

The Accidental Cathedral

Thoughts on rebuilding the energy system

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Mijnheer de rector magnificus, zeer gewaardeerde toehoorders,

What is sustainable energy? This might seem a simple question if we equate it with renewable energy. Renewable energy is easy to define. That is the energy that we can harvest directly or indirectly from incident sunlight. It is solar energy, in the form of solar panels or solar boilers. It is the power from wind turbines and hydro dams that tap the energy of the weather system. It includes the energy from biomass, which has the unique feature amongst renewables that it can be turned into liquid fuel. Wave, tidal and geothermal energy complete the list. These are the main categories - a simple, relatively short list of energy sources.

But the ambiguity of the word sustainable leads to probing questions if other forms of energy provision should be included or excluded. For instance: does that include nuclear energy, which produces no carbon dioxide, but leaves long-lived nuclear waste and carries operational risks as we see play out so dramatically in Japan this week. Does it include fossil energy with carbon capture and storage? This would be an effective way to deal with the issue of CO₂ emissions, but some argue we are thereby prolonging our dependence on fossil fuels and hindering the development of renewables. And is the use of biomass for energy purposes sustainable? The answer can be yes or no, depending on how effectively we deal with issues such as land-use change and competition with food production. And what level of energy use is sustainable?

These are just a few questions that illustrate that sustainable energy is much less easy to define than renewable energy. Where renewable energy is a collection of energy sources, sustainable energy only has meaning at the level of the energy system. We must consider how *all* energy sources *together* meet all the energy services the world needs. In the words of the Brundtland definition, it is energy that “meets the needs of the present generation without compromising the ability of future generations to meet their own needs”.

We all know our energy system at present is *not* sustainable. A full 80% of our energy system runs on fossil fuels - coal, oil and gas. This represents a finite resource that sooner or later must run out. Fossil fuels also produce CO₂ which is a natural greenhouse gas. The prodigious amounts of fossil energy we presently use will soon double the level of CO₂ in the atmosphere compared to the pre-industrial level, and this is very likely to cause dangerous climate change. So says the International Panel on Climate Change and I have no reason to doubt the consensus.

Of the two issues with fossil fuels - resource depletion and global warming - one must conclude that global warming is the more pressing one. In fact, global warming is a problem precisely because the world's endowment of fossil fuels is so rich. So rich in fact that if we burn it all and allow the resulting CO₂ to build up in the atmosphere, we move the climate over a tipping point.

Thus, the prime challenge of sustainable energy is to make most of our energy carbon-free. To transform the energy system into a “low-carbon” one.

I mentioned that 80% of the world's energy supply is currently of fossil origin. Of the remaining 20% roughly half is biomass and waste. Most of that is in the form of “traditional biomass”, that is firewood, agricultural residues and dung as used for basic energy provision, notably in the developing world. It is a form of energy that is intended to be phased out in exchange for modern use of (bio)energy. Nuclear energy contributes 6%; most of the rest is hydropower, a very mature form of renewable energy whose potential has already been tapped significantly. Wind and modern use of biomass including biofuels are approaching the one percent level, and solar energy contributes less than a tenth of a percent. Such is the make-up of our energy system.¹

So it is clear that the energy mix must change. But not just that. The world asks for *more* energy, rather than less. This is

primarily a consequence of the growth of energy demand in the developing world. Perhaps an additional 5 billion people will by mid century adopt a pattern of energy use similar to ours, which would double energy demand. Over the same period IPCC advises that humanity reduces its CO₂ emissions to significantly less than half of what they are today. The combination implies that by mid century at least 80% of energy must be carbon-free. For this we will mostly have to rely on new renewables that presently only contribute at the percent level and on carbon capture and storage which is still at the demonstration stage. This is the challenge of “sustainable energy”. It is the challenge to rebuild the energy system by the middle of the century, and prepare for further changes later on. It is a challenge of unprecedented magnitude.

But what is the *nature* of the energy challenge? Is it a technical challenge? Or a social challenge? or both? My chair here at Leiden is in the Industrial Ecology department of the Institute of Environmental Sciences. Industrial ecology is the science that looks at the interplay between the technical and social. So this issue is at the heart of what industrial ecology is about and key to answering the question what sustainable energy is.

Feasibility

To illustrate that change at the level of the energy system is not a simple technical matter, I want to cite two early examples of people who considered the prospects of running the energy system fully on renewable energy.

