Nuclear power - examining the energy balance

Jan Willem Storm van Leeuwen
(Ceedata Consulting, Netherlands)

8Mar06
Arup, 13 Fitzroy Street, London, UK

[a] 1/54 Ladies and gentlemen, English is not my first language so I hope you will enjoy my terrible Dutch accent. The title is climate change and nuclear power. I have to introduce several things to you. First something about myself and my co-author, and then something about the study, the methodology, and then about the nuclear system and then to the results.

2/54 I ask my friends and show them this photograph, "What do you see?" Someone said, "I think it's some artwork, a novel technique." Another said, "No, it's an etched surface from a nanotechnology laboratory." A musician said, "No, I think it's the score of an experimental piece of music."

3/54 I return to this question.

4/54 This presentation is based on a study, *Nuclear Power, The Energy Balance*, by Phillip Smith and me. Phillip Smith was a professor of nuclear physics at the University of Groningen in the Netherlands. I am very sad to say "was"; he passed away last December. I studied physics and chemistry at the University of Utrecht and took my Master of Science degree at the Technical University of Eindhoven.

My fascination for nuclear technology was sparked by the US exhibition, *Atoms at Work*, in 1966. As a young student I had the job as reactor assistant with a real operating research reactor. For years now I have been an independent consultant, technical assessment, and the laregest job I did is this one. Besides that I am working for the Dutch Open University to develop courses for chemistry teachers.

5/54 With Phillip Smith, I prepared two reports published in 1982 and 1987 by invitation of the Dutch government. During that time I was senior scientist at the Centre of Energy Conservation and Sustainable Technology in Delft, a member of a team working on the development of an innovative social economic scenario. The task of Phillip and me was to

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[a] Cross reference to PowerPoint show by slide number and total number of slides.

assess all aspects of nuclear power in that scenario. The scenario had the profound effect on the Dutch energy policy during the 1980s and 1990s. In 2000 the Greens of the European Parliament asked me to update that study and to prepare a paper for the UN Climate Conference, COP6 in the Hague. Phillip Smith and I continued the in-depth study of nuclear power and we decided to publish the results on the web[b] to facilitate the interaction with our target group: scientists, policymakers and all people who are interested.

Some of our results seemed to be at variance with other studies on nuclear power. I will briefly explain some of the origins of the differences. We based our approach on the thinking that nuclear power should be as sustainable as possible. That implies avoidance of harmful and irreversible effects.

6/54 About the study – the methodology. The difference with other studies doesn't lie in the database. We used the same database as World Nuclear Association and the International Atomic Energy Association.

7/54 Our method is an energy analysis describing the energy and mass flows of a complex system. This requires a complete life cycle analysis, LCA, and that is a detailed description of all processes needed to free the nuclear energy in the uranium and to convert it into electricity. Energy and mass are conserved quantities whereas the value of money is unpredictable beyond the short-term horizon. Especially the case of nuclear energy, this is an important factor because the completion of a nuclear project may take 100 to 150 years, an unprecedented timescale. Each nuclear power plant leaves behind an energy debt. The time at which the debt should be paid is irrelevant; it must be paid, quite different from monetary debts. An energy debt can't be written off as uncollectible.

8/54 Process analysis – what we did is all flows of energy and mass, as you see. The blue block in the middle, that is the process, can be everything: making a brick or making a TV or a car or whatever. Every industrial process needs energy as fossil fuels, as electricity, human labour, services, materials, capital goods. The process has a product but also some waste heat and material wastes.

9/54 Some unique features of our study is it is exhaustive. We analysed all things we could find. New is the energy debt. Its caused by construction and by dismantling. I will return to that.

The third importance difference is the ore grade energy relationship. I will return to that as well. We used empirical figures, not unproven concepts, and we used a large database and recent data larger than most other studies.

10/54 First I discussed the reactor technology, which reactor can be used, then the concept, energy for energy. Then something about emission of greenhouse gases, nuclear share, how much nuclear can we get, energy from uranium, and conclusions, of course.

