M. Santappa. His students create an endowment from which an Award for practicing Polymer Scientists is created; the first such award for polymer scientists in In
- **1991:** Polymers@1991 is convened at CSIR-NCL, Pune in January 1991.International participation. Doyens of Indian Polymer Science, Professor Santappa, Professor S.K. De, Professor R.D. Patel, Professor Ms Indra Verma and Professor Ashok Misra, Professor V.B. Gupta and many more attend Polymers ’91.

THE SOCIETY FOR POLYMER SCIENCE (INDIA)

Operates through ten chapters, pan India

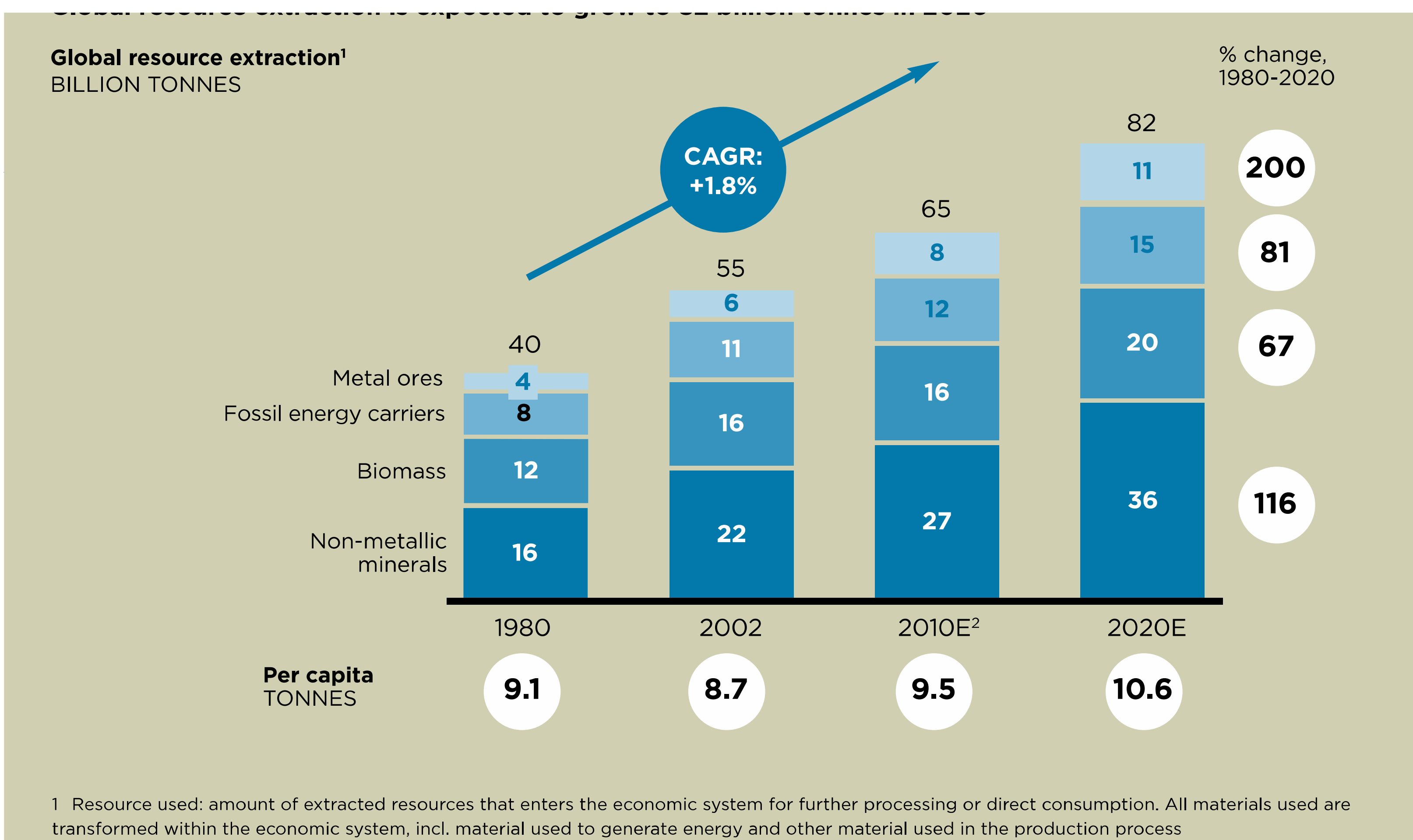
Since 1990, about 15 scientists have received this Award

TRANSITION TO RENEWABLE ENERGY: HOW SUSTAINABLE ARE THEY ?

CHALLENGES TO SUSTAINABILE DEVELOPMENT

- Population and earth's carrying capacity (> 9 billion by 2030)
- Irreversible changes in global climate (+3°C ⇧)
- Providing enough food for the people (land use pattern)
- Access to affordable clean energy (societal and quality of life inequities)
- Depletion of earth resources (excessive consumption and rapid urbanization)
- Increasing burden on environment by "end-of-use" objects and materials in a "throw-away" society

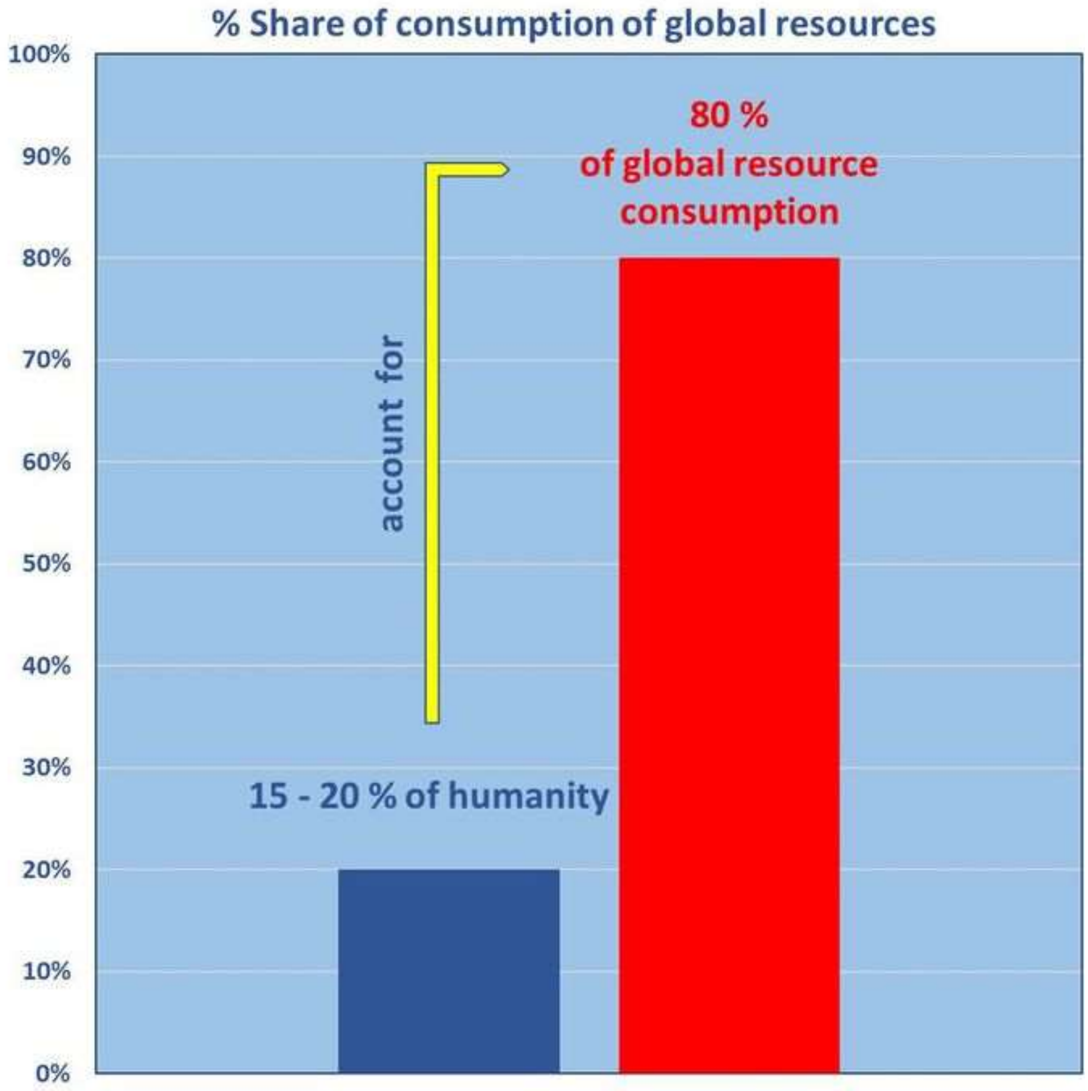
GLOBAL RESOURCE EXTRACTION



Using resources at the current rate we will need " the equivalent of more than two planets to sustain us " by 2100 !

The growing role of minerals and materials in a low carbon future, World Bank Report, June 2017

CONSUMPTION INEQUALITY OF GLOBAL REOSURCES: PARETO PRINCIPLE IN ACTION



WHAT IS THE PROBLEM WITH SUSTAINBILITY ?

For a long time we have

- Ignored the impact of technological progress, which comes at a cost
- Concealed the consequences of unbridled growth
- Followed the prescription *"multiply" and "subdue the Earth"*
- Put *"having*" before *"being*"
- Kept thinking as if there were still as few people on earth as there were 200 years ago.

Our dilemma is that we live in a finite world, but behave as if it were inexhaustible.

TRAGEDY OF COMMONS

- A resource that belongs to ***everybody*** will not be cared for by ***anybody***
- The biggest fallacy : Decisions that are reached individually based on rational thinking will in fact be the best thinking for the society, collectively
- As rational human beings, each one of us, try to maximize our gain without limits in a world that is limited.
- Ruin is the destination towards humanity rushes , each pursuing her best interests in a society that believes in freedom of the commons. Freedom in a commons leads to tragedy

Elinor Ostrom
1933-

All common resources are well-managed when those who benefit from such resources are in close proximity and in control of them. Tragedy occurs when external groups exert their power(economic, political and social) to gain personal or selfish advantages

The Tragedy of the Commons

The population problem has no technical solution; it requires a fundamental extension in morality.

Garrett Hardin

At the end of a thoughtful article on the future of nuclear war, Wiesner and York (*1*) concluded that: "Both sides in the arms race are . . . confronted by the dilemma of steadily increasing military power and steadily decreasing national security. *It is our considered professional judgment that this dilemma has no technical solution.* If the great powers continue to look for solutions in the area of science and technology only, the result will be to worsen the situation."

