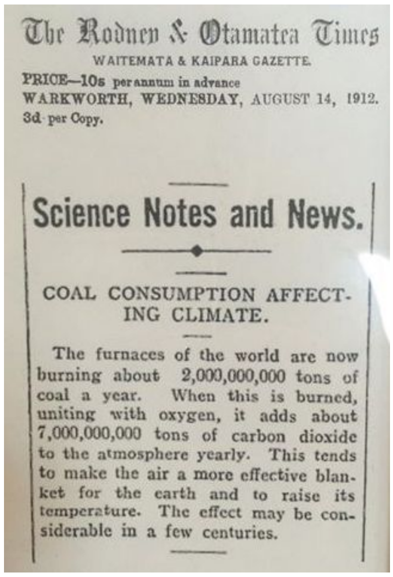
The Energy Transition through a Complexity Lens

Peter M.A. Sloot, Roland Kupers and Bob van der Zwaan
Institute for Advanced Study, University of Amsterdam
Amsterdam, September 2019

Climate change is an old story

A century ago, in March 1912, a remarkable article by Francis Molena in the journal 'Popular Mechanics' discussed the effect of the combustion of coal on the climate. In the same year the *Rodney and Otamatea Times, Waitemata and Kaipara Gazette* from New Zealand included the headline "Coal Consumption Affecting Climate". These observations were among the first tell-tales of the intricate coupling between humans and natural systems.


The Rodney & Otamatea Times
WAITEMATA & KAIPARA GAZETTE.
PRICE—10s per annum in advance
WARKWORTH, WEDNESDAY, AUGUST 14, 1912.
3d per Copy.

Science Notes and News.

COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

One important difference with other environmental issues such as the ozone hole or the 20th century pollution of Europe's rivers is that mitigating climate change touches many societal systems. Dealing with the ozone hole required interventions in only a few industries that were relatively isolated. This is not the case with climate change mitigation, which impacts vastly more societal and economic systems, which are in turn deeply interwoven with each other and the environment: construction, agriculture, social norms, IT, power, transportation, consumption, inequality etc.

However, the good news is that in the past couple of decades we have made remarkable strides in understanding the dynamics of such deeply interconnected systems. The research field that studies this is now known as complexity science, following the root of the word 'plexus' which means 'braided'. Complexity is the science of braided, or interconnected systems. These systems display endless signatures of order, disorder, self-organisation, tipping points and self-annihilation. Understanding complexity is one of the biggest scientific challenges of our time. In the past couple of years, the Netherlands scientific institutions, like the UvA Institute for Advanced Study in Amsterdam, have quickly expanded their complexity competence.

The challenge we are facing is clear, and there is a high degree of consensus: as reflected in the Paris Agreement, we need to realise net zero CO_2 emissions in 2050 in order to have a two thirds chance to reach the 1.5°C maximum average temperature increase target over pre-industrial times [IPCC 2018]. Therefore, our global energy system, hitherto largely based on the combustion of CO_2-emitting fossil fuels, needs to be subjected to a fundamental transformation, commonly referred to - in the Netherlands - as the 'energy transition'.

In many ways the term energy transition may be misleading, as it suggests that only the energy system requires changing. Terms such as the Green New Deal in the US, or the Chinese vision of an Ecological Civilization, or the European Green Deal, better capture the systemic nature of the challenge. These terms imply that the problem is much broader than simply changing the energy system, and signal to society that many more systems will be impacted. Climate activists intuitively grasp this when they call for

Published: https://www.rijksoverheid.nl/documenten/publicaties/2019/11/27/essay-de-energietransitie-door-een-complexiteitsbril

"Systems Change not Climate Change". But how does one translate such slogans into real-world policy?

In the Netherlands, much of the energy transition challenge lies in urban areas. While nature takes raw energy from the sun, transforms it into life, cools the Earth, cleanses water, absorbs CO_2 and releases oxygen, cities do the reverse. We have transformed from rural individuals consuming 300 Watts into voracious city dwellers gobbling up 11.000 Watts. And worldwide there are now more people living *in* cities than *outside* of cities [UN 2007; Pop 2007]. This has a consequence for all aspects of life. From the physical, to the biological, to the sociological, psychological and political, everything is intertwined and affected. It is the interplay between all these components that makes the energy transition a truly complex problem. However, reducing the energy transition challenge to its components will make us miss the very aspects we are looking for. We need an integrative, all-inclusive approach.