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[b] www.stormsmith.nl

11/54 There are several technologies available. Roughly you can divide them into classes. The thermal neutron reactors, the LWR[c], that is the most common reactor. The breeders: there are two kinds, the uranium plutonium breeder and the uranium thorium breeder. The last two are so-called fast reactors. Fast means the neutrons are fast. They aren't operating fast, but the neutrons, which cause the fission, are fast.

12/54 At present, 88% of all power reactors in the world are light water reactors. You can see in this diagram.

13/54 Important in the discussion is the prospect of the breeder.

What we call a breeder is not just a reactor: it is a system, it is a cycle. You see in this diagram three processes, three blocks. Each has its own processes. The red circle is the cycle. We can start at the left, the yellow box. We start with uranium and plutonium. We make fuel with it, we put it in a breeder reactor, it is a fast reactor cooled by sodium. Then the fission takes place. In a fast reactor, the fast neutrons can convert uranium 238 into plutonium. When it works well, there are more plutonium atoms formed than are fissioned. Therefore it's called a breeder.

But you also get fission products. They have at first effects on the fission process. So the spent fuel has to be repossessed in a separation facility, and in that facility the plutonium is separated from the uranium and the fission products, and higher aconites such as curium and americium. They must be removed because they have very nasty effects in reactors. They are very reactive and they are neutron emitters. They make a reactor unpredictable.

14/54 State of technology – the light water reactor is a major technology. In a light water reactor, no more than 0.7% of the natural uranium can be fissioned[d]. Advanced reactors have the same property. They can fission more than .7%. At present, the present newest reactors achieve .6%; .7% is the maximum. The uranium plutonium is not feasible.

15/54 That's because the system has to work finely tuned. It must work as one system. If one component fails, the whole system fails. None of the three components have ever demonstrated operation as needed, let alone the cycle as a whole.

16/54 The choice for the next decades will be thermal neutron reactors in case the light water reactor in the once through cycle. That means, no repossessing; no recycling of uranium or plutonium.

17/54 So, now we have had the introduction, now we can go to the content of the study. Key points: nuclear, greenhouse gases, nuclear share and how much energy can we get from the uranium.

18/54 Energy for energy, that's an important concept. Releasing energy from uranium costs energy. This applies for any energy system. To make useful energy out of a raw energy carrier, you have to invest energy. The nuclear reactor is part of a very complex

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[c] Light water reactor, in contrast to reactors that use heavy water (deuterium instead of hydrogen) such as the CANDU.

[d] Because the naturally occurring proportion of the fissile isotope, uranium 235, is 0.7%.

system. The nuclear process chain consists of conventional, industrial and nuclear operations.

19/54 This is a simplified diagram of the nuclear system. The large blue box is the system as a whole as we see it. We start with uranium ore in the ground and it goes through a number of processes and we end at the geological repository. The inputs are fossil fuels and materials, as for every industrial process, and the outputs are, in this case, only electricity and radioactive activity - the radioactivity in a reactor balloons a billion fold during its operation - and we have non-radioactive wastes.

20/54 The next slide is only to let you see the whole system, but it’s not very useful to know all the processes. You see the three main parts. What we call the head of the processing, that is the blue box above. In the middle we have the reactive construction but also operation and maintenance and refurbishment. To get a reactor operating for 13 years, major components have to be refurbished. The lower part, that’s the back end, the notorious back end of the nuclear process chain.

21/54 This is not a readable diagram I am afraid. The nuclear system, the yellow box on the left, all inputs, and there are two main flows of wastes that are the non-radioactive wastes including greenhouse gases and the radioactive. In our view, radioactive waste should be contained and disposed of in a safe way and isolated from the biosphere.

22/54 What do we call net energy? I have the blue box, that’s the nuclear system. The input is uranium and fossil fuels. The output is electricity, it’s put into the grid, and from the grid electricity is used in the processes before and afterwards. The grid, you can see it’s a shared pot of electricity and the suppliers put electricity into it and the consumers empty that pot. Electric kilowatt-hours are not earmarked. What we did, all electric inputs of the nuclear system were subtracted from the electricity production. That’s the current situation.