One of the first of such analyses that caught my eye was a paper by John Turner of the US National Renewable Energy Laboratory, published in *Science* back in 1999.² He considered whether solar panels could generate all US electricity. Simple arithmetic allowed him to calculate that an area of roughly 100 by 100 miles packed with panels is enough to produce the electricity the US consumes. He then drew the 100 by 100 mile patch on the map - in empty and sunny Nevada- and

concluded that it was doable. His paper was called *A realizable renewable energy future*. There is plenty of sunny desert. You just need to start manufacturing and installing the panels.

But strange enough, using similar technical data, the environmentalist Ted Trainer concludes the opposite in his book *Renewable energy cannot sustain a consumer society*.³ He cites the claim on land as infeasible, and points out the fact that solar power is intermittent, so that a lot of excess capacity and storage would be needed, making the system impractical and unaffordable. He concludes that a world running on renewable energy - of whatever type - must inevitably be a simpler world.

Later on I will quote more recent, more elaborate work, but the polarization of views as to what is feasible remains very strong to this day. It is simply very difficult to realistically picture a deeply decarbonized energy system. When we do, we are thrown back at what Schumpeter called our “pre-analytic visions”. We know the answer before we start analysing the question. And when we do press on with analysis we will tend to develop cases that support our initial intuition. It is in the nature of questions such as the one we are presently considering, that the data and context are sufficiently ambiguous to support either view - that it is easy, or that it is impossible.

A mental model

So we see that opinions are deeply divided about the feasibility of the energy transition and whether or not this will require a social change. Therefore, people have been searching for images; for analogues with challenges that we have successfully addressed in the past.

Those who resist the idea that life style change will be necessary usually resort to the analogy of an industrial war effort.⁴ It is an analogy that allows one to illustrate how the numbers of wind turbines, solar panels and electric cars that are needed to realize the energy transition are similar to the enormous numbers of

airplanes, tanks and ammunition that were built during the second world war - the common reference. If we could do it then, we can do it now - so the argument goes. But I find the war analogy ultimately problematic. After all, a war effort and a war industry the very opposite what one would deem sustainable. Its chief characteristic is a massive, short-term conversion of industrial capacity to a single purpose for a number of years. It tends to leave unpaid bills behind and an industry sector that has been turned upside down. Once the war is won, it has to revert back to normal again. But what is that normal state in the fight against climate change? And will a massive new industrial effort bring a sustainable society any closer?⁵ I am not sure about that and I therefore would like to offer a different image.

I propose we view the rebuilding of the world's energy system as a task that is like that of building a medieval cathedral. The parallels I see are the following. Firstly, it took more than a generation to build those cathedrals. And those who started the project were aware they might not live to see it completed. Secondly, while the construction process may have started on the basis of a grand design, many of the engineering details had to be worked out as work progressed. Thirdly, more often than not the cathedral ended up looking quite different from its initial design. But in spite of the muddled process of building, when it was finished the cathedral dominated the towns that had build it. Massive and visible; the pride of the town and its people. Fourthly, cathedral building was an irresponsible undertaking, financially and otherwise. But in the end cathedrals came to be enjoyed as buildings that captured the essence of the medieval Christian civilization. And lastly, a cathedral is more than just the physical thing, the building. It is a cathedral only because of the spiritual dimension it also has. They were built to celebrate Christianity, a religion that was at the heart of medieval civilization.

While there are inherent dangers to this sort of parallels and I surely don't want to push it too far, I believe that the five aspects of cathedral building I just highlighted are relevant to the rebuilding of the energy system. It will take a long time

to complete; we basically do it for our children, for posterity. We have to start now, even if we haven't sorted out the details. The energy system may end up different from how we now imagine it. It won't be cheap, but so long as it doesn't bankrupt us that shouldn't stop us. It will be massive and visible so we must really want it. And finally, we will only be able to muster the courage to build it if we have a shared vision, a common purpose that unite us.

