Jesse Ausubel, Breakthrough Dialogue East, 17 Nov 2017

The question for our panel is the origin of energy transitions. I might re-phrase the question as "Does energy policy matter?" My essential point is that strong constraints greatly reduce the freedom of strategists.

Let me begin with a transition from American history known as Manifest Destiny. The term, first used in 1845 by a journalist, referred to the continuing westward territorial expansion of the United States through conquest and purchase, or, I would say, diffusion. Maps which all of us saw in school show the major spatial changes, encompassing the transition from colonial settlements with foot paths into the forests to a nation integrated by transcontinental railways, interstate highways, gas pipelines, and electricity grids.

Five years ago we plotted the areal growth of the USA like the growth in height of a sunflower. The fit is beautiful, over 250 years, through wars, depressions, epidemics, and other disturbances. Thomas Jefferson as well as Lewis & Clark and Sacajawea were actors in a play. Obviously, technologies such as the railroad and telegraph and associated institutional developments had to come to fruition to allow control.

Most people, whether generals or bandits, like to believe they are decision-makers, not the blind executors of a blind but all-powerful fate. In Greek mythology all gods reported to Zeus, but *tuchē* or fate – abstract, invisible, and all-pervasive – ran the system, Zeus included. Americans still have much to learn from the ancient Greeks.

Before zooming to energy, let me introduce a general concept about how systems grow and evolve. Systems grow by substitution, by mutation and selection, by evolution. Evolution is a series of replacements. An innovation, a mutation, enters the picture and if fitter gains a share of the ecological niche or market. Often the substitution process follows an s-shaped curve. A familiar example is recording media, where tapes overtook long-playing records, and in turn CDs replaced tapes, and MP3s and systems of downloading and streaming have now overtaken CDs. The superior competitor spurs system usage to grow.

Now to energy. The explanation for the long-term pattern of growth of the energy system is simple. The evolution of the system is largely driven by the

increasing spatial density of energy consumption at the level of the end user, that is, the energy consumed per square meter, for example, in a city. Finally, fuels must conform to what the end user will accept, and constraints become more stringent, as spatial density rises. Rich, tall, dense cities accept happily only electricity and natural gas, and, incipiently, hydrogen. For about 150 years, until about 1990, the substitution of hydrogen for carbon in the energy system, and from wood & hay, to coal, to oil, to gas, and the resulting decarbonization, beautifully described the ongoing energy transition.

About a generation ago, humans managed to stall decarbonization through a series of incredibly contrived energy policies. Had the energy system not become so self-conscious, it would probably be far closer to its destiny today.

But finally, after many rationalizations, supply systems that benefit from economies of scale will produce the lion's share of the electricity and gases. If you might dismiss scale, think of Facebook, Amazon, and Google, or Samsung and Alibaba. In a society of flash trading and flash mobs, perfect power, that is, ultra-reliable electricity, also wins in the Darwinian game.

Planning and R&D should essentially support the invariants in the system. Importantly, one can avoid the wild, painful excursions around the trends often proposed and organized by politicians and stakeholders. In the case of the USA, the policy prescriptions for energy supply are simply: favor natural gas (with some capture and sequestration), nuclear, and hydrogen. Although few notice, USA hydrogen production is climbing nicely. And fuel cells, engines on hydrogen, will multiply their market, as General Motors and other automakers understand.

On the demand side, we naturally seek to raise the rates of efficiency gain, to shrink usage, to decouple energy from GDP and carbon from BTU. A key is to focus on systems and practices with big upsides, such as the share economy which can lift capital utilization, and magnetically levitated trains, which carry neither engine nor fuel and thus weigh far less per kilo of passenger than traditional cars, trains, and planes. Understanding the trends and rules may lead humans to devise a more coherent, restricted, and useful set of possible courses than we have done.

Historians traditionally view their subject as unfolding in an essentially random way, contingent upon the violent, retributive whims of a citizenry and the political machinations of a handful of influential individuals. But, history is more

accurately seen through a more deterministic lens in which it obeys its own internal logic, unbeknownst to those staffing the think-tanks or Sandinistas.

Let me add a philosophical note. We feel a freedom of decision inside ourselves, which economists and politicians assume as sacred dogma, in the face of the obvious determinism of many global or national outcomes such as Manifest Destiny. The situation fits the famous analogy between the somewhat free and unobservable behavior of single molecules and the beautifully clean pressure-volume relationship in a gas on a macroscopic scale. The determinism and feeling of liberty may not be contradictory. For example, the system requires the kamikaze behavior of entrepreneurs to evolve.

But in the end we all feel the breath of fate. Most of the energy transition is pre-programmed. Don't forget the system. It won't forget you.