I would like to focus your attention not on the subject of the article (national security in a nuclear world) but on the kind of conclusion they reached, namely that there is no technical solution to the problem. An implicit and almost universal assumption of discussions published in professional and semipopular scientific journals is that the problem under discussion has a technical solution. A technical solution may be defined as one that requires a change only in the techniques of the natural sciences, demanding little or nothing in the way of change in human values or ideas of morality.

In our day (though not in earlier times) technical solutions are always welcome. Because of previous failures in prophecy, it takes courage to assert that a desired technical solution is not possible. Wiesner and York exhibited this courage; publishing in a science journal, they insisted that the solution to the problem was not to be found in the natural sciences. They cautiously qualified their statement with the phrase, "It is our considered professional judgment. . . ." Whether they were right or not is not the concern of the present article. Rather, the concern here is with the important concept of a class of human problems which can be called "no technical solution problems," and, more specifically, with the identification and discussion of one of these.

It is easy to show that the class is not a null class. Recall the game of tick-tack-toe. Consider the problem, "How can I win the game of tick-tack-toe?" It is well known that I cannot, if I assume (in keeping with the conventions of game theory) that my opponent understands the game perfectly. Put another way, there is no "technical solution" to the problem. I can win only by giving a radical meaning to the word "win." I can hit my opponent over the head; or I can drug him; or I can falsify the records. Every way in which I "win" involves, in some sense, an abandonment of the game, as we intuitively understand it. (I can also, of course, openly abandon the game—refuse to play it. This is what most adults do.)

The class of "No technical solution problems" has members. My thesis is that the "population problem," as conventionally conceived, is a member of this class. How it is conventionally conceived needs some comment. It is fair to say that most people who anguish over the population problem are trying to find a way to avoid the evils of overpopulation without relinquishing any of the privileges they now enjoy. They think that farming the seas or developing new strains of wheat will solve the problem—technologically. I try to show here that the solution they seek cannot be found. The population problem cannot be solved in a technical way, any more than can the problem of winning the game of tick-tack-toe.

What Shall We Maximize?

Population, as Malthus said, nat
tends to grow "geometrically," or,
would now say, exponentially.
finite world this means that th
capita share of the world's goods
steadily decrease. Is ours a finite w
A fair defense can be put forwa
the view that the world is infinit
that we do not know that it is not.
in terms of the practical problem
we must face in the next few g
tions with the foreseeable technolo
is clear that we will greatly in
human misery if we do not, durin
immediate future, assume that the
available to the terrestrial human
ulation is finite. "Space" is no e
(*2*).
A finite world can support o
finite population; therefore, popu
growth must eventually equal zero.
case of perpetual wide fluctu
above and below zero is a trivial v
that need not be discussed.) Whe
condition is met, what will be the
tion of mankind? Specifically, can
tham's goal of "the greatest goo
the greatest number" be realized
No—for two reasons, each suf
by itself. The first is a theoretical
It is not mathematically possib
maximize for two (or more) variab
the same time. This was clearly
by von Neumann and Morgenster
but the principle is implicit in the t
of partial differential equations,
back at least to D'Alembert (
1783).
The second reason springs di
from biological facts. To live,
organism must have a source of e
(for example, food). This ener
utilized for two purposes: mere
tenance and work. For man, m
nance of life requires about 1600
calories a day ("maintenance calo
Anything that he does over and
merely staying alive will be defin
work, and is supported by "wor
ories" which he takes in. Work ca
are used not only for what we call
in common speech; they are als
quired for all forms of enjoyment,
swimming and automobile raci
playing music and writing poet
our goal is to maximize populatio
obvious what we must do: We
make the work calories per perso
proach as close to zero as possibl
gourmet meals, no vacations, no s
no music, no literature, no art. .
think that everyone will grant, wi

The author is professor of biology, University of California, Santa Barbara. This article is based on a presidential address presented before the meeting of the Pacific Division of the American Association for the Advancement of Science at Utah State University, Logan, 25 June 1968.

13 DECEMBER 1968

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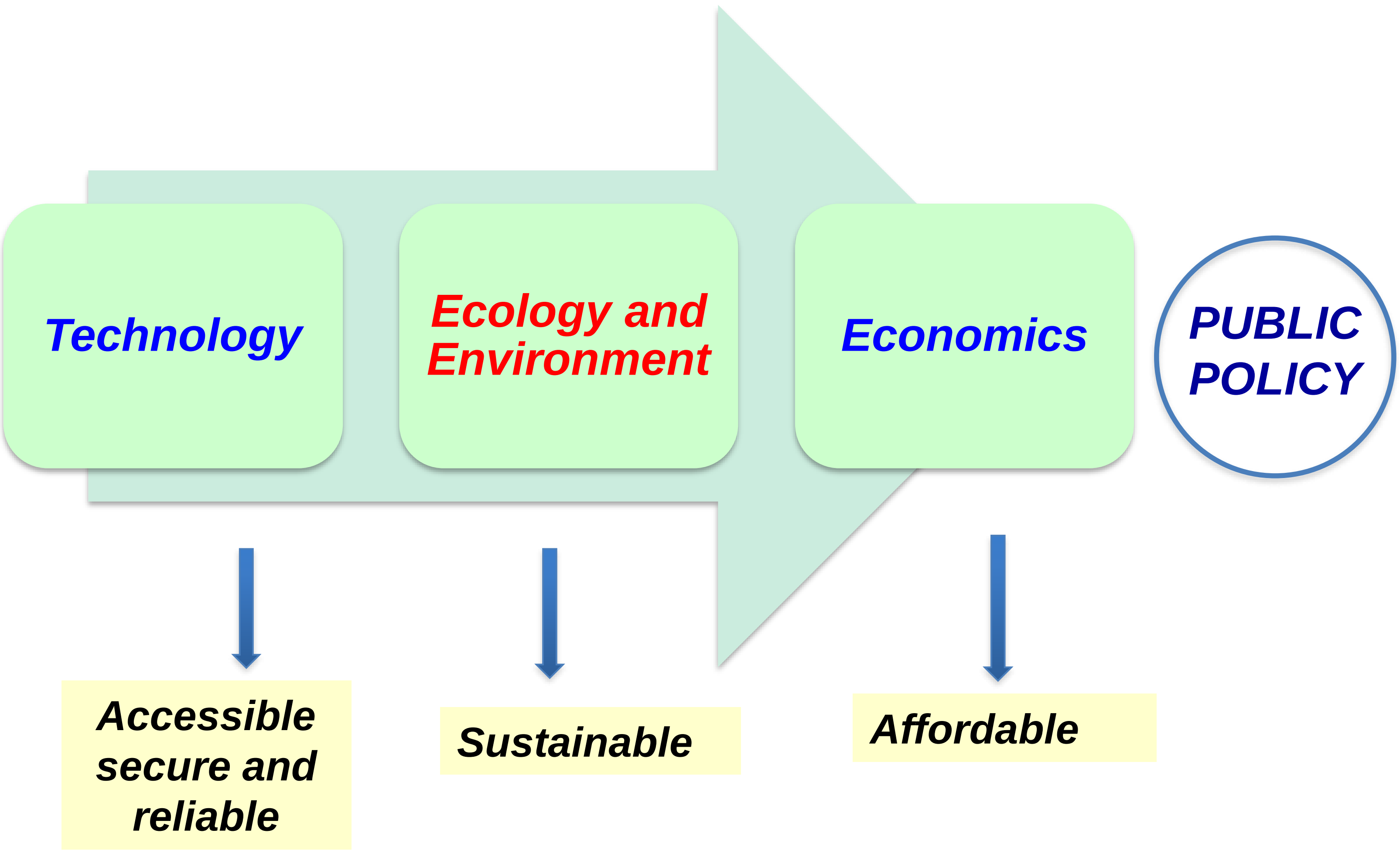
Garret Hardin, Science, 13 December 1968, p.1343

PUBLIC POLICY IN ENERGY ISSUES ARE SHAPED BY ....



SUSTAINABILITY IS A “WICKED “ AND “COMPLEX” PROBLEM

- A “wicked” problem as that having: no definitive formulation; a solution that is ‘good or bad’ rather than ‘right or wrong’
- No immediate or ultimate test of its resolution; no possibility of learning by ‘trial and error’; no well-described set of potential solutions; causes with no unique explanation
- The concept of “wicked” problems has been generally used to denote problems that standard approaches find difficult to define clearly and often impossible to solve owing to their innumerable causes, incomplete or contradictory knowledge, competing interests and opinions, and interdependencies
- The list of “wicked” sustainability problems is long. Climate change, energy, water resource management, urban planning, waste disposal, biodiversity loss

Rittel HWJ, Webber MM. Dilemmas in a general theory of planning. Policy Sci. 1973;4(2):155–169; Azapagic A and Perdan S. Sustainable chemical engineering: Dealing with “Wicked” sustainability problems, AIChE Journal, 2014; 60(12); 3998-4007

For every complex question, there is a simple answer; and it is, invariably, wrong