23/54 To make a nuclear comparable with renewable systems, it should be self-sustaining. All input should be supplied by the energy system itself. In theory, it’s possible. You can convert electricity into hydrogen or oil liquid fuels that can replace the fossil fuels.

24/54 Then we come onto a very important concept, the energy debt. I hope you can decipher this diagram. We start at the left. First you have to construct the reactor of the power plant. Then it starts up and begins to deliver electricity, and when it’s closed down, after a number of years, the reactor has to be maintained for maybe a century. Afterwards it has to be dismantled and the wastes should be disposed of. The height of the lines are a measure of the quantity, not the area. You see E1 is that large bar to the left. That’s the gross electricity production. That’s what you find in the statistics of BP and The World Nuclear Association.

E2, the second bar, there we subtract the operational energy input for making fuel from uranium, but the energy debt is looming and when we have cleared all nuclear wastes after a hundred years, we have spent another amount of energy. So the real net energy production is A3 in this diagram.

25/54 What we did to analyse the system is to capitalise the energy debt at the start of the energy production. We summed up the energy needed to construct the reactor but also to dismantle it and to dispose of the wastes.

26/54 Greenhouse gases - the nuclear process chain emits carbon dioxide. We did analyse that and I have some thoughts about other greenhouse gases and I will return to that.

27/54 Construction is a major energy consumer. Here are some figures. In our study we found that construction of a nuclear power plant of 1 GW produces 2.5, 7.5 teragram. A teragram is a million metric tons of CO_2. When you average it on the whole lifetime production - the gross lifetime is E1 a few diagrams ago - then we get 12 to 35 grams CO_2 per kilowatt hour delivered to the grid. That is not a net energy.

There is a study in the UK of Sizewell B and you see that it falls within our range - that's by the ExternE[e], I mean AEAT[f].

28/54 The CO2 emissions of the whole cycle can be seen as this. The contributions of the four components. The green one at the left is construction. There's a large uncertainty range in it. That's not because we did this but because the data is very uncertain and because numerous reactors have different construction masses. The second, the blue green, that's the head of the cycle, the front end which means making, from uranium ore, nuclear fuel. That bar is not, as this diagram suggests, a fixed value. It depends on the ore grade, I will return to that. The third bar is the back end, that means the operational wastes. The fourth one, that's the dismantling of the nuclear power plant. The last, the purple one, that's the sum of all contributions.

29/54 We analysed this as a function of the ore grade and you see that the horizontal coordinates, that is logarithmic. The vertical one is linear. You see that the first part is nearly horizontal. At present the ore grade - the average worth of ore grade - is .15% uranium. It is still on the flat part of the diagram. You see below the .1% the curve is steeper and steeper, and at about .01%, a nuclear power plant produces as much CO2 as a fossil fuel power plant fuelled by gas. You see two variants: the full debt end and partial debt. The "full" means including dismantling and the "partial" means excluding dismantling, and we make the difference between hard ores and soft sores, but that's not important.

30/54 What do we know about other greenhouses gases by nuclear? One figure is solid. Enrichment in the USA produces about five grams CO2 equivalent per kilowatt-hour and freon 114, that's one of the CFCs[g]. What do we know about the other greenhouses gases? Nothing. Don't they use greenhouses gases or fluorine and chlorine? Yes, they do, lots of it. To produce fuel from uranium ore, you consumer a lot of fluorine, chlorine and it's compounds. Maybe it's the largest consumer of that component in the countries where it happens. It's never investigated, and no data doesn't mean no emissions. So if MIT[h] and

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[e] Extern-E – externalities of energy, a research project of the European Commission, www.externe.info

[f] AEA Technology Limited, www.aeat.co.uk

[g] CFC is chloroflourocarbon

[h] MIT is the Massachusetts Institute of Technology, is a research institution and university located in the city of Cambridge, Massachusetts, USA.

the World Nuclear Association claim nuclear is GHG[i] free, they should publish the results of such an investigation.

