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BOOK REVIEW: *POWER DENSITY, A KEY TO UNDERSTANDING ENERGY SOURCES AND USES*[1]

HIGHLIGHTS

- Power density—expressed in a form that accounts for the spatial requirements of energy extraction, conversion, and use—is critical to understanding paths forward for energy transitions.
- Physical space matters in the calculation and consideration of impacts, beginning with the fuels we use in our energy systems.
- It is impossible to achieve full conversion from today's energy system to a fully renewable system within 15 to 35-years, the timeframe of many countries' current GHG reduction targets.
- It would more effective to focus on the three conditions and investments necessary for a future renewable energy system:
  - a marked increase in the efficiency of all final energy uses;
  - discovery and use of large-scale electricity storage to manage challenges with renewable flows; and
  - support for innovations aimed at affordable use of electricity to produce liquid fuels.

INTRODUCTION

Energy is a complex and often contentious topic. By the most basic definition, energy is the capacity of a physical system to perform work. Most of us have an intuitive understanding of energy: we eat food to fuel our bodies; put gasoline in our cars and trucks to enable travel; use electricity to run our appliances and manufacturing facilities; and rely on natural gas to heat our homes. We think and talk about energy as if it is a tangible object. The formula for energy is expressed as:

Work =
Force x Distance x the angle of the force and distance

At times, we confuse the term power with electricity. Power is the rate (measured in time) at which a physical system performs work. It is applicable equally to all forms of energy. The formula for power is:

Power = Work / time

We also tend to misunderstand the difference between primary and secondary energy sources. The former are found in nature and can be used in their direct form to do the necessary "work." Primary energy sources include coal, natural gas, oil, uranium, solar, wind, geothermal, water, and biomass. Secondary energy is a transformed primary source; the most common example is electricity.

Harnessing energy has been a pursuit of humankind throughout the ages. Energy is the "oxygen" in modern and emerging economies, highly valued for the activities and services it enables. We spend significant time thinking about and assessing energy availability, reliability, affordability, accessibility (and equity), and

[1] Vaclav Smil, Professor Emeritus, University of Manitoba.

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the environmental footprint from extraction, conversion, and use.

Our current obsession with energy is related to concern over the impact of greenhouse gas emissions from fossil sources (e.g., coal, oil, natural gas). What we have so far chosen not to do, either deliberately or by omission, is to compare energy across all its forms in an apples-to-apples way that gives insight into both qualitative and quantitative differences. As such, we fail at conversations about the true issues, impacts, and trade-offs involved in energy choices — how we got here, where we are going, and the cost and timing of alternate energy paths.

Professor Vacliv Smil's book provides a quantitative measure to facilitate the conversation — **power density** (PD). The calculation captures the land or water surface used (m^2) — spatial considerations. The formula is simple:

$$PD = \text{Watts/meters of land squared} = W/m^2$$

This measure enables comparisons of a "*variety of energy fluxes ranging from natural flows and exploitation rates of all energy sources (be they fossil or renewable) to all forms of energy conversions (be it the burning of fossil fuels or water or wind driven electricity generation)*".[2] His extensive bottom up analysis is concrete. The examples he illuminates through history anchor the analysis in the human experience rather than theoretical possibilities. The book provides easy-to-understand calculations, progresses in a logical manner, and provides an understanding of spatial power density. The ideas are a valuable contribution to current discussions about the place and shape of the current global energy system and where we might be heading, particularly in light of the significant economic, environmental, and social trade-offs of change. In fact, of all the measures we can use, power density is "*one of the most crucial parameters that predetermine[s] the structure of energy systems.*"[3] Yet we have not paid much attention to the spatial construction of our energy systems. As a result, the global conversation about the possibilities, costs, and timing of energy transitions is neither comprehensive nor complete.

WHAT IS POWER DENSITY?