H. L. Mencken
(1880-1956)

CLEAN AND RENEWABLE ENERGY

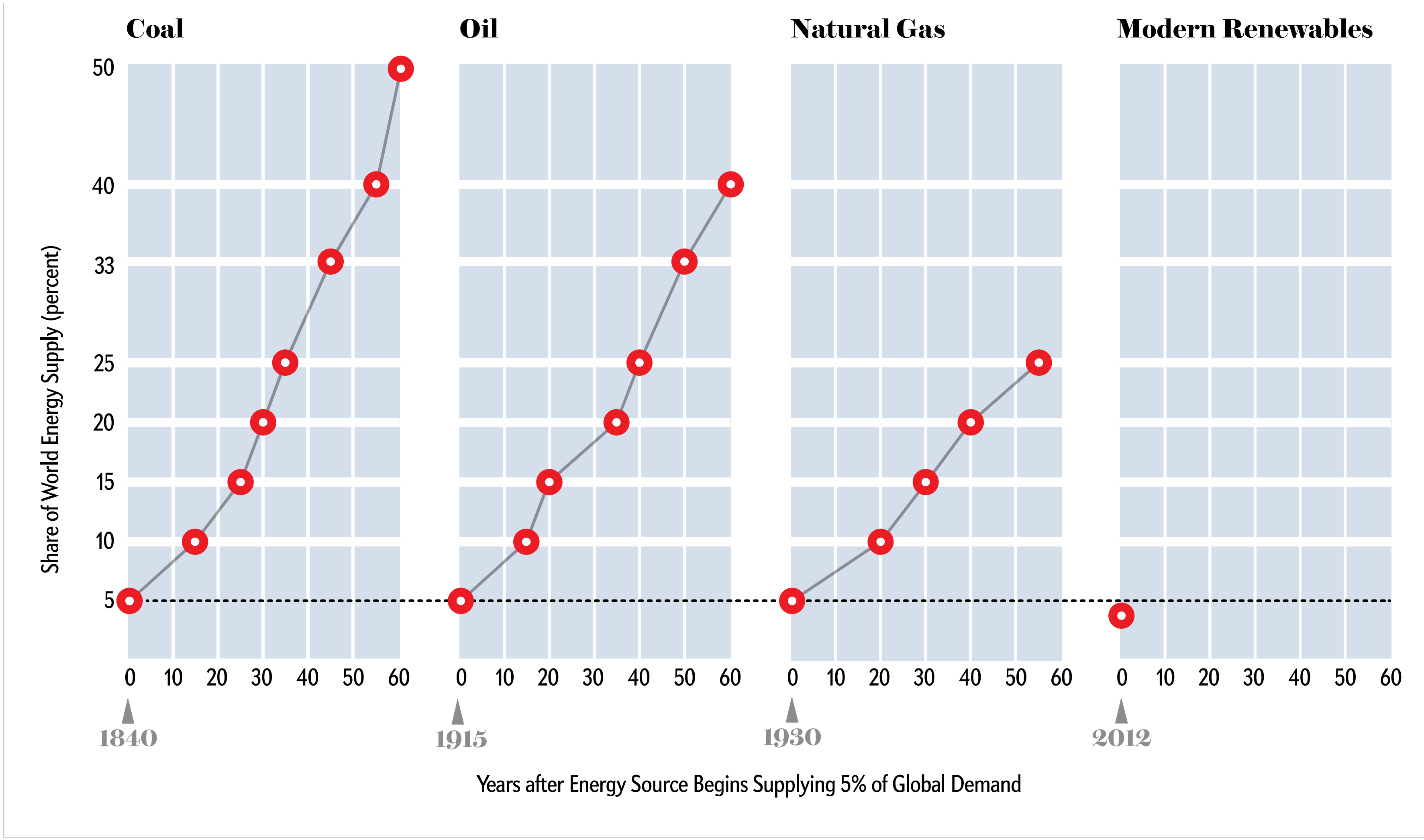
- In our quest to reduce the green house gas emissions, there is a haste in shifting to renewable energy based solutions
- These decisions have long term consequences, in the sense that , infrastructure will get locked-in for centuries and shifting to alternatives will be as difficult or impossible
- So all shifts in energy technologies should be based on careful consideration of long-term sustainability of material availability and the technology needed to convert the material to devices that will power our future
- Regrettably, such analysis is sadly lacking and decisions are being made based on insufficient information

Should we be concerned about "unintended consequences" of such decisions?

THE LAW OF "UNINTENDED CONSEQUENCES"

- Human intervention in a complex system tends to create unanticipated and often undesirable outcomes
- Most modern technologies have negative consequences that are both unavoidable and unpredictable. For example, almost all environmental problems, from chemical pollution to global warming, are the " unintended consequences" of the application of modern technologies
- As we introduce adapt new technologies in the renewable energy area, we need to think of the unintended consequences, which may show up only after several decades; by that time it may be too late to correct
- **Wisdom in hindsight** is at best a learning opportunity; however, managing and ensuring sustainability requires **wisdom in foresight**

TRANSITIONS IN ENERGY : ALWAYS SLOW !



V. Smil, Scientific American, January 2014

ELEMENTS FOR CLEAN ENERGY

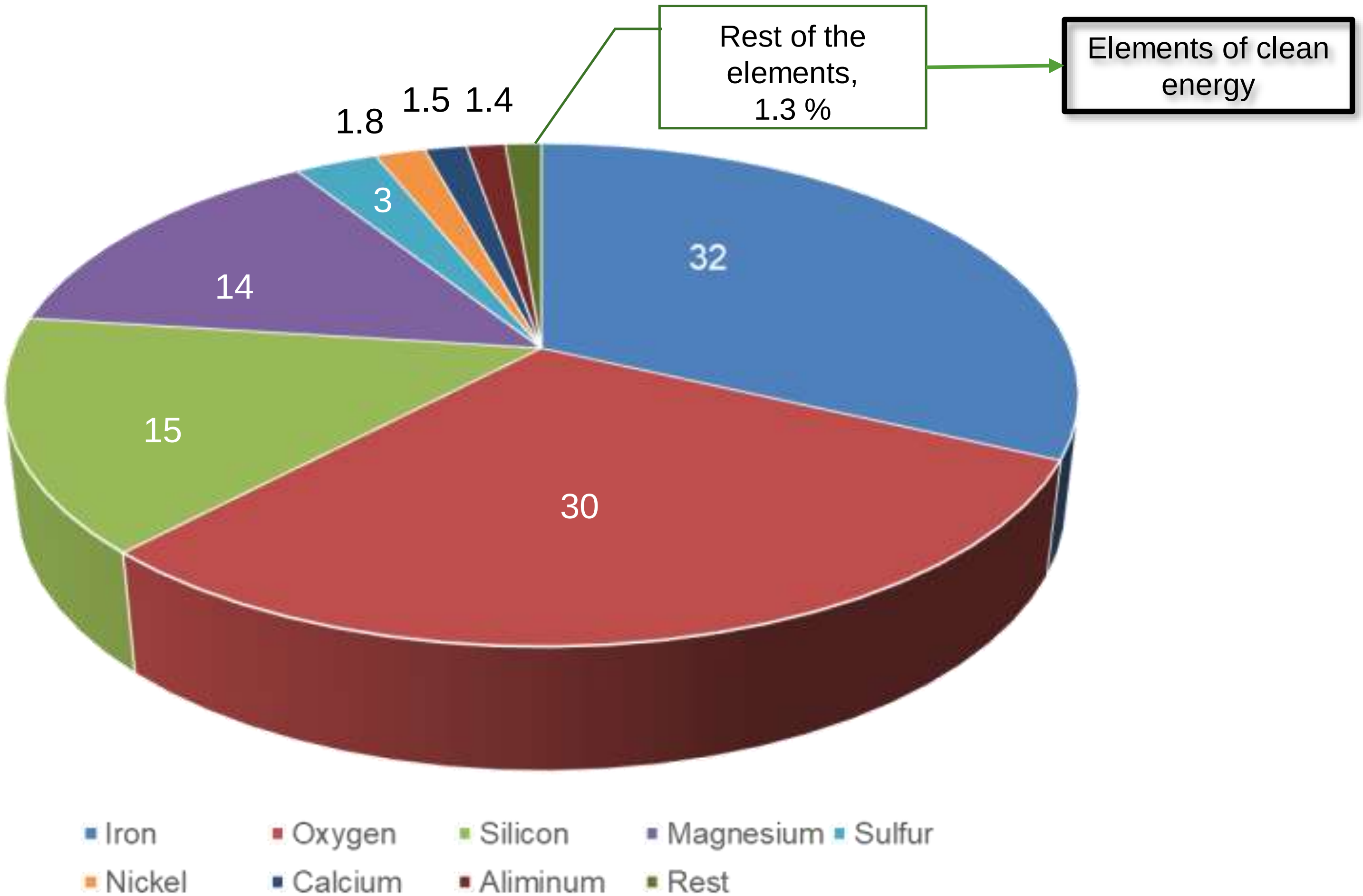
Many of the elements are either toxic or too little is available on earth. Will our dependence on them be sustainable?

- *Energy*
- -Solar : Silicon, Lead, Silver,
  - -Perovskites : Lead
  - -CIGS : Indium and Selenium
  - -Cd/Te :Cadmium and Tellurium
  - -Wind : Neodimium, Dysprosium, Praseodymium, Samarium Rhenium

- *Lighting*
  - - LED : Gallium, Indium
- *Electric Mobility*
  - - Batteries : Lithium / Cobalt / Mangnese Nickel
- Fuel Cells : Platinum and Palladium

Energy infrastructure once created, is difficult to dismantle; therefore, material choices must be made with caution

ABUNDANCE OF ELEMENTS ON EARTH, % WEIGHT



Mass of earth : ~ 6x 10^{21} tons

SUSTAINABILITY OF THE ELEMENTS IN THE PERIODIC TABLE

Except uranium all elements are indestructible.
Helium and neon being lighter than air escape into the stratosphere and are lost to earth
Carbon fixed on earth is lost as carbon dioxide upon combustion

However, metals cannot become extinct because atoms are immutable

So where lies the problem ?

Human activity is taking elements from relatively concentrated ore deposits and distributing them so thinly across devices and gadgets that they are present in the environment in dilute forms, and no longer easily recoverable from wastes

Once again , entropy is in action !

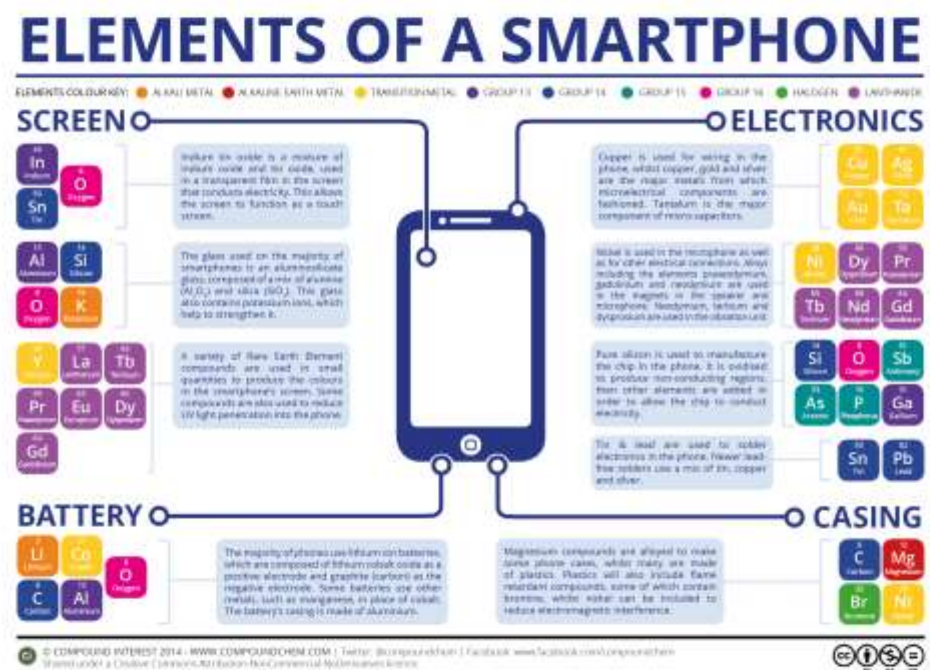
THERMODYNAMICS OF SUSTAINABILITY

- In every process energy is transformed and part of it is degraded with respect to its ability to perform useful work
- Consider use of natural gas that is burnt to generate heat of combustion which turns a turbine to generate electricity. Here chemical energy is converted to electrical energy and thermal energy of the exhaust gas. When the exhaust gas reaches the temperature and pressure of the atmosphere, no useful work can be extracted. In addition, high concentration of carbon in the natural gas is diluted to low concentration of carbon dioxide.
- When any process generates waste and yield dilute streams, it increases entropy. Such dilute material can be reconcentrated (and the associated entropy decreased) only through expenditure of energy
- From a sustainability point of view, processes that increase entropy are less sustainable