I will occasionally come back to the cathedral metaphor as we go along. But before moving on I want to highlight which requirements for cathedral building I miss most in relation to the transformation of the energy system. On the physical side that is our willingness to accept this big new thing in our midst. Just think of the opposition there is to wind turbines, to carbon storage projects, to nuclear power stations, even to large-scale solar farms. We clearly haven't come to terms with the physical presence of a sustainable energy system. On the social side we lack motivation, a purpose, a coherent and encompassing vision of what sustainable energy is and how it fits in the larger image of a sustainable society. There can be no doubt that we need this in order that we have the motivation to build the sustainable energy system and have the wherewithal to sustain the effort for as long as it takes to build.

Are our prospects somehow constrained?

So let us review the status of the societal consensus for building a sustainable energy system. We saw earlier how opinions on the technical feasibility of a renewable energy system were polarised. The central question that divides opinion with regard to the wider social context is the following:

Are the prospects of humanity somehow constrained because we live on a finite planet?

This is such a deep question that over the centuries two intellectual traditions have emerged around positive and

negative answers to this question. I will refer to those who deny constraints as optimists, and to those who believe that the human prospect is fundamentally constrained as pessimists. Other labels are possible, but for the purpose of this lecture a simple distinction in optimists and pessimists is useful. Let me briefly describe these intellectual traditions, starting with the optimists.

The optimist, business-as-usual tradition

The optimist tradition that was created by scientists - or rather by the men who first conceived of the *concept* of science. It is common to refer to Francis Bacon in the early 17th Century as the starting point of this tradition. In his *Novum Organum* he introduced the modern scientific method. Here, and his utopian *Nova Atlantis* he articulated how rational investigation of nature was to inspire practical and useful inventions to improve life - what we now call innovation. What started out as utopian musings, was after an incubation period of one or two centuries turned into reality once the industrial revolution took off in the 19th century. It further accelerated and diversified in the 20th century, spawning the information revolution most recently.

Within this tradition one anticipates that one of the next revolutions will be an *energy revolution* that will usher in an era of cheap and plentiful renewable energy, smart grids, super grids and - who knows - nuclear fusion. The tradition sees civilization moving onwards and upwards at an ever-increasing pace. Technological progress is vital to keep this process going but luckily technical progress knows no bounds; science is - to quote a famous report⁶ - *the endless frontier*. We may run out of new continents to discover and exploit, but our ingenuity will never run out. In fact, the pace of technological change has steadily increased over the centuries. Technology guru Ray Kurzweil has said it explicitly: “technological progress is exponential, not linear.”⁷

So we see how innovation-based growth underlies the optimist’s vision that constraints will always be overcome by

new innovations. We cannot tell what these are, but we must be confident. What was started four hundred years ago by scientists has now become a leading paradigm for economists and almost a dogma for politicians. There are no limits to growth, just limits to imagination.

The pessimist, limits-to-growth tradition

The pessimist reading of history and of the prospects of humanity goes back much longer than the optimist tradition. After all, growth is only a relatively recent phenomenon. The starting point of the modern pessimist tradition is Robert Malthus’ famous essay *On the Principle of Population*. It famously explains that unless Man somehow keeps population growth in check, the diminishing returns of new agricultural land will cause humanity to overshoot the limits of what the land will provide. This was the first exposition of the idea of *Limits to growth* which forcefully came back in 1972 with the Club of Rome report of that title.⁸ It made essentially the same point as Malthus did, but in an updated and generalized context. It works from the basic notion that all resources are finite - not just agricultural land but also mineral resources and the capacity of the earth to absorb waste. According to *Limits to Growth*, this finitude must imply that the prospect for growth diminishes over time, lest we overshoot the carrying capacity of the earth.

It is not that the pessimists do not consider technical progress. They do. But by contrast to the Baconians it assumes that there are diminishing returns of that technical progress so that it ultimately is not fast enough to allow growth to continue indefinitely.

The need for a synthesis

When we look at the influence these traditions have in the real world, we must conclude that the optimist, Baconian tradition is the *de facto* standard world outlook. It defines what one might call Business as Usual. It defines the expectations

of the future for virtually all actors: businesses, governments, politicians, but also of most people - if not as citizens, than certainly as consumers. Neo-Malthusian pessimism is perhaps more frequently encountered in academia, but isn't very influential today in practical life. In my mind it is pointless to ask who is right and who is wrong. The fact that both traditions have existed side by side for so long suggests that both have a point, and the debate between them is both continuous and useful.