Demonstrating the general applicability of a land area-based power density measure begins with a history lesson – starting in 1548, with the invention of the steam engine. British society of the day had concerns about wood supply, used for everything from house and ship building, to charcoal in iron mills. The land requirements were massive and the supply of wood insufficient to support the multitude of competing needs. For example, the typical 1700's British iron smelting furnace producing 12,000 t of bar iron required a wood supply from an area 32 km by 32 km in size (~1,000 km²), an area roughly 9 times the size of the City of Vancouver. Clearly unsustainable, the switch to coke — coal transformed via pyrolysis — enabled a 100-fold expansion of the iron smelting industry by the mid-1850s; this industry has yet to reach its peak. The transition from wood charcoal to more energy-dense coking coal reduced the environmental impacts from human activity. Clearly, the environment and the economy both benefitted from technological innovation and fuel-switching to a more power-dense form of energy (see table 1); it also saw an improvement to the quality of life.

The spatial element of energy sources is key to understanding both power densities and the possibilities for energy transitions — their speed and likelihood — in today's context where many want hope for a low carbon future. The bulk of the book's narrative is a detailed

TABLE 1: **COMPARISON OF POWER DENSITY OF CHARCOAL AND COKE (MID-18TH CENTURY)**

Charcoal	0.22 W / m²
Coke	500 W / m²

[2] *Power Density, A Key to Understanding Energy Sources and Uses*, P. 21.
[3] *Power Density, A Key to Understanding Energy Sources and Uses*, P. viii.

assessment and comparison of various renewable and fossil fuels as both primary and secondary energy sources, coupled with a revealing discussion of energy uses. Professor Smil reminds us of some forgotten and fundamental laws, namely those of thermodynamics,[4] and the fact that power densities of all final energy uses are also the power densities of heat rejection. This is important, because we tend to think of technology like microprocessors (green business) as benign, small users of energy. But in fact, the smallest energy users have the highest heat rejection and therefore the highest energy need for cooling. As we incorporate more and more energy intensive technology into our economies the need for power dense energy will increase.

We must keep this in mind when thinking about future economies filled with new energy use equipment that requires as high, or higher, power densities than the equipment that exists today, also keeping in mind our desire for ubiquitous renewables. There is an inverse relationship between the power densities of renewable energy (tables 2 and 3) and the ever increasing energy requirements of modern economies.

Humanity has always been in the process of seeking and transforming energy sources to improve the quality of life.

TABLE 2: **POWER DENSITY BY ENERGY SOURCE OR COVERSION PROCESS**

Energy source or Conversion Type	W/m²
Biofuels	0.3
Wind Turbines	1
Water	3
Solar	5
Electric Transmission	30
Geothermal	50
Wind Footprint	50
Hydrocarbon Pipelines	300
Nuclear	500
Coal	1,000
Crude Oil	1,000
Fossil Fuel Electricity	1,000
Natural Gas	2,000

WHY IS POWER DENSITY IMPORTANT TO UNDERSTAND?

The world is in the midst of a global conversation about energy transitions to a low carbon future. In 2010, the book suggests a renewable energy supply of 130 GW, requiring 270,000 km² of land (or 2,076 km²/GW) with 0.5 W/m². The most recent Renewables 2015, Global Status Report[5] suggests there is now 1,712 GW of renewable energy supply, a 13 fold increase. Given the nuances of calculating land requirements by the type of energy source, a simple extrapolation (e.g., 2,076 * 1,712) is not an appropriate way to arrive at the new total spatial requirements for today's renewables. But it is