W.S. Hermanowicz, Entropy and energy: Towards a definition of physical sustainability, escholarship.org/uc/item/2f01968r, December 2005

ENDANGERED METALS

- Endangered species : Cu, Zn, Pt
- Strategic Shortage : Ga, In, Hf, Li
- Geopolitical risks : Re, Co, Li, Pt (90% Re : China; 90 % Pt : S. Africa; 90 % Li : Chile; 90 % Co : Republic of Congo)
- Fuel Cell: Pt at cathode; 25 reactions /sec/site; Pt cost alone is $3000 per cost of an automobile engine
- Mobile phones : 40 elements; 36 mg of gold is contained in every iPhone
- A semiconductor chip on PC: 60 elements

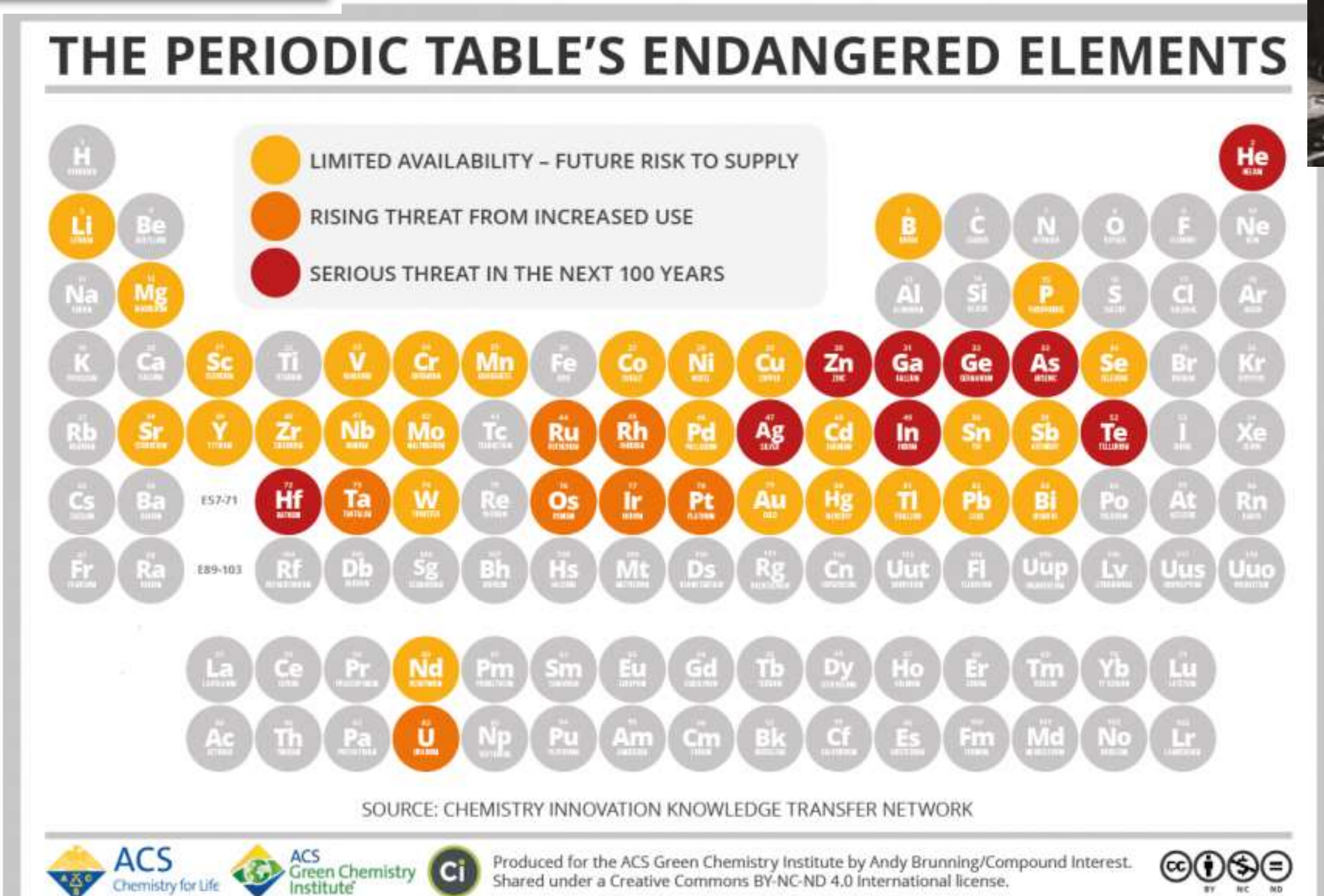


One ton of mobile phones would deliver 300 times more gold than a ton of gold ore and 6.5 times more silver than a ton of silver ore

Endangered elements, critical raw materials and conflict minerals, C.J. Rhodes, Science Progress, 2019, 102(2), 304-350

UNESCO
United Nations Educational, Scientific and Cultural Organization

2019 IYPT
International Year of the Periodic Table of Chemical Elements



The "Sustainability" of the Periodic Table is itself in question

SILICON SOLAR CELL PANELS

MAKING SILICON IS AN EXPENSIVE PROCESS

- High temperatures, invariably produced using electrical energy
- Long reaction times
- Several unit processes, all of which are batch processes
- Large number of waste and by products
- Highly corrosive environment

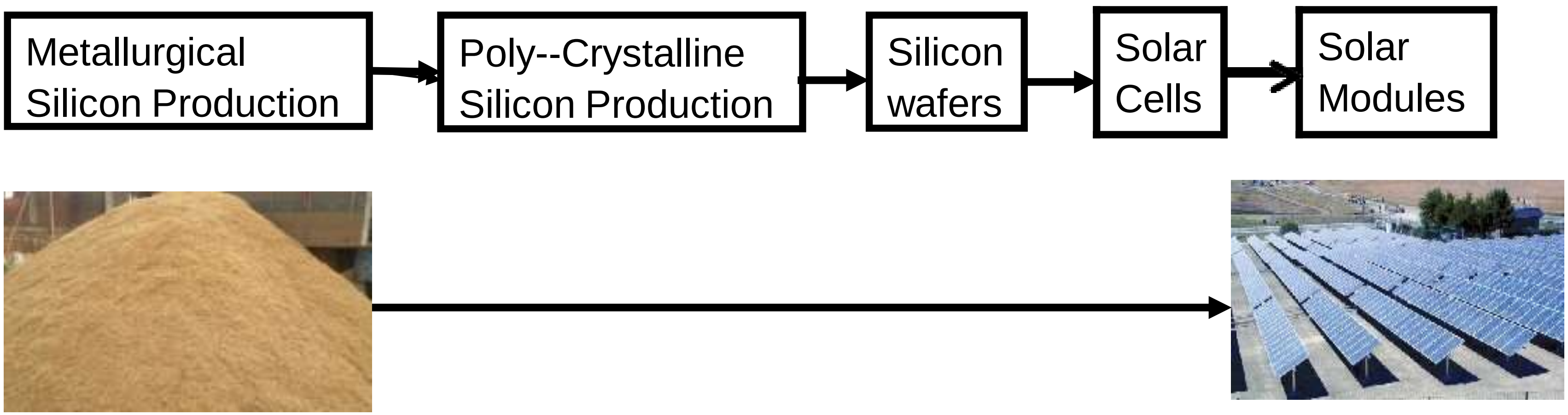
- Global capacity for solar grade silicon : ~ 0.5 million tons per annum
- Minimum viable economic capacity : 10,000 tons per annum
- Highly capital intensive : US $1.5 million per ton of production

By contemporary standards of chemical manufacturing, the process for producing silicon is a highly complex process, heavily polluting with impact on both air and water quality

IS SILICON PV GREEN ENERGY ?

Consider the following facts

- Solar PV manufacturing processes involve converting quartz to metallurgical grade silicon and then to polysilicon ingots which are sliced to form wafers



- Every ton of metallurgical grade silicon production results in 4 tons of silicon tetrachloride; Material utilization efficiency is a mere 30%
- 1 ton of crude silicon production results in 10 tons of carbon dioxide; Purification process results in additional 45 tons of carbon dioxide ; for manufacturing in China, 70 g carbon dioxide is generated per kWh of electricity
- 99.999% pure silicon requires energy intensive crystal growth and vapor deposition methods (> 200 Kwh/ kg)

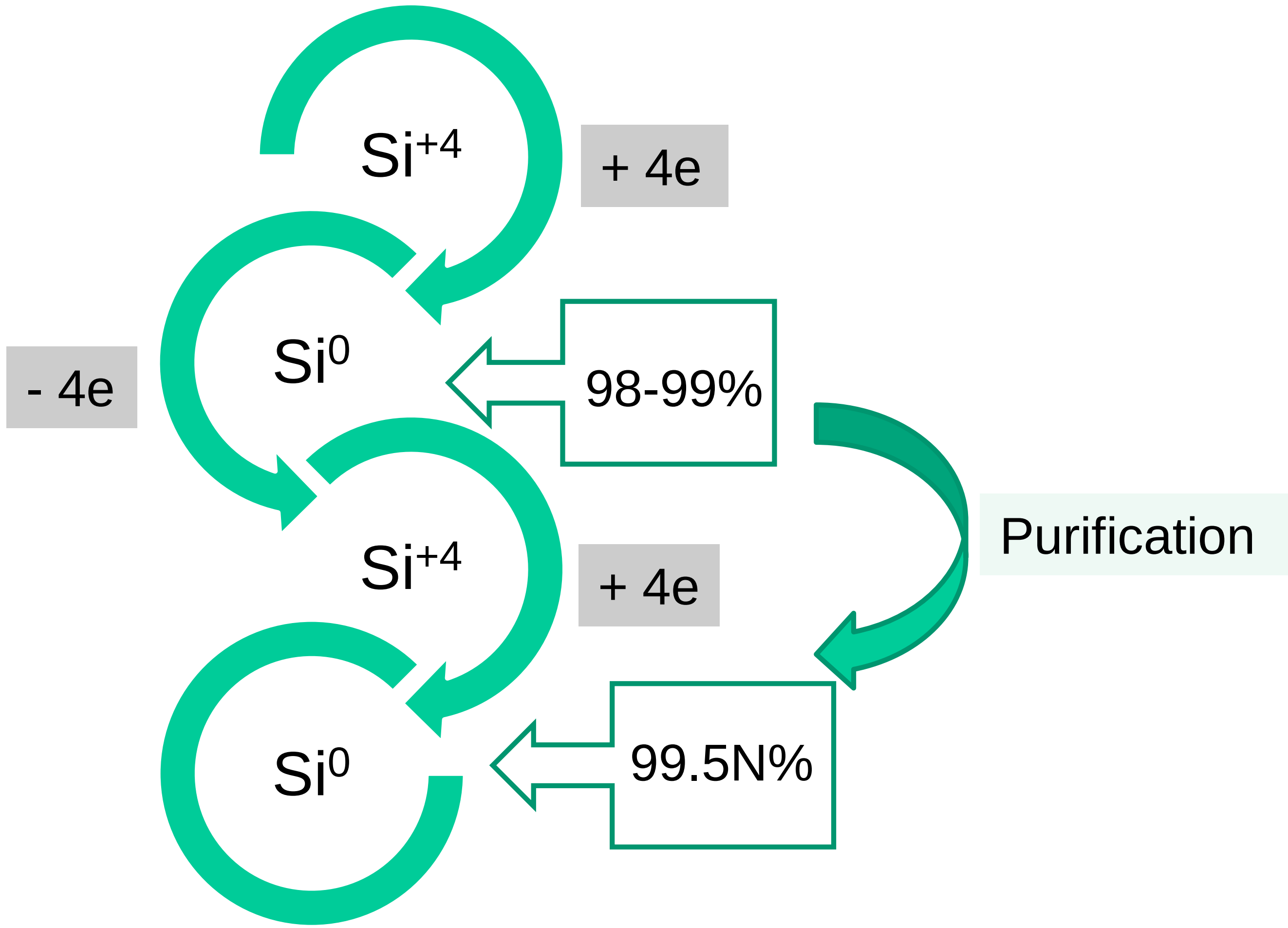
IS SILICON PV GREEN ENERGY ?