I started the investigation of optimism and pessimism because I sense a lack of common purpose. The absence of a coherent societal vision of how to deal with the energy transition. We have seen that the traditions are divided on the nature and speed of technical progress and how that impacts the prospects for growth on our finite planet. The two different perspectives translates into opposing pre-analytic visions of the role of social or lifestyle change in relation to the dual challenges of energy and climate change.

Because in the Baconian, business-as-usual tradition technology is essentially a panacea, social or life style change does not need to be actively considered. If, however, one accepts that the Malthusians have a point, and that technology will ultimately not deliver enough to sustain growth, than change in the social sphere becomes inevitable. Malthusians from Malthus to the Club of Rome have been careful to present their findings neutrally and to leave that conclusion to the audience, but the conclusion is so obvious that they are accused of pushing a social change agenda nonetheless. We see this play out in the polarised political debate around energy and climate change. Those who point out that climate change imposes limits are often accused of forcing unacceptable lifestyle changes.⁹

I believe that in order to move forward with the energy transition and to build the new energy system - the cathedral of our time - we must resolve the tension between the Baconian and Malthusian pre-analytic visions of the future.

We must address to what extent limits are still forced upon us, even as technical progress is as rapid as it has been in the past centuries.

To see how and why that is the case, let us return to the technical side of the debate and consider recent technical work that has come out and that describes the technical requirements for the energy transition. It will show that even when technical innovation and deployment is as rapid as it has been in the past centuries, there are still limits to what can practically be achieved.

The physical plan

Earlier I cited the early, simple assessments by Turner and Trainer of whether or not the world could be run on renewable energy. In the meantime much more detailed work has been done. Much of this was triggered by the publication of the fourth IPCC assessment report, which made clear that by 2050 we need at least a four- or fivefold reduction in the carbon intensity of energy delivery. It effectively means that by 2050 the energy transition should be almost complete, and this provides useful focus. The forty years between now and then is the sort of timeframe over which anything that can *at all* be built should be a good way towards completion *if we put our minds to it*. It is the timeframe of cathedral building.

I want to highlight the salient points from four different studies.

The first point is land use and visibility. There is no better illustration of the physical impact of massive renewables deployment than David MacKay's masterful book *Sustainable Energy - without the hot air*.¹⁰ MacKay is rigorously quantitative in his assessment of what a carbon-free Britain looks like. On the assumption that Brits will consume as much energy in 2050 as they do today he starts allocating resources to match the demand. He places wind turbines on the map - on-shore and off-shore. He allocates land for biomass; he adds nuclear plants where

this is possible - that is where they are today. He puts a carbon sequestration infrastructure for 'clean coal' in place. He builds a tidal energy barrage across the beautiful Severn. This delivers about 10 GW - equivalent to ten large power plants - but at the expense of fundamentally altering a unique wetland area.

Taken together, this shows that if renewables are to contribute materially, they will be "all over the map". MacKay speaks about the "industrialization of the country side". There is probably no clearer way to indicate what planning battles lie ahead, especially when we remind ourselves that even now many low-carbon projects are opposed. MacKay's straightforward analysis shows that that must change. A low-carbon energy system will be just as visible as the cathedral of a medieval town. And no cathedral was ever built in a town of agnostics.

8 A second point that is suggested by the analysis is that in order to fully decarbonize the energy system, one must develop all options and all energy resources pretty well to the maximum. This includes all renewables, but in many cases nuclear and clean fossil energy as well. The more categories one excludes, the more daunting the challenge of decarbonisation looks.

A third issue with low-carbon energy is that they require a lot of material. Work that René Kleijn, Laurant van Oers, Ester van der Voet and myself have done here at Leiden has assessed the material intensity for energy service provision and how in that respect a low-carbon energy system differs from the current fossil-based system.¹¹ The initial results indicate that in aggregate low-carbon energy requires more material, more metals than fossil energy provision does. This fact challenges the tacit notion of the optimists that as the world progresses we become ever more efficient, and that through technical progress we need ever less inputs to produce a unit of output. When it comes to energy the world will not "dematerialize", but rather the opposite will happen. It reinforces a point we easily forget, namely how efficient and convenient fossil fuels are in comparison to the low-carbon alternatives. It also is an

illustration of the Malthusian idea that technological progress doesn't remove all constraints.