31/54 The nuclear share – what can we have globally? Global warming is a global problem so we approach this problem globally. Now, I address four points: the current share, nuclear scenarios, world energy scenarios and uranium requirements.

32/54 The current nuclear share is this one. You see electricity is about 16% of the final energy consumption of the world. Of that 16%, it's 16% produced by nuclear. Nuclear contributes 2.5% of world energy gross, not the net energy but gross energy. Hydro has the same contributions as you see. The other is generated by fossil fuels. The total energy consumption in 2004 is about 400 EJ - EJ is a very large energy unit[j] - but this is the final energy consumption and you may take that 400 EJ as needed to produce the fossil fuel electricity generation.

33/54 We can make three extreme scenarios; all three can be real. The blue part to the left is the historical development. You see nuclear power raised to a level just under 400 GW and remains flat. We can conceive three scenarios. We can go down, we do nothing, the reactors, which are operating now will be closed down after the lifetime of 30 or 40 years, and in the year 2050 we have no nuclear power anymore. Then we can hold the nuclear capacity flat, but you see in the diagram the light purple area means - the area is here represented of the amount of reactors - has to be built new. These are new reactors because the old ones are closed down. Then the third scenario, the large peak, is proposed by MIT and they propose to build 1,500 GW nuclear power by 2050.

34/54 When you put it in the context of the world energy scenario, we see this. The blue areas represent the IPCC[k] scenarios - not the area as represented for the value but the height. You see the electricity consumption will grow a little faster than the total energy consumption, and even in the ambitious MIT scenario the nuclear share will be minor.

35/54 We can clarify that a bit more in this diagram but I think it tells about the same. This is only electricity but I think it tells the same. The blue parts to the left are the historical development. Scenario 1 is doing nothing and closed down when it is time for it. Scenario 2, that means to keep the nuclear capacity flat, will mean in effect that the nuclear share will drop to below 1% in 2050. The MIT scenario will give a little larger share.

36/54 I return to this diagram. The future doesn't end at 2050. When a utility thinks, we go building a nuclear power plant, in the year 2050, nobody will start constructing a nuclear power plant without assured uranium supply.

37/54 So we have to extend the scenario until the last reactor, coming online in 2050, is closed down and reaches operational lifetime. and then you can calculate the amount of uranium that is needed to accomplish that. The yellow figures in this diagram are additive - you have to sum up to get the whole. For instance, the red scenario, the high one, needs

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[i] GHG greenhouse gas

[j] EJ is exajoules, 10^{18} joules.

[k] Intergovernmental Panel on Climate Change, www.ipcc.ch

about 15 million metric tons of uranium. That's 10 times the amount of uranium, the all time consumption of uranium up until now, so that has to be found here.

38/54 Energy from uranium. We introduce the energy cliff. We address the uranium sources, and then we can get an idea how much energy is possible from the uranium deposits in the world.

39/54 An important factor of extracting uranium from ore is the yield. Uranium has to be extracted from rock. The rock has to be ground to powder and then treated with chemicals, such as sulphuric acid or other ones, including fluorine and chlorine. But as every chemist knows, the lower the concentration in the matrix, the more energy it costs to get it out and the larger the loses will be. I have a very nice experiment to show that but it's not possible here. The red dots, the orange red dots, are empirical values from mines all over the world. The blue curve connects the dots and you see that about .01% uranium in the ore, the yield – that's the fraction of uranium as present in ore you get in the end - is about zero. There are studies that have hypothetical values – that are the green diamonds - are not proven values but hypothetical. We used a green curve in our study. As you can see, at low ore grades, that means a large overrating of the yield and a large underrating of the specific energy consumption.

40/54 This is the energy cliff. When we calculate the energy needed to get the uranium from the ore, the amount of energy needed to do that will grow with declining uranium ore grade. As you see, it is about a mirror picture of that green one of the CO2 emission. At about .02%, the net energy production will fall to zero. Here we analyse the self-sustaining energy system, nuclear system. In this case all energy inputs, including the thermal ones, the fossil fuel ones, are provided by the system itself. You see the gross electricity sent into the grid, that horizontal line at about 150 or more TJ per Mg. A Mg is one metric ton.