The urgency of the problem

The time is now, because our geopolitical world is quickly altering the way in which we live. China, for instance, with its Belt and Road Initiative, is rapidly penetrating our social, economic and energy infrastructure. With China having soon accomplished its transformation into one of the world's major economic, technological, political and perhaps also cultural powerhouses, other regions will likely follow suit. In a few years India will be the most populous country in the world, and its economy currently grows with a rate similar to that of the Chinese economy during recent decades. As a result, India will probably have turned into one of the world's main players in economic, political and strategic respects in one or two decades from now. Likewise, Africa has, during recent years, embarked on critical socio-economic changes. Not only in terms of for instance demography and economy, but also in the field of energy. Climate and the environment cannot be factored out anymore from the global power equation by 2050 or earlier [van der Zwaan 2018]. All these developments have important bearings on the global energy transition.

We know that some elements will certainly play a role in the required energy transition up to 2050, including the large-scale deployment of renewable technologies such as those based on biomass energy, and solar and wind power [IPCC 2014; IEA 2018; IRENA 2018; IPCC 2018]. Such strategies require further elaboration, like how precisely we are going to eliminate emissions of greenhouse gases from industry, whether electrification will suffice to obviate CO_2 emissions from the road transport, and by what means we can decarbonise aviation and shipping. Even more challenging will be to find solutions for the conundrum that after (or perhaps even before) 2050 substantial net *negative* CO_2 emissions need to be realised in order to comply with the ambition of not letting the increase in atmospheric temperature surpass 1.5°C [Detz 2019]. A net negative balance of CO_2 emissions necessitates that the amount of CO_2 annually removed from the atmosphere exceeds the quantity that humans deposit into it every year.

What distinguishes a complexity approach?

Complex systems have *emergent properties*. These are collective system-level properties that are not entirely determined by the individual agents in the system, but also by the structure and dynamics of the system itself. A familiar example is when phantom traffic jams arise: notwithstanding sufficient road capacity, the interconnections between individual drivers give rise to congestion. This appears spontaneously and random, but it can be modelled, understood and mitigated. Another example concerns obesity: complexity scientists have established that this is largely a network phenomenon and

not simply the sum of individuals who eat too much and exercise too little [Christakis, 2007]. This implies a very different approach from legacy policy that focuses on individual behaviour, to intervention policies that aim at changing the structure of the contagion network.
More generally, in climate policy we are interested in changing the emergent properties of socio-economic systems. This requires an understanding of how this emergence occurs in the first place, and how it may be influenced. Through parallel experiments, we can find ways to assess possible future states following various intervention hypotheses, as well as methods to translate the successful interventions into adaptive policies.

Complex systems behave in highly *non-linear* ways. One of the basic consequences of intervening in complex systems is that the system will adapt, either instantaneously or with a delay, to the intervention and possibly steer the outcome of it in totally unpredicted and unwanted ways. Much like discussions on reducing natural gas consumption that might actually kick-start a revival of coal mining. The main reason for this unpredictable behaviour comes from the fact that we are dealing with a range of intertwined infrastructural, social and political networks that operate on non-linear spatial and temporal scales. In complexity science such systems are studied by quantifying the dynamics of processes operating *on* the networks and structural changes *of* the underlying networks [Sloot 2013].

While traditional scientific reductionist approaches put the elimination of *uncertainty* at the core of their efforts, complexity redefines the domain of complex dynamic problem solving as 'decision making under irreducible uncertainty'. The belief that more data will necessarily reduce uncertainty does not hold for complex systems. More data often means more noise. This should not be seen as a plea for ignoring data, quite the contrary, but data can only be interpreted through testing a hypothesis that represents the causal structure of the data. The data itself does not provide the answer. Moreover, in complex systems micro-random effects will propagate and be amplified to macro-levels and render the system inherently uncertain. But that doesn't mean we don't know anything. Complexity science has focussed on taking systems as they are and uncovering what is knowable about their evolution.

Unlike the more traditional 20th-century way of academic exploration and reductionism, complexity science has booked substantial progress in understanding some of the world's most pressing problems and most intricate questions. For example, by taking a Bayesian approach to understanding what makes a situation controllable, or makes it appear controllable to a problem solver, and hence what cognitive, social and psychological factors are brought to bear on the situation [OECD 2017].