TABLE 3: **LAND REQUIREMENTS POWER DENSITY BY FUEL TYPE OR COVERSION PROCESS**

Fuel or Conversion Type	km²
Biofuels	263,300
Water	131,700
Electric Transmission	58,000
Wind Turbines	40,000
Hydrocarbon Pipelines	27,000
Fuel Transportation	27,000
Fossil Fuel Extraction	12,000
Crude Oil	5,400
Coal	4,700
Other (sum of list below)	8,900
Thermal Electricity Generation	*2,100*
Natural Gas	*1,800*
Fossil Fuel Electricity	*1,500*
Crude Oil Refining	*1,000*
Wind Footprint	*800*
Solar	*600*
Nuclear	*600*
Geothermal	*200*
Tanker Terminals	*200*
LNG Terminals	*100*

clear that, absent a dramatic leap in innovative technology, there is a current and growing increase in land requirements for renewables, all of which conflicts with the collective desire for more protected land areas, an increasing global population (which puts exponential pressure on land required for food production), and an ever-more diverse set of energy-using technologies. Given that the next generation is set to inherit today's infrastructure, "*two or three orders of magnitude more*

[4] First Law: energy cannot be created or destroyed in an isolated system (law of conservation). It can be converted to a different form and all of the conversions eventually end in dissipated heat. Second law: entropy of any isolated system always increases (the measure of a system's thermal energy per unit of temperature that is unavailable for doing useful work). Third law: entropy of a system approaches a constant value as the temperature approaches absolute zero.
[5] Renewable Energy Policy Network for the 21st Century, www.ren21.net/wp-content/uploads/2015/.../REN12-GSR2015_Onlinebook_low1.pdf.

space [is needed] to secure the same flux of useful energy if they are to rely on a mixture of biofuels and water, wind, and solar electricity."[6]

> *"Converting the entire global harvest (1.69 Gt in 2010) to ethanol would yield 105 GW, merely 3% of the global liquid fuel demand in 2010. Production of the world's 2040 liquid fuel demand (4 TW) would require 800 Mha of the crop [sugar cane], which would take slightly more than half of the global cropland and about 50% more than all the tropical and subtropical farmland suitable for cane cultivation."*
>
> *Power Density, A Key to Understanding Energy Sources and Uses*

ENERGY TRANSITIONS

In today's debate about greenhouse gases and climate change, the final chapter in the book is the most relevant and thought provoking. Humanity has always been in the process of seeking and transforming energy sources to improve the quality of life. Transitions have been long and protracted, starting with the discovery of fire 1,000,000 years ago, and arriving at the modern industrial era beginning in 1850, still underway – a scant 166 years of modern life. Against this backdrop, Professor Smil argues—rather controversially—there are only two near-term solutions: nuclear energy and large scale CO_2 capture and storage. Only the former is proven and deployable. But the global dialogue mostly excludes the nuclear option as public opposition is great in many places.

The book's closing chapter provides evidence to support the impossibility of a full conversion from today's energy system to a fully renewable one in a 15 to 35-year timeframe. The spatial (land) requirements are enormous and, while an admirable goal, there are some energy uses that cannot be met with renewables, such as biofuels for aviation. The power densities are too low regardless of any increases in biomass yield or conversion efficiencies, and ironically the amount of land required (an expansion from today) has the opposite outcome in terms of GHG emissions. Even Canada, with an inheritance of land to accommodate the spatial requirements of renewables, will still find it challenging without substantial changes in technology and the pressures from high power densities of final energy uses.

> *"Modern civilization is thus a material and intellectual embodiment of converting fossil fuels into the useful energies of heat, electricity, motion, and chemical potential."*
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> *Power Density, A Key to Understanding Energy Sources and Uses*

Ending on an upbeat note, *Power Density, A Key to Understanding Energy Sources and Uses* describes the three conditions necessary for future renewable energy systems:

- Increased efficiency in all final energy uses
- Large scale electricity storage to manage the problems with renewable flows
- Affordable means of using electricity to produce liquid fuels.

These are significant challenges, but also point to areas where we need investments of both intellectual and financial capital. The physical space needs of renewable energy matter. Remarkably, humanity seems to have forgotten this fundamental feature of energy systems. The conversation about energy systems and GHG emissions reductions in this context just got a little bit harder.

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[6] *Power Density, A Key to Understanding Energy Sources and Uses*, Chapter 7, p 208.