- Silicon solar cells use 1000 times more light absorbing materials than organic PV cells, because silicon does not absorb light strongly
- Silicon is intrinsically brittle and must be supported on glass with heavy metal frames making the panels heavy
- Silicon production uses sulfur hexafluoride (to clean the Siemens Reactor), HF (to clean wafers and texture the surfaces), 1,1,1 trichloroethane and large quantities of strong acids. SF_6 is a potent GHG.
- Conversion of ingots to wafers requires mechanical sawing, generating upto 10 % waste and a significant amount of fine silicon dust (inhalation hazard)
- Silver that is used for making panels at 5 % of current power demand will consume 50 % of current silver produced
- Little or no recycling of silicon in process waste or end of life panels

Solar cell fabricated with Siemen's process needs minimum 6-8 years of operation to recover the energy used to make it. This is called the "energy payback period". Ironic that we consider silicon PV as a clean and sustainable form of energy !

D. Mulvaney, Solar Energy Isn't Always as Green as You Think*, IEEE Spectrum, 26 August 2014; S. Deambi, EHS Concerns in Solar Photovoltaic, The Solar Quarterly, January 2010, p.14*

FROM MG Si TO SOLAR Si : THE REDOX PARADOX



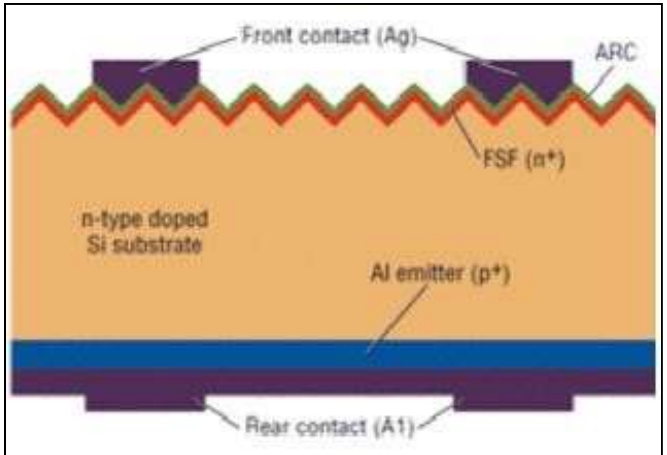
CLEAN ENERGY MATERIALS: SILVER

- Silver used for making solar panels at 5 % of current power demand will consume 50 % of silver produced across the world
- 100 GW of solar electricity requires 4000 tons of silver per year. India's silver production is 500 tons per annum and we import 7000 tons of silver per year!
- Today's silver price is about Rs 62,500 per kg; The price was Rs 39, 250 per kg in 2017.

METAL PASTE: SILVER AND ALUMINUM

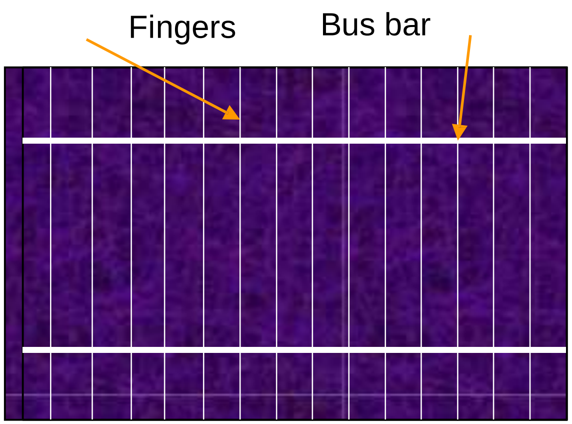
- Metal pastes are used in crystalline silicon solar cells to improve conversion efficiency. These pastes form a path for the conduction of the generated electricity from the silicon substrate while reducing the effective area exposed to sunlight.
- It is estimated that metal pastes contribute to more than 20 percent of the cost of the module
- The industry currently uses two main types of metallization pastes:
  - Silver metallic paste
  - Aluminum metallic paste
- Metal pastes of silver are applied on the front of the cell in the form of grid contacts (fingers). Thicker bus bars connect the fingers to the external circuit. Silver paste is the dominant variety used in front contacts.
- The solar power industry accounts for more than 10 percent of global silver consumption. Each panel contains about 20 grams of silver.
- Rear contacts are made of aluminum and silver pastes, and cover the entire back portion of the cell forming a back surface field. Approximately 90 percent of the rear contacts are made out of aluminum, owing to lower costs.

Front and Rear Contacts in Solar Cells



Source: www..images.pennet.com

Front Contacts in Solar Cells



SOLAR PANELS: END-OF-LIFE OPTIONS

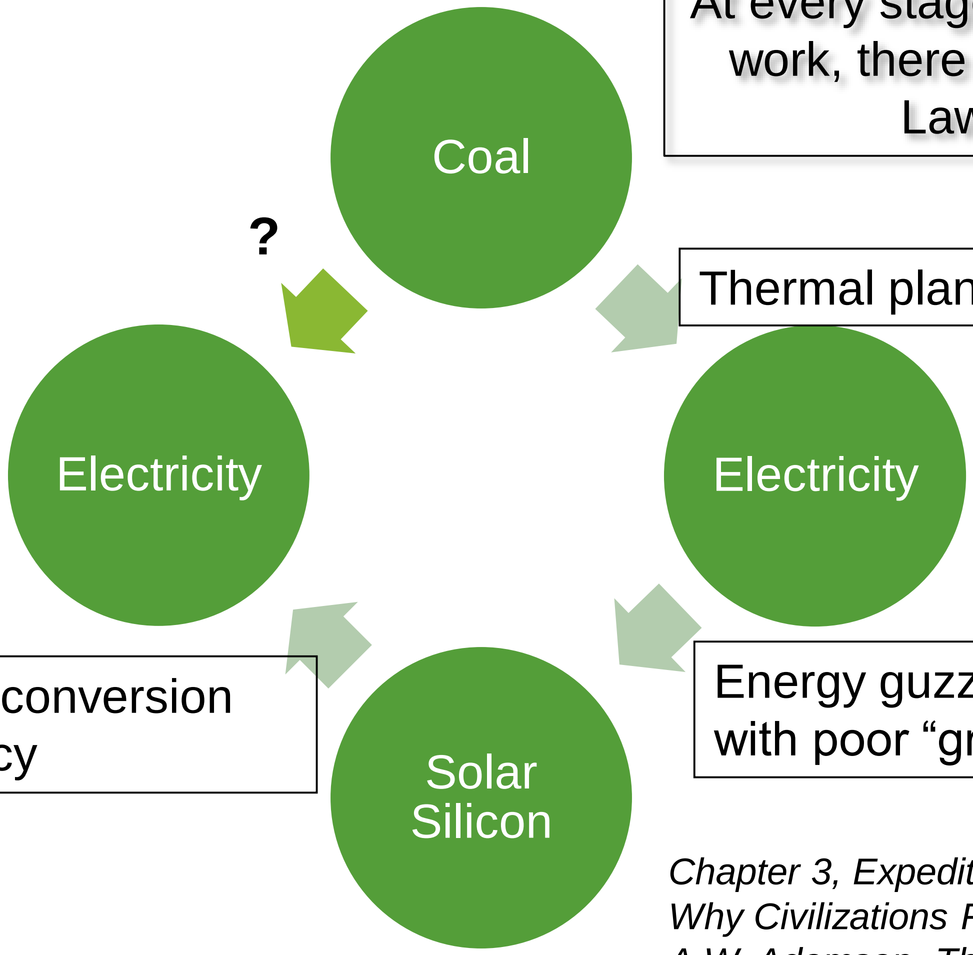
- Anticipated used solar PV panels that will be scrapped by 2050: 60 million tons !
- Typically they will consist of 76% glass, 10 % plastics, 8 % aluminum, 5 % silicon and 1% other metals
- What do we do with this electronic and hazardous waste (contains, tin and lead) ?
- Can used solar panels be rejuvenated for life time extension ?
- What will the economics of recovery of the constituents?
- How easy it is to disassemble a solar panel for recovery of useful materials?
- Is there a risk of toxic wastes leaching into the soil and ground water by carelessly discarded solar panels or back-yard recycling processes that are not environmentally friendly?

We do not have answers to many of these questions. As of today land fill appears to be the only solution. Cost of recycling appears to be greater than the cost of embodied materials. We need to guard against "unintended consequences"

J. Park et al, An Eco Friendly Method for reclaimed Silicon Wafers from a PV Module: Separation to Cell fabrication, Green Chem., 2016, 18, 1706; Y. Doff, Solar Panel Recycling: Photovoltaics Rebirth, May 24, 2020; https://www.whatsorb.com/waste/solar-panel-recycling-photovoltaics-rebirth

DOES THIS CYCLE MAKE SENSE?