A fourth point in the realization of the physical plan for a low-carbon energy system is the time scale over which it can be deployed. On this topic, my Shell colleague Martin Haigh and I wrote an opinion article in *Nature* a year ago.¹² Entitled *No quick switch to low-carbon energy*, we estimated the timelines for future deployment of new energy technologies on the basis of past experience. We argued that scale-up has never been faster than one order of magnitude per decade when technologies are young, and much slower after they have reached one percent of the mix. These empirical laws are essentially the outcome of prudent investor behaviour in the development of new technology. These "laws" constrain what can be done between now and 2030, but beyond that point in time our analysis suggests that what can be achieved out to 2050 is first and foremost dependent on the market share that new forms of energy can capture. In other words, on how the individual forms of energy supply can be fitted into a working system.

Precisely this point was recently addressed in a study called *Roadmap 2050*, published last year by the European Climate Foundation.¹³ It lays out a plan that would allow Europe to meet its target of 80% CO₂ reduction by mid-century by rebuilding the energy system. It considers a Europe that electrifies as much of its energy needs as possible, and completely decarbonises that sector. The reference case assumes 60% renewables and the remainder split between nuclear and clean fossil. One fascinating aspect of this study is that it shows it can be done - at least theoretically. The plan proposes massive deployment of solar power in the Mediterranean belt, and equally massive amounts of wind power in the windy north of Europe. In order that this produces a working power system, the power transmission grid across Europe must be massively strengthened so that supply can be matched with demand which may be half a continent away. Even then, in order to make up for those odd days when

the wind doesn't blow and the sun doesn't shine there needs to be a very significant amount of back-up gas-fired power plants. The conclusion that is drawn in this study is that an unprecedented level of planning, co-ordinated action and commitment is needed to make this happen.

I am not aware of any studies of similar preciseness at world scale. Most of what exists at that level still boils down to rather crude assertions that there is plenty of renewable potential. Much more needs to be done to work this into a plan.

What this overview of the physical aspects of a sustainable energy system has made clear is that there are perhaps no hard physical limits to what can be achieved by way of a low-carbon energy system. There may well be bounds on the time within which we can realize this. We certainly cannot do it by 2030. Whether or not we can rebuild by 2050 is a more open question. We now know how massive the task is, how much material, how much effort, how much willingness to spatially accommodate the new energy, and how much co-ordinated planning will be needed to realize it.

In the final analysis this must mean that even to the extent that the physical limits can be pushed out, the limit becomes a social one. The situation is well summed up in a quote from Friedrich von Hayek:

[There] is little question that almost every one of the technical ideals of our experts can be realised within a comparatively short period of time if to achieve them were made the sole aim of humanity. There is an infinite number of good things, which we all agree are highly desirable as well as possible, but of which we cannot hope to achieve more than a few within our lifetime, or which we can hope to achieve only very imperfectly.¹⁴

The Grand Narrative

On reflection, this is a most painful observation as it makes expert opinion on mere technical feasibility almost irrelevant.

Knowing a sustainable energy system is possible is one thing. The task then becomes to move the task to the top of the priority list. Experts will say that the task of rebuilding the energy system is an obvious priority in the light of climate change and the pivotal role of energy in development and sustaining modern life. But other experts will argue for other priorities. Just think of health care, clean air, liveable cities, education, a balanced budget ... If we follow this line of reasoning to its logical end, the question becomes: What is the Grand Narrative that tells how humanity might deal with the planetary boundaries while simultaneously aspiring for a better life? Grand Narrative is a good term to use, I believe. Just as the cathedrals of former days were built as the embodiment and expression of religious aspirations, so can a sustainable energy system only built - be completed - on the basis of an overarching vision, a Grand Narrative that gives it a place and a purpose.

Historians and archaeologists who have studied the waxing and waning of civilizations over millennia - as opposed to those who study only the growth of the past two centuries - easily recognise the challenge of sustainable energy for what it is, namely a challenge to civilization as a whole, for which civilizational renewal is the answer. The great historian Arnold Toynbee noted that civilizational renewal, societies' search for a new model, a new set of aspirations, a new Grand Narrative is the ultimate and greatest act of human creativity.¹⁵

It is no wonder then, that so many of us who contemplate the issue find themselves challenged to paint a clear *and concrete* picture of what new set of aspirations are commensurate with sustainable development. Most books on the subject of energy and climate change follow a similar pattern. They first make clear just how awfully big the challenge is and then present a vision. But those visions are without exception either very personal or very abstract. Apparently the moment for all this good thinking and creativity to congeal into a Grand Narrative hasn't arrived yet. Let me illustrate that by quoting three examples.

The environmentalist and former presidential advisor James Speth refers to the energy/climate challenge as “our Great Work” and observes that it will require “a new consciousness”. He quotes scenario work that shows that without a change in *values* all scenarios run into big trouble. He also notes that whereas “[i]n the past, leadership most often came from scientists, economists and lawyers [...], [t]oday we need especially the preachers, the philosophers, and the poets”.¹⁶

The environmentalist David Orr also calls the climate and energy challenge “our Great Work” as he ponders how to achieve it he asks himself: “What is the right narrative for our time?” and immediately admits “Frankly I don’t know”. But he offers a few suggestions still, one of which is “radical hope”, a concept developed to describe how native Americans looked out to the future once their ancient hunting grounds were gone. The most brave amongst them anticipated a future goodness, but still lacked the concepts with which to understand it.¹⁷

These maybe people whose background associates them most naturally with the limits-tradition, but even commentators who are arguable closer to the growth-tradition see the need for a change in the social sphere. One example is Thomas Friedman. His book *Hot, Flat and Crowded* discusses extensively the entrepreneurial opportunities of a future “energy internet” providing clean energy. Still, he is explicit that none of that will happen - or not nearly enough of it will happen - unless there is action at the political level. He points numerous times to the democratic deficit, quoting twice Prof. Maniates who has pointed out the fallacy of the business-as-usual view of “greening”, which is that a lot can be achieved through easy, cost-effective actions. And that that is *all* we can hope for anyway since we lack the means to persuade people to do anything that “isn’t private, individualistic, cost-effective and, above all, easy”. He concludes that “Never has so little been asked of so many at such a critical moment.”¹⁸

I interpret these ideas as attempts to reach out towards a synthesis. One that allows the constraints of our finite planet to find their way into the business-as-usual world that is predicated on growth. But so far it hasn’t been translated into a program that is acceptable to the public, either through their behaviour as consumers or through their democratic action as citizens.

Conclusion

So we come to the inevitable conclusion that the energy challenge is both a social *and* a technical one. I hope that in this lecture I have shed some light on how the optimist and the pessimist traditions are both relevant in formulating a path forward. Climate change is a clear imposition of limits. There is only a finite budget for CO₂ emissions left. Before that runs out, that is before the middle of the century, we must significantly convert the energy system into a low-carbon one. New low-carbon technologies will be developed and deployed as the optimist tradition would have it: wherever we encounter limits, new technology provides the solution. And no doubt it will - to a degree.

But we have also seen that there are limits to the scale and speed of deployment which will not go away by technical progress. These are social limits on what it takes to implement the new technologies at scale and in time. They come in the form of prioritization, of planning and co-ordinated action. And *that* will only be possible when our collective views on what is feasible and what isn’t, becomes more aligned.

Clearly, renewables - all renewables - are being deployed rapidly - but not nearly rapidly enough to meet the climate challenge. Nor is there agreement where the practical limits to their deployment lie. In the absence of such agreement, we are wavering as to whether or not fossil energy with carbon storage or nuclear energy should be part of the future energy mix. Or that we should simply reduce our energy consumption. It all entails compromises and trade-offs.

In the developed world we have grown accustomed to a very high level of energy use at the time we were unaware of the big trade-off that exists between fossil fuel use and climate change. When the deployment of new energy technologies progresses from the one-percent to the ten-percent level we should hope that opposing pre-analytic visions give way to an agreed understanding emerges over what is feasible and what isn't and the trade-offs energy use entails, enabling decisiveness and a coherence of vision that is presently lacking.

We will almost inevitably stay in business-as-usual for a while longer, raising the stakes of our bet over climate change. But meanwhile we are laying the foundations of the cathedral of the future energy system. Here and there the first above-ground structures are visible in the form of the steady growth of renewable energy and pilots for carbon capture and storage. The rebuilding of the energy system before 2050 is a project of which we do not know if it will exceed our capacity to complete it. But as so often with cathedrals, the generation to come may find the foundations useful, even as it decides to complete the cathedral one size smaller than anticipated. It will be... the accidental cathedral.

Closing remarks

This brings me to the end of my lecture. But before closing I would like to briefly indicate how these thoughts inform my plans and activities here at Leiden, and thank a few people.

The story I have told today and the questions it raises is a vital part of the curricula on sustainability and sustainable energy, which cannot go without a deep analysis and discussion of the energy and climate debate. In particular the interplay between technical advance and the limits to deployment is a topic of my interest. I have given lectures on this topic in the past and will continue to do so with much enthusiasm. If the energy transition is “our Great Work”, much of it will come down on the present generation of students.

As for research, my work at the Institute for Environmental Sciences (CML) in collaboration with Gjalt Huppel, René Kleijn, Ester van der Voet, Jeroen Guinee and others is aimed at quantification of the energy transition through scenario-based input-output and life cycle analysis. We also will be looking at quantifying the prospects energy technologies that are still in their infancy, such as bio-based solar cells that Huub de Groot and others are trying to develop. The ultimate aim of this work is to give us a better, a more granular picture of the possibilities and limits of technical solutions to the energy challenge. As I have made clear, such improved understanding will be vital to allow society to find out where the balance lies between deployment of new technology and social accommodation of the planetary boundaries.

In all of this I hope that my role builds a useful bridge between academia and industry, between Leiden and Shell. My work in Shell exploring energy futures benefits from a diversity of inputs, including academic insights. Conversely, I hope that the university benefits from my exposure to the realities of the energy business.

Perhaps not much of that transpired in today's lecture. The setting in this auditorium for once forced me to step away from PowerPoint, charts and numbers. This presented an interesting challenge and put me naturally in a mode of intellectual reflection, which I hope you enjoyed.

In closing I would like to thank Gjalt Huppel, René Kleijn and Geert de Snoo and Sjoerd Verduyn Lunel for inviting me to come to Leiden and work at the Institute for Environmental Science. I have much enjoyed the atmosphere, the lively discussions, the quality of the work and the interaction with students, and I very much look forward to the coming years.

Ik heb gezegd.

References

- 1 Rounded numbers based on International Energy Agency, *Key World Energy Statistics* (2008)
- 2 J.A. Turner, *Science*, **285**, 687 (1999)
- 3 T. Trainer, *Renewable Energy Cannot Sustain a Consumer Society* (Springer, 2007)
- 4 See e.g. M.Z. Jacobson and M.A. Delucchi, *Scientific American*, **301**, 58 (November 2009)
- 5 An more subtle account of the wartime mobilization analogy and the impact on society is given by D. Bartels, *Human Ecology Special Issue No. 10*: 229-232 (2001)
- 6 V. Bush, *Science: the Endless Frontier*, report to the President of the US (1945).
- 7 R. Kurzweil, *The Singularity is Near - When Humans Transcend Biology* (Duckworth, 2005)
- 8 D.H. Meadows, D.L. Meadows, J. Randers and W.W. Behrens III, *The Limits to Growth: a Report to the Club of Rome's Project on the Predicament of Mankind* (Universe Books, 1972)
- 9 This point is well illustrated in R. Pielke Jr., *The Climate Fix - what scientists and politicians won't tell you about global warming* (Basic Books, 2010)
- 10 D.J.C. MacKay, *Sustainable Energy - without the hot air* (UIT Cambridge, 2009)
- 11 R. Kleijn, E. van der Voet, L. van Oers and G.J. Kramer, *Metal use in low-carbon power generation*, submitted to *Energy* (2010)
- 12 G.J. Kramer and M. Haigh, *Nature*, **462**, 568 (2009)
- 13 European Climate Foundation, *Roadmap 2050, a practical guide to a prosperous, low-carbon Europe* (2010), www.roadmap2050.eu
- 14 F. von Hayek, *The Road to Serfdom* (Routledge, 1944)
- 15 A.J. Toynbee, *A Study of History* (Oxford University, 1934-1961)
- 16 J.G. Speth, *The Bridge at the Edge of the World - Capitalism, the Environment, and Crossing from Crisis to Sustainability* (Yale University Press, 2008), p. 205, 233-235.
- 17 D.W. Orr, *Down to the Wire - Confronting Climate Collapse* (Oxford University Press, 2009), p. 99, 172-173.
- 18 T.L. Friedman, *Hot, Flat and Crowded - why the World needs a green revolution, and how we can renew our global future* (Penguin, 2008), p. 207-208.