A few illustrations

Leveraging network dynamics
Our knowledge of the behaviour of networks has advanced considerably. This could provide relevant insights for policy decisions. For example, the spread of the adoption of solar panels is well documented to be a network phenomenon, but only specific knowledge of the structure of the network within specific Dutch geographies and population groups can point the way to accelerating the network effects.
Networks evolve over time and show a remarkable robustness and resilience to interventions. Examples are protein-protein networks [van Dijk 2010], slime-mold networks [Adamatsky 2013], phylogenetic-social networks [Zarrabi 2013], sexual networks [Mei 2011] and criminal networks [Duijn 2015]. This robustness and

resilience are often realised through dynamic modification of the network topology, as well as the behavioural and functional changes of the links and nodes. The dynamics *on* and *of* the network may emerge from a variety of causes. Yet, they seem to lead to specific classes of behaviour. An important aspect may be resilience with respect to uncertainty and noise. For instance, it has been shown that stochastic resonance in the presence of noise can actually enhance information transfer in hierarchical complex social networks [Czaplicka 2013]. It seems likely that resilience in complex networks has emerged from 'evolutionary' adaptation, but little is known about it. Resilience of complex systems is an open research area.

Recent research has shown that the most effective way to influence the outcome of an intervention in such networks is not by addressing the strongest connected nodes (hubs like influencers in social networks, Kingpins in criminal networks, or highly connected virus spreaders in sexual networks), but intermediate connected nodes, the 'Goldilocks' of the system [Quax, 2013]. But even then, the response of the system remains mainly unpredictable in the long run. What is needed are small interventions on intermediate nodes followed by intensive monitoring of their outcomes, that themselves result in new interventions. That way we can iteratively nudge the system into the required state.

For the energy transition to be successful one could, for example, start with imposing changes in small and medium-sized enterprises, instead of unrolling transition strategies across major industrial companies. By carefully monitoring the side effects of interventions we can learn how the total intertwined system reacts, and apprehend how to steer the outcome in the desired way.

Complexity science could also play a role in investigating how an increasingly heterogeneous and decentralized supply of energy can match intermittent distributed energy demand in an optimal way, and in determining the evolution of energy prices in a complex network of entities that both produce and consume energy services (so-called 'prosumers').

The evolution of social norms

We know from studies that social norms spread and evolve over networks. The energy transition will require social norms to change in many respects, such as in the reduction of meat consumption, in curbing air travel desires and in many dimensions of consumer choice. The approach of changing these norms through top-down state interventions is simply not realistic in an open society. Understanding how social norms are changing and spread will be essential to drive the emergence of different social norms, and will be a more effective approach than trying to change every individual agent [Kupers, 2020].

The economic impact of climate policy

Macro-economics is great for equilibrium systems, or small deviations from it. But it struggles with non-linearity change, such as a financial crisis – or indeed, what is required for the climate crisis. Complex systems are far from equilibrium systems. The macro-economic projections of DSGE policy models, such as GEM-E3, are unlikely to provide even a close approximation of the growth and employment impacts of climate policy [Jaeger et al., 2011]. A complexity approach would include many types of multi-scale modelling, different from and complementary to the integrated assessment models customarily employed to inform policy makers on possible energy use and climate management scenarios.

New developments such as metrics of economic fitness do have the potential to make projections of economic growth in changing economic systems [Cristelli et al., 2017]. These algorithms quantify the path dependence that is embedded in the network of products (and services) that a country produces. This leads to a credible projection of the probabilistic range of economic growth, based on the unique structure of the underlying network. These methods could readily be expanded to include more precise environmental indicators, building on the initial work of [Sbardella et al., 2019].

Being able to describe the growth and employment impact (and its uncertainties) of climate policy is essential for political support. Continuing to use models that are known to be incompatible with the problem is not sensible [Stern 2016].

Changing the energy system by changing other systems
Interconnected systems raise the question how changes in one might influence the other. In particular for climate policy, this translates into asking what changes in peripheral systems could reduce the GHG emissions of the energy system.

It is clear that deriving policies through a complexity lens can lead to plausible solutions that would otherwise not have been considered [Colander and Kupers, 2014]. An early exploration is described in the report "Who is the Wolf? A Systems View of the Energy Transition in the Netherlands" [Kupers et al., 2015], such as autonomous vehicles as a climate, rather than a transport solution, that plausibly loosens social norm and urban design lock-ins.

Conclusion
It seems that the 1912 warnings by Francis Molena were spot on, albeit way too optimistic: we affect the climate not in a few centuries but rather on a scale of mere decades. In this essay we argue that, in order to answer some of the fundamental queries that the required energy transition is posing us, we need to complement more conventional thinking with complexity research, in which all disciplines are involved. Jointly, these distinct academic fields can contribute to resolve one of the largest challenges facing mankind during the 21st century: climate change mitigation. We cannot afford to disregard the lessons learned from complexity science when considering the energy transition challenge.

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