At every stage of energy conversion to useful work, there is a loss of efficiency (Second Law of Thermodynamics)



Thermal plants, 30 % efficiency

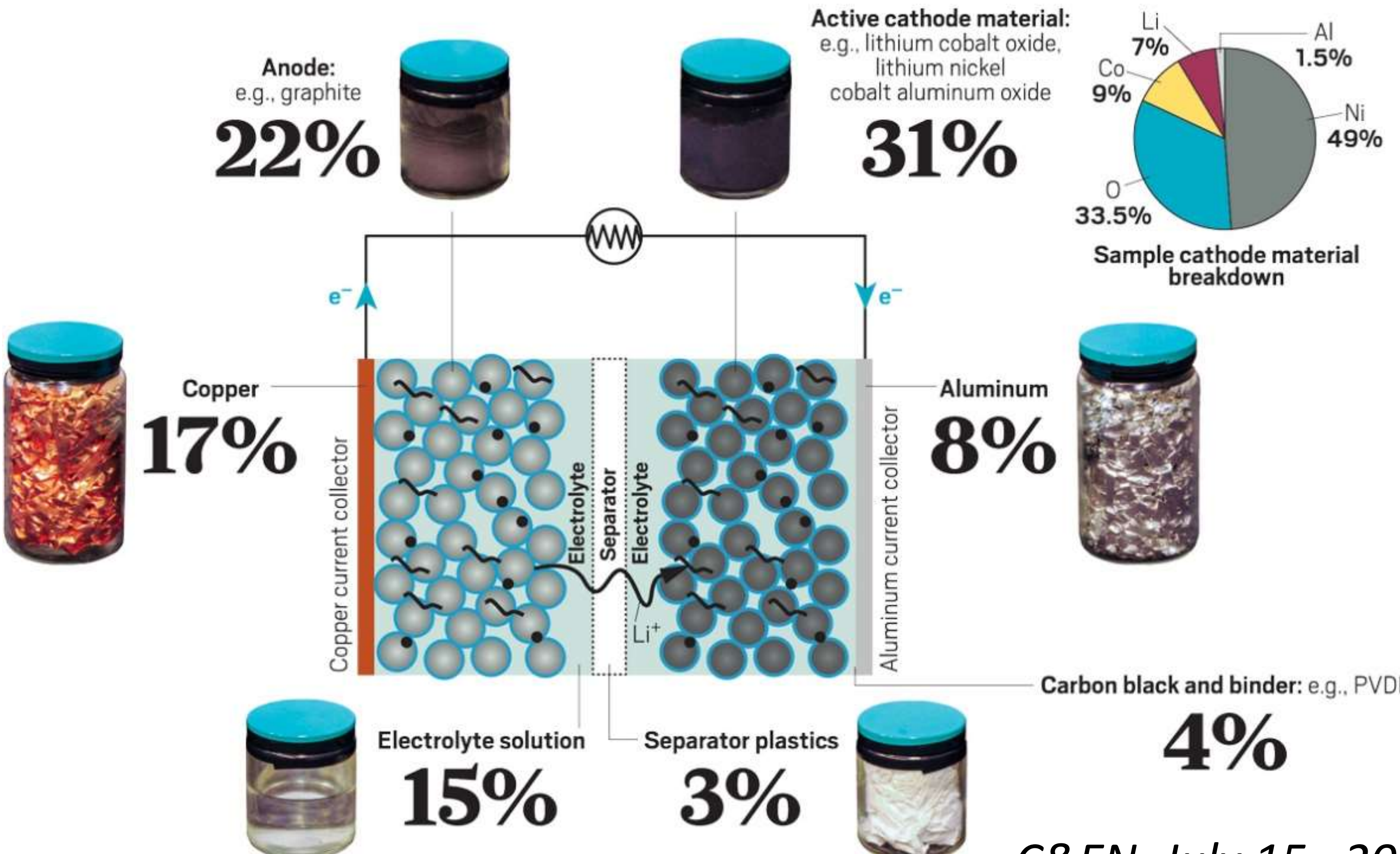
Energy guzzling manufacturing process with poor “green” chemistry metrics

~ 20 % conversion efficiency

Chapter 3, Expedited Entropy, in Immoderate Greatness: Why Civilizations Fail, William Ophuls, 2012
A.W. Adamson, Thermodynamic Inefficiency of Conversion of Solar Energy to Work, J. Chem. Educ., 1984, 61, 221

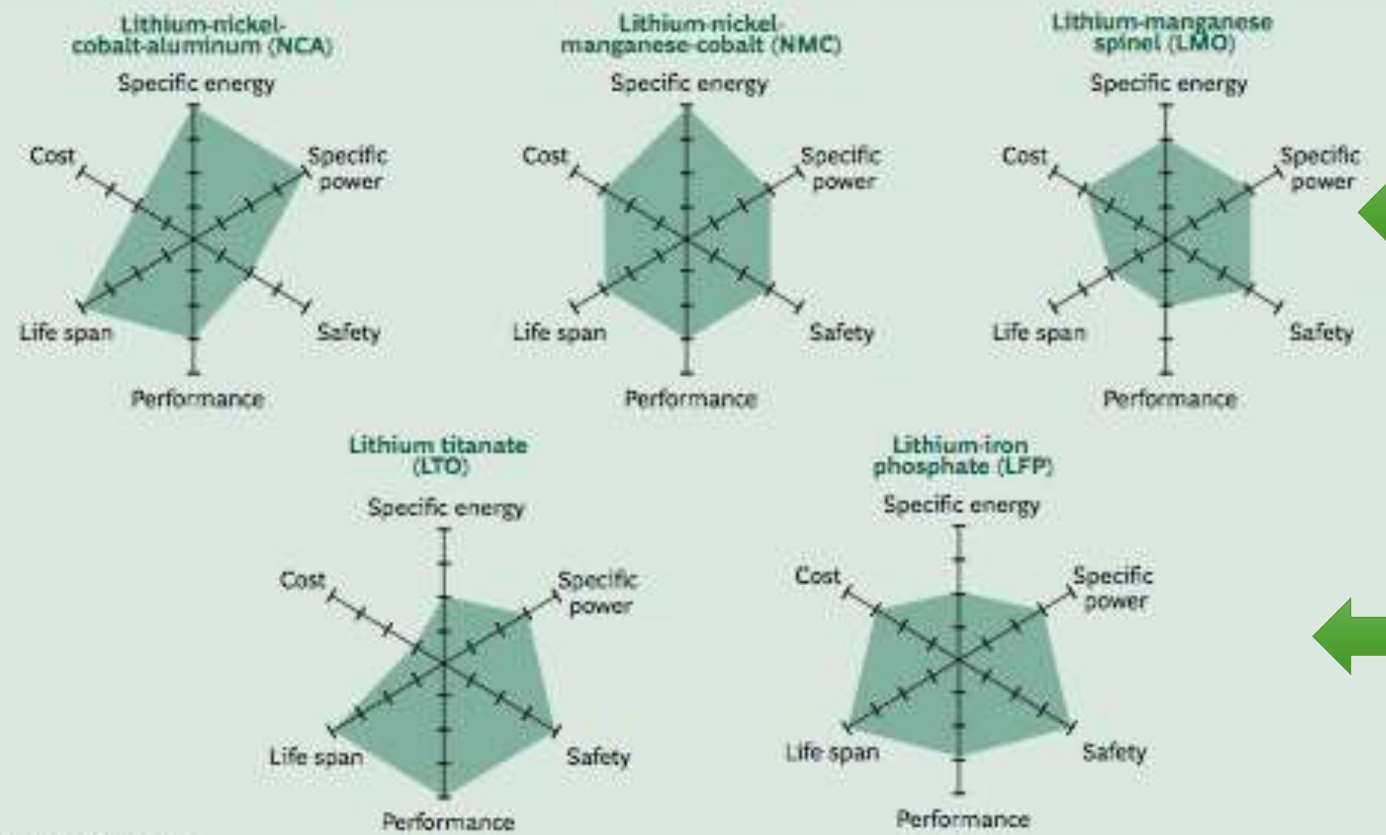
LITHIUM ION BATTERY

Li-ION BATTERY MATERIALS



C&EN, July 15, 2019

Exhibit 2. There Are Tradeoffs Among the Five Principal Lithium-Ion Battery Technologies



Source: BCG research.
Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.

Used for mobile power storage; High energy +power density

Used for stationary grid power storage; High power density

Global Lithium Reserves

(Spodumene and Petalite)

No decent resources of Lithium !

Reserved Resources	In Metric Tons
Bolivia	**9,000,000**
Chile	**7,500,000**
China	5,400,000
US	4,000,000
Argentina	**2,600,000**
Brazil	1,000,000
Congo	1,000,000
Serbia	1,000,000
Australia	630,000
Canada	360,000
Total	32,490,000

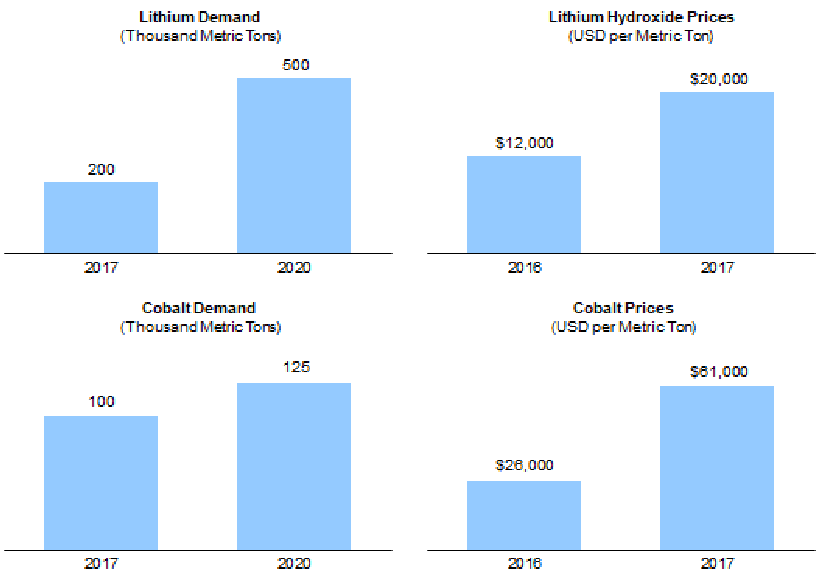
From Organisation of Petroleum Exporting Countries (OPEC) to Organisation of Lithium Exporting Countries (OLEC)

Source: Bottled Lightning-Super Batteries, Electric Cars & New Lithium Economy by Seth Fletcher, Hill & Wang, NY (2011).

Global recoverable Lithium reserves - 4 million tonnes.

Strain Geopolitical relations.

LITHIUM AND COBALT : DEMAND AND PRICES



2019 : US $ 75,000 per ton

CLEAN ENERGY MATERIALS : LITHIUM AND COBALT

- Current battery technology for mobile applications uses 20 % cobalt, 50 % nickel, 20 % manganese and 10 % lithium

- The world demand for lithium for battery application is about 80,000 tpa today and will increase to 100,000 tpa by 2021. Supply of lithium is from four countries, Chile (52% of global reserve), China (22%), Argentina (14%) and Australia (11%) and is controlled by four MNC's. The global reserve of lithium will last only for about 75 to 100 years at today's rate of consumption !

- Congo accounts for greater than 70 % of cobalt production and is controlled by two MNC's, one of them Chinese. Cobalt based NMC is the work horse battery cathode for electric vehicles and also for the 5G technology for mobile phones

WIND ENERGY

SUSTAINABILITY OF WIND ENERGY

- One megawatt of wind turbine installation requires about 100 tons of steel, 400 tons of concrete, 7 tons of fibre glass and several other materials (polymers, copper, cast iron) etc

Unintended Consequences

- Windmills tend to colonize hills and ridges and pose a threat to low flying birds (e.g the great Indian Bustard)
- 30,000 birds are killed by windmills in Denmark per year
- End-of-life disposal issue of windmills; life time of a windmill ~ 20 years

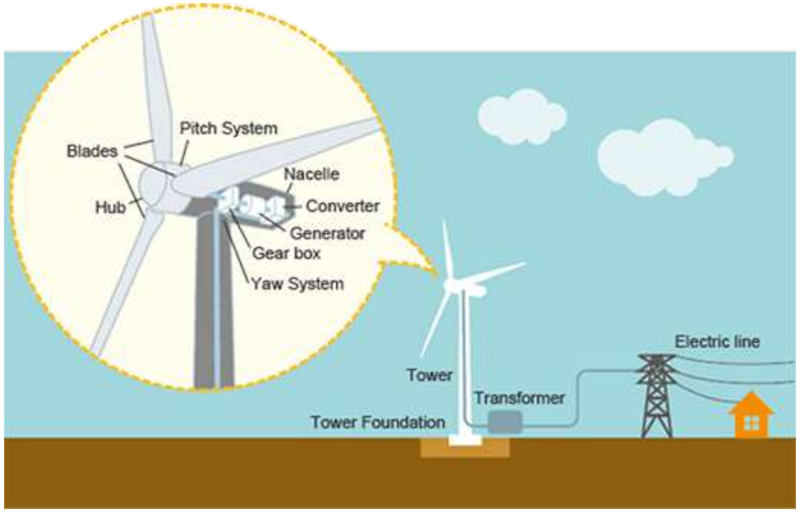
ELEMENTS IN A WIND MILL

Metal	Geared	Direct Drive
Aluminum	x	x
Chromium	x	X
Copper	x	x
Iron	x	x
Lead		x
Manganese	x	x
Rare earths		x
Nickel	x	x
Steel	x	x
Zinc	x	x

Geared wind mills are used on land; direct drive are used in oceans; 30 % of windmill are direct drive and balance is geared. Maintenance costs are higher for geared wind mills

CLEAN ENERGY MATERIALS : RARE EARTHS

- Nd, Pr and Dy are used as permanent magnets in electric generators in direct drive wind mills
- We consumed 9500 tons of rare earths in 2011-15 for this application. This is projected to increase to 100,000 to 230,000 tons by 2050
- We will need 80,000 to 175,000 tons of Nd alone by 2050. For every I ton of Nd we will need 0.25 tons of Pr
- Global wind energy capacity is expected to be around 2900 GW by 2050, from the present capacity of 600 GW



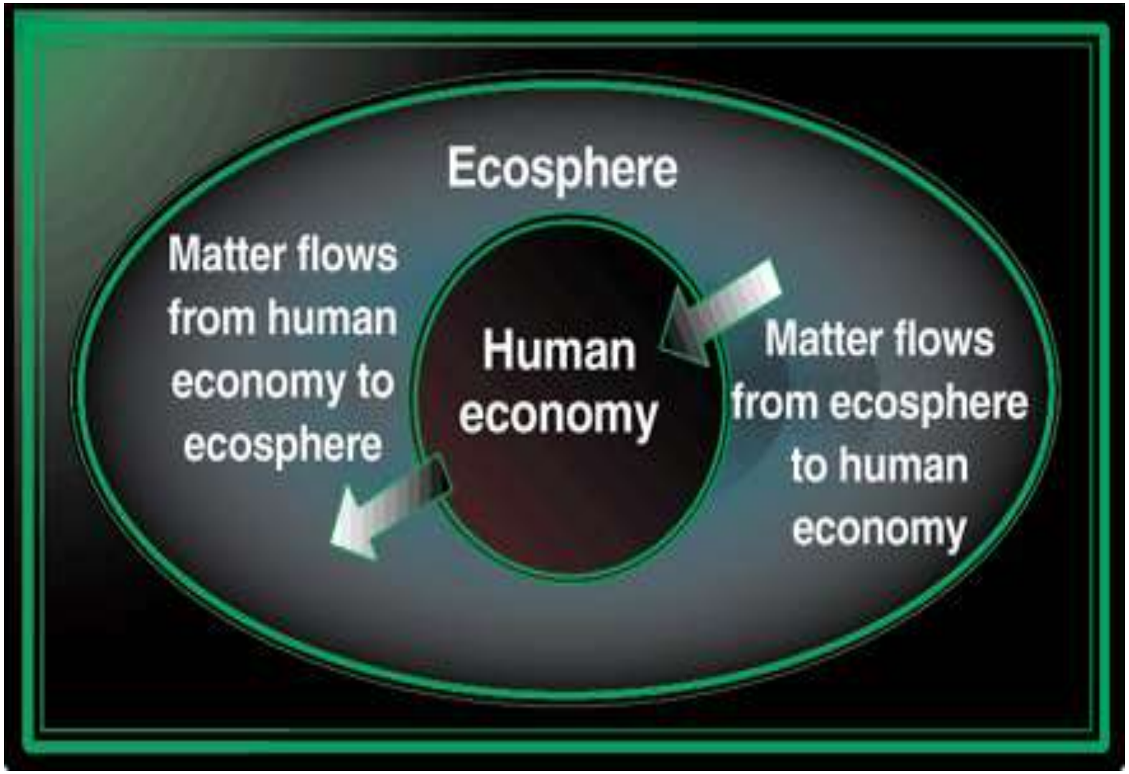
J. *Li et.al, Critical rare earth elements mismatch global wind power ambitions, One Earth, 2020, 3, 116*

CLEAN ENERGY MATERIALS : RARE EARTHS

- Global production of RE: 125,000 tons per year (2015); 85 % from China
- World reserves of RE: 125, 000,000 tons; more than 50 % found in China and Brazil
- India produced 1600 tons of RE in 2015. To keep pace with projected increase in wind power, we will need 30,000 to 60,000 tons of RE by 2050
- Mining of rare earths is beset with problem of dealing with associated radioactive wastes in effluent water, gaseous emissions and tailings. Plants in USA and Malaysia closed down due to rising public awareness and concerns of radioactive contamination in water
- Additionally good technology for reducing rare earth oxides to metals is still elusive

KEY TO SUSTAINABILITY

- The present economy remains utterly dependent on a massive inward flow of natural resources. This is followed by a reverse flow of economically spent and dilute matter back to the ecosphere.
- Sustainability problems are determined largely by these economy-ecosphere material flows which is linear in fashion



Collins T. Towards sustainable chemistry, Science, 2001; 2919(5501); 48-49

URBAN "ANTHROPOGENIC" MINES (URBAN MINING): RESOURCES IN OUR WASTE

- Mobile phone , one phone per person, average use per phone ~ 2-3 years
- 250,000 tonnes of unprocessed Li ion battery waste will be produced when the electric cars sold in 2017 reach the end of their lives
- End-of-life automobiles: Platinum and Cerium (catalytic converters) Gold, Neodymium and other rare earths. In fact there are 28 elements in a modern automobile!
- LED bulbs and lighting accessories

Urban mine platform http://www.urbanmineplatform.eu/; Recupel Annual Report: http://annualreport.recupel.be/en/2016#recycling-figures; Chem.& Ind., July 2018, p.22; Chemistry World, April 2017, p.18

CIRCULAR ECONOMY: RETHINKING THE SYSTEM

- The circular economy model is a different way to think about production and consumption that changes the linear “take, make, dispose” model to one that is restorative and regenerative by design.
- Designing and implementing circular economy processes into production and design of products and services offers significant long-term advantages.
- Circular economy models can help reduce the need for virgin materials, help find new markets for by- products, and offer better connections to consumers.

CLOSING THE CYCLES

- **The Elements cycle**
- The Carbon dioxide cycle
- The Hydrogen cycle
- The Carbon cycle
- The Nitrogen cycle
- The Phosphorous cycle
- The Fuel cycle

Our ability to understand and close these cycles is critical for sustainability of resources on planet; where it is not feasible or practical to close the cycles, we need a deep introspection

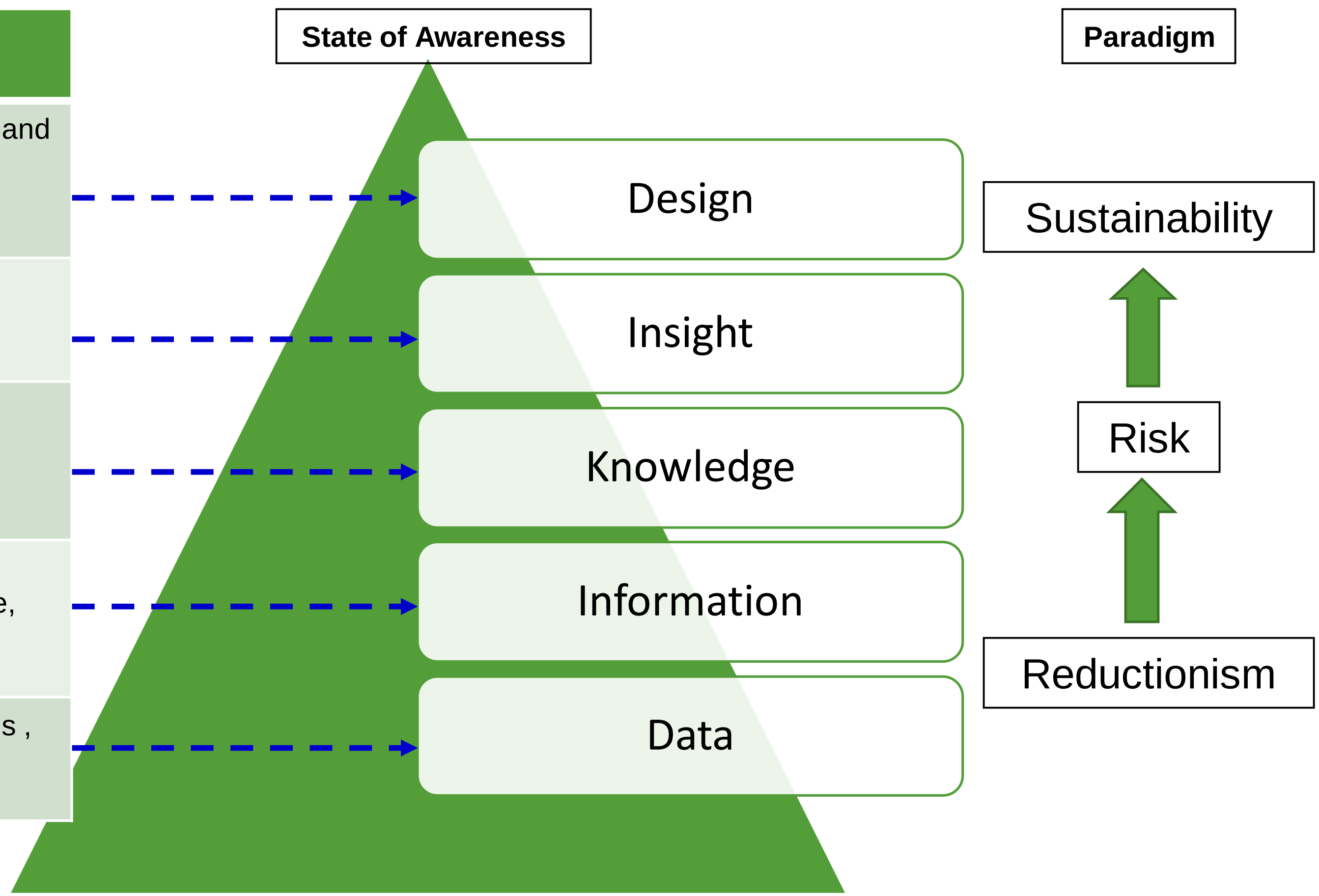
SUSTAINABILITY: BEYOND REDUCTIONIST THINKING

- Sustainability is a systems challenge, requiring a combination of reductionist approaches and integrative systems and design thinking
- Therefore sustainability is a "Complex" problem
- Climate change, depleting natural resources, generation of hazardous wastes and introduction of chemicals and materials with human and eco-toxicity are unintended consequences of the focus on reductionist approach
- We live in a fast changing dynamic world. Therefore our approach to solutions must also be dynamic and adaptive.

A. Azapagic and S. Perdan, Sustainable chemical engineering :Dealing with the "wicked" sustainability problems, AIChEJ, 2014, 60, 3998; P.T. Anastas, Trends in Chemistry, May 2019, Vol 1, p.145

INTEGRATION OF REDUCTIONIST APPROACH WITH SYSTEMS THINKING

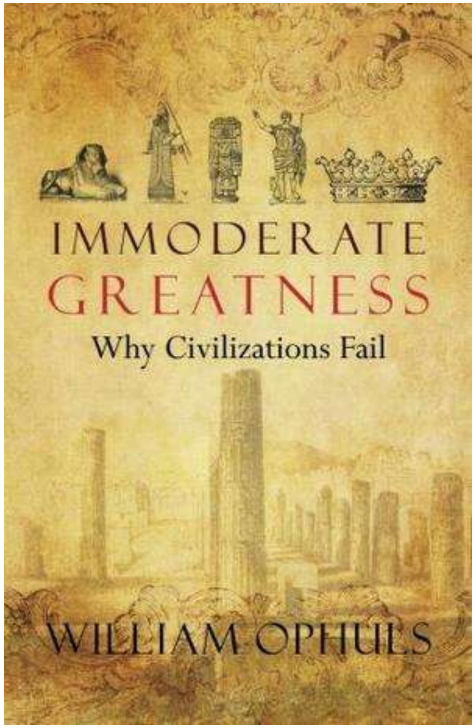
Approach	Tools
Maximize benefits, pursue wellness	Green chemistry and engineering
Manage and minimize risk	Environmental sciences and remediation
Assess risks and predict impacts	Chemical risk assessment, genetics, susceptibility
Model and study effects	Toxicology, exposure science, observational studies
Measure and monitor concerns	Chemical analysis , environmental assessment



P.T. Anastas, Trends in Chemistry, May 2019, Vol 1, p.145

THE PERILS OF UNBRIDLED CONSUMPTION

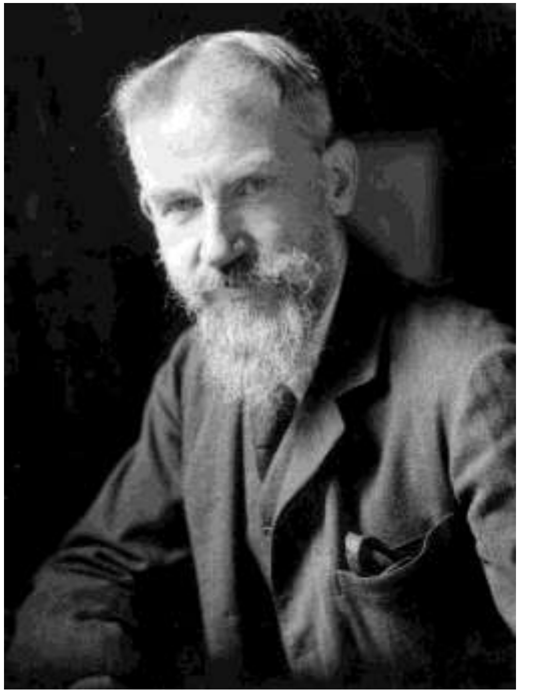
- Civilizations progress by over-exploiting renewable and non-renewable resources
- In the process, they convert ecological wealth into economic wealth. As the bubble expands, a spirit of “irrational exuberance” sets in
- As the economy booms, he ecology disintegrates. We tend to see the natural world as a source of inexhaustible resources; we do not comprehend the power of exponential growth
- Human mind is incapable of perceiving the longer term future and the consequences
- A mature civilization is caught in an entropy trap from which It cannot escape. Because the available energy and resources can no longer maintain the existing level of complexity, it begins to consume itself by borrowing from the future or feeding off the past. As massive demands conflicts with dwindling supplies civilizations begin to implode
- We belong to a complex adaptive system whose stability depends on a delicate equilibrium; When they are overstressed, they become unstable and can collapse abruptly



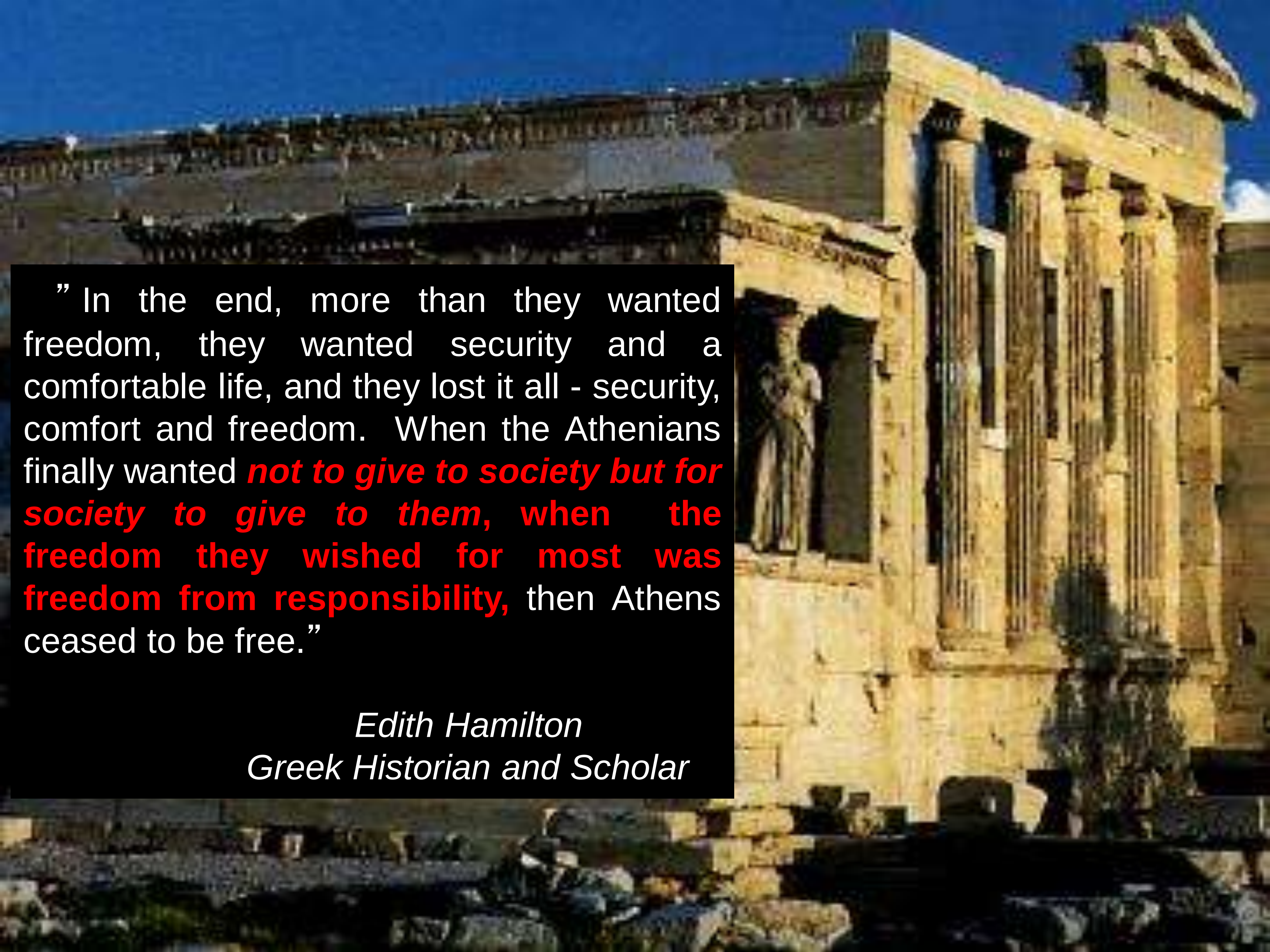
2012

Humans in this “complex” adaptive eco-system can control almost nothing, yet can influence everything

We are made wise not by the recollection of our past, but by the responsibility of our future



George Bernard Shaw
(1856-1950)



" In the end, more than they wanted freedom, they wanted security and a comfortable life, and they lost it all - security, comfort and freedom. When the Athenians finally wanted ***not to give to society but for society to give to them*****, when the freedom they wished for most was freedom from responsibility,** then Athens ceased to be free."

Edith Hamilton
Greek Historian and Scholar

IISER PUNE

THANK YOU