41/54 This diagram we made from the data of the World Nuclear Association. You see there are several ore deposits known, that are the known recoverable resources. That means resources that can be mined economically at this moment. You see at the left a peak with very high ore grade, that's Canada. By the way, the height is a measure of the amount, not the area of the bar. The width of the bar is the range of ore grade. We made distinctions between hard ores and soft ores. Hard ores are something like granite - they are much harder to mine and much harder to grind to powder and much harder to extract the uranium - and soft ores like sandstones. As you see, the leaner the ores, the more hard the ores are. That is a common phenomenon in geology.

42/54 "That's no problem," says the World Nuclear Association. You can say higher prices stimulates more exploration, more exploration means advanced techniques are becoming available. Then we get more discoveries and the cost will go down. We have more resources. Conclusion – uranium is a sustainable energy resource.

43/54 The physical facts are a bit different. The larger the amount of uranium in the earth crust, the lower its grade. For instance, granite contains about four grams per ton rock, it's very low, but the amount of granite is so huge, so immeasurably large, that the total amount of uranium in granite is huge. But the problem is to get it out.

The easily discoverable and mineable uranium resources are already in production. The physical laws stay in force and cannot be circumvented by economics. I mean to say low grades means more energy. There are large ore deposits but it will cost more energy to extract the uranium from it.

44/54 When we put two figures together, the energy cliff and a diagram of the resources, we get this one, and by chance or not you see that at a zero level grade there are no more recoverable uranium resources. The higher curve, the yellow one, is the partial depth, which means without dismantling, and the lower one is the full depth. This includes all the dismantling and all other things.

45/54 We have to say something about uranium in seawater. You can read these figures yourself; it's not very interesting to do now. These are figures which pass by in programmes and in the papers. I hear someone say we have 4.5 billion metric tons of uranium in the oceans. Yes, that's true.

46/54 To get uranium out of seawater you need a very complex system, at least six processes.

47/54 The system will be large; it will be measured in tenths of kilometres. To fuel one reactor for one year, you need to treat 285 cubic kilometre of seawater each year.

48/54 A summary for nuclear is: do they emit greenhouse gases? Yes, carbon dioxide and others I'm sure. Enrichment is sure and I think the other processes should be investigated very thoroughly.

Nuclear share in the future? Marginal to negligible.

Availability of nuclear energy from uranium? There are serious misconceptions. One of the large misconceptions you meet is uranium is energy. There are very large uncertainties. We don't know how much energy exactly will be needed to pay off the energy debt. A lot of things are still unknown. We don't know if it will be possible to dispose of all wastes safely, to isolate it from the biosphere.

49/54 Are there alternatives? If nuclear is unusable, what other options do we have? This introduces the renewables.

50/54 The alternatives should be subjected to the same tests as nuclear. That means among other aspects we have to look at the net energy production, it should have a minimum global warming protection and minimum irreversible adverse effects, something like the release of radioactive substances into the biosphere.

51/54 I will give you two examples, PV and wind.

PV in the climate of the UK and the Netherlands as well of course, the construction pay back time of PV systems is typically four to five years. The operational lifetime of PVs is at least 20 years, maybe more. The decommissioning of the energy debt will be less than two months, and what's more, it's immediate after close down of the facility. We don't have to wait a hundred years. That is what I am worried about.

Yesterday I saw this article in the Financial Times, "All industry asks for help to ease skills shortage." How do we think over 50 years about nuclear skills to clean up the wastes?

52/54 Wind turbines – these are rough figures. Energy payback is typically half a year. Operational lifetime – ten years, maybe more. Decommissioning – about three months to pay back its energy.

53/54 That takes me to my concluding remarks. The industrial society meets the thermodynamic limits in drawing its energy needs from mineral resources. The time has come to defer to the only entropy free energy source – the sun.

54/54 Now I return to this photograph. This photograph was made by sun, sand and wind, and that’s what we need. Thank you.

